The Promise of Power-

The Power of Promise:

Sustaining Six Decades of Solid Oxide Fuel Cell Research and Development

A thesis presented in partial fulfilment of the requirements for the degree of
Doctor of Philosophy

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Declaration of Authenticity and Author's Rights

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

Date: 17th June 2024

Abstract

The promise is enticing: an energy conversion “black box” that will produce electricity cleanly, silently and efficiently. This technology, known as the solid oxide fuel cell (SOFC), was promised as an important bridge to a low carbon energy future. However, despite the promise, the SOFC has still to cross the boundaries from promise to realisation. Repeatedly rejected by some on grounds of cost or reliability, its hold on the imagination persists. This persistence raises an interesting question: how have fuel cells managed to maintain validity as such a promising technology over decades of repeated false starts? In this thesis I follow historical pathways of SOFC development and find a device repeatedly reframed around the promise of new materials and processing, with expectation constructed around these promissory materials and designs. These offered new applications, which when facilitated by reorganisations of R&D management and changing energy markets, sustained sponsorship.

Drawing on my 25 years as an SOFC researcher and augmenting documentary records with oral history, I also argue that the reframing of the SOFC reflected changing public policy imperatives around energy and the environment, from energy crises in the 1970s, pollution worries in the 1980s and climate concerns in the 1990s. Furthermore, my research adds to the evidence that the narratives and expectation around fuel cells have played a social role, providing plausible keystones for the technological optimism prevalent in policy responses to challenges around energy. This contributed to the impression that solutions to energy and environmental crises were close at hand, allowing difficult social decisions to be postponed and perpetuating business as usual. I suggest the SOFC inhabited two worlds, one of laboratory results and experiments, the other of ideas and imaginaries. Together these worlds constructed futures were the SOFC could flourish and remind us of the need to understand technologies within the social and cultural contexts in which they are both created and exist.

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Although a doctoral dissertation is the focus of an individual, this research and the resulting thesis could not have taken place without the input and support of many people whose efforts I would like to acknowledge here.

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Above all, my greatest thanks go to my wife Diane Cassidy, who for the second time in her life found herself in the unenviable position of living with a PhD candidate. Without her endless patience and constant support, I would not have been able to complete this work.

I dedicate this thesis to Diane.

Chapter 1: Introduction

In September 1995, early in my career as a materials scientist working on materials and process development, I attended a symposium at the Commonwealth Institute in London to present my latest research findings in the field of fuel cell technology. One evening, after the formal proceedings of that day had finished, we attended the conference dinner before returning to our hotels by coach. Spirits were high and there was a jovial atmosphere. During the trip, one esteemed professor of materials with a reputation for wit asked a question. “If the cover falls off a set of fuel cell conference proceedings, how can you tell what year it was held?” After a short pause he then interjected. “Go to any paper regarding commercialisation, look for the year they say fuel cells will be commercial, take five away and that is the year of your conference!” We all laughed at the joke. In the close-knit materials science community, everyone understood the adage that fuel cells were always five years away from commercialisation.[1]

Intended as a humorous comment, it harboured more than a grain of truth. The “always five years away” adage raised an interesting question: how have fuel cells managed to maintain validity as a potential energy conversion technology, a validity which is still held today, after so many decades of repeated rejection by different energy focussed actors? In his 2019 history of fuel cells, Harold Wallace related this persistence of the idea of the fuel cell to the tenacity of human imagination linked to changing societal contexts, where the two together serve to construct futures where the fuel cell could flourish.[2] Starting from Wallace’s premise, I follow the history of the development of one of the fuel cell types, the high temperature solid oxide fuel cell (SOFC). I looked to investigate the multiple reframing of this technology, and ask how changes in materials processing technology, accompanied by changes in political economies of both energy and R&D

[1] Wallace, Harold Duane, 'Fuel Cells: A Challenging History', *Substantia,* 3 (2019), p. 95.
[2] Ibid. pp. 94-95.

facilitated these reframings, so maintaining the legitimacy of SOFC imaginaries for over six decades.

Drawing on my own 25 years as an active laboratory-based SOFC researcher and augmenting documentary records with oral histories, I will argue that these shifting frames responded to changing public policy imperatives around energy and the environment, from energy crises in the 1970s and pollution worries in the 1980s to concerns around combustion based energy conversion in the 1990s. I also claim that new narratives were facilitated by changing boundaries in ceramic processing, organisation of R&D, and energy markets. Furthermore, I will also suggest that the enduring validity of SOFC framing was embedded in the wider societal need for a “technological fix”, the belief that technology can solve social problems, prevalent in responses to energy crises and climate change. I will contend that fuel cells have played a social role, providing plausible technological keystones for such optimism, creating the impression that solutions to energy and environmental crises were not far away facilitating the continuation of “business as usual”.

The Promise of the Fuel Cell and SOFC

Fuel cells are a family of technological devices which for many decades have provided the basis for a promissory path to a highly efficient, low emission electricity generation system when compared to the combustion-based heat engines which have predominated since the industrial revolution. The key to the highly efficient electrical generation within a fuel cell is the method of energy conversion: electrochemistry. The electrochemical reaction directly converts chemical energy into electrical energy and while inefficiencies are still realised as heat, these thermal flows do not form the prime component of work within the system. As such the electrochemical reaction avoids the thermodynamic efficiency limitations of a combustion-based heat engine. Further the direct electrochemical reaction avoids the convoluted combinations of thermal and kinetic energy which are required in the conversion of a fuel to electricity in a combustion-based system, with each separate step adding an additional set of efficiency losses to the system.[3]

The electrochemical reactions either disassociate or combine electrons with chemical reactants on the surface of the fuel cell electrodes, providing a stream, or current, of electrons which can be routed through an external circuit to perform work as they flow between the two electrodes. This provides an elegant method for energy conversion with no moving parts. While the fuel cell may share several features with a galvanic battery, such as two electrodes where the electrochemical reactions take place and an electrolyte which separates the two electrodes, there are important differences. In a galvanic battery the material of the electrodes themselves take part in the reaction, being consumed at one electrode and deposited at the other. This sets a physical limit in the energy that can be stored in this type of device, as it is linked to the size of the electrodes (referred to as the capacity). In a fuel cell, however, the electrodes are not themselves reactants, they are catalytic surfaces upon which the reactions take place.

The reactants are supplied to either side of the cell from external sources and this removes the capacity limit of the electrochemical cell inherent in a battery. In an ideal scenario, so long as reactants (a fuel and an oxidant) are supplied to either side of the cell the electrochemical reaction will continue. [4] This electrocatalytic behaviour of the electrodes in a fuel cell, known as the “fuel cell effect”. It is what makes the fuel cell distinct from a galvanic battery and was first observed and discussed in the 1830s by two scientists, Welshman Sir William Grove and the Swiss-German chemist Christian Friedrich Schönbein.[5]

Despite the fuel cell effect first being observed almost 200 years ago and around 70 years focussed and concerted development efforts starting in the decades after the end of the Second World War the fuel cell remains a technology of the

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[3] Kartha, Sivan and Patrick Grimes, 'Fuel Cells: Energy Conversion for the Next Century', *Physics Today,* 47 (1994), pp. 57-59; Singhal, Subhash C., 'Solid Oxide Fuel Cells: Past, Present and Future', in *Solid Oxide Fuels Cells: Facts and Figures,* (Springer London, 2013), pp. 1-23 (p. 1).
[4] For description of SOFC operations see for example Minh, Nguyen Q., 'Ceramic Fuel Cells', *Journal of the American Ceramic Society,* 76 (1993); Singhal, "Solid Oxide Fuel Cells: Past, Present and Future".
[5] Grove, W. R., 'On Voltaic Series and the Combination of Gases by Platinum', *Lond. Edin. Phil. Mag. Ser.3,* 14 (1839); Faraday, Michael, *The Letters of Faraday and Schoenbein, 1836-1862: With Notes, Comments and References to Contemporary Letters,* (London: Williams & Norgate, 1968).

future. While there have been several noted successes in specialised areas, such as applications in the space programme, which have been important in establishing and reinforcing the promise of the fuel cell, none of the variants of this device have seen the mass deployment which would be required for it to live up to its enduring promise to fundamentally change our relationship to energy through the highly efficient generation of electricity from multiple fuels with minimal pollution. Historian Matthew Eisler characterized the promise of this technology, as perceived by its supporters, in terms of a "universal energy convertor", and "power panacea."[6]

Yet over the same time, fuel cells have never been consigned as a failure, even with many disappointments and false dawns. Through the hopes, promises and expectations associated with this technology it has continued to exert a strong hold on the imaginations of scientists, engineers, funders and policymakers. Each time the fuel cell failed to meet the claims and expectations of those developing it, this 'disappointment' was also accompanied by the belief that the solution was just around the corner and with just a little more research effort or a slight change in development direction, expectations would be realised, and the promise delivered.

Revised expectations would often be constructed to help rationalise this belief, which would often be linked to wider shifts in the contextual landscapes around energy supply and demand, whether this be the energy crises of the 1970s, or the emerging awareness of the damaging effects of carbon dioxide emissions from combustion processes on the climate of the planet across the 1990s.[7]

The expectations around fuel cells were also reinforced by ongoing improvements in performance reported at the laboratory level, either through the incorporation of a novel material or the application of a new processing method. Both factors informed the construction of modified narratives around new applications which helped to mobilise new sources of funding or sponsorship. Such new materials or methods would often produce exciting new results demonstrating better output or longevity, however, the difficulties of replicating these promising laboratory test bench or demonstration results outside of these protected environments were often underestimated or misunderstood. Both Eisler and Wallace

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[6] Eisler, M.N., *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*, (Piscataway, NJ: Rutgers University Press, 2012).
[7] Wallace, "Fuel Cells: A Challenging History".

have suggested that such misunderstandings often formed around the boundaries of the fuel cell and its associated support system, with development activity often focussed on the electrochemical elements at the detriment to the wider range of components required to realise a fully operationalised energy conversion system.[8]

The various members of the family of devices known as fuel cells are defined by their electrolyte, the ionically conducting membrane separating the electrodes. Fuel cells based around phosphoric acid, alkaline or molten carbonate have liquid electrolyte. Conversely, the Polymer Exchange Membrane (PEM) and the SOFC have solid electrolytes. This made both the PEM and the SOFC attractive to developers as it was hoped these types of fuel cell would have simpler, more cost-effective designs through the removal of the need for liquid containment. The PEM is based on a polymer electrolyte and runs at lower temperatures (80-90°C). This lower temperature operation requires the use of expensive platinum metal catalysts and the need for highly pure hydrogen as the fuel. The PEM has also been closely associated with transportation applications and has therefore become most prominent in the public imagination, this, along with the need for hydrogen has been a strong driver in the public perception of the need for a hydrogen supply infrastructure to enable the widespread use of fuel cells.[9] While scholarly output on sociological and historical aspects of fuel cells in general, or those associated with transportation or potential hydrogen economies, have increased over the last two decades, research focussing in more detail on the SOFC have been largely absent from this literature.

The SOFC is often regarded as the least mature of the main types of fuel cell, even though it has still been subject to significant research effort for at over 60 years.[10] While SOFCs can take a number of physical forms based on tubes or flat plates all SOFCs have several common features. These are, as the device name would imply, an electrolyte based on a solid oxide with high ionic conductivity.

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[8] Ibid. p. 91; Eisler, Matthew N., '"A Modern 'Philosopher's Stone'": Techno-Analogy and the Bacon Cell', *Technology and culture,* 50 (2009), p. 350.
[9] Ogden, J. M., 'Prospects for Building a Hydrogen Energy Infrastructure', *Annual Review of Energy and the Environment,* 24 (1999).
[10] Suurs, Roald A. A., Marko P. Hekkert, and Ruud E. H. M. Smits, 'Understanding the Build-up of a Technological Innovation System around Hydrogen and Fuel Cell Technologies', *International Journal of Hydrogen Energy,* 34 (2009), p. 9643; Minh, Nguyen, Junichiro Mizusaki, and Subhash C. Singhal, 'Advances in Solid Oxide Fuel Cells: Review of Progress through Three Decades of the International Symposia on Solid Oxide Fuel Cells', *ECS Transactions,* 78 (2017).

Either side of the electrolyte are the electrodes, an anode where the fuel is reduced, liberating electrons to the external circuit and a cathode, where oxygen from the air is reduced by combinations of electrons from the external circuit, again both based around ceramic materials. The current of electrons through the circuit can be used to perform work. One result of having a solid ceramic electrolyte is the need to operate at high temperatures (in early designs this was around 1000°C).

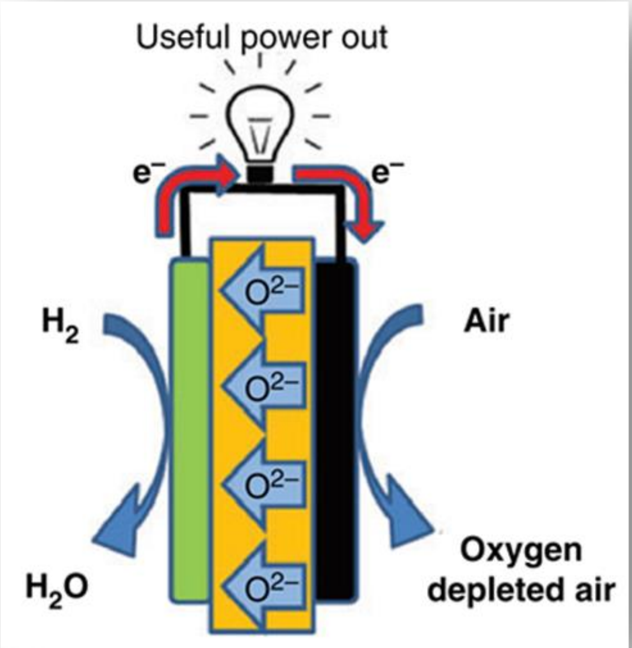

Figure 1; Schematic view of SOFC operation, showing anode to the left, cathode to the right and a flow of oxygen ions across oxide based electrolyte in the centre. Reproduced with permission from figure 1 in Cassidy, Mark, 'Trends in the Processing and Manufacture of Solid Oxide Fuel Cells', WIREs Energy Environ, 6 (2017), e248.

It is the high operation temperature of the SOFC, that allowed developers to frame the SOFC as being able to utilise a wider range of fuels, including natural gas or gasified coal, directly within the cell. This promise of operating on hydrocarbon fuels and the resulting potential to simplify the surrounding fuel processing systems have formed a major driver in the development of SOFC across its development history.[11] These high temperatures of operation have also created many issues, especially around the availability of materials which can withstand these high

[11] Steele, Brian, 'Running on Natural Gas', *Nature*, 400 (1999).

operational temperatures and not corrode or degrade while in operation. Similarly, the processing of these materials to fabricate the SOFC, especially the ceramic oxide components have continually proved challenging.

I will argue that these challenges positioned new materials and processing as key components in the promissory value chain. Utilising the promise of new materials and manufacturing processes demonstrated in the laboratory, developers could reframe the technology against changing crises and concerns around energy supply and environmental issues. This maintained the legitimacy and expectation in the eyes of policymakers and funders that the SOFC would form a plausible part of the near-term technical solutions they desperately sought to mitigate the multiple issues around energy. I will further explore how the history of the SOFC reflects the changing locus of technical knowledge-making in the last quarter of the Twentieth Century. Mirowski and Sent have described how this period saw the relegation of the large US corporate R&D laboratories of the Cold War as the engine room of innovation, to be superseded by the academic laboratory and start-up company in the 1990s and beyond.[12] This change was part of a wider shift in practices around the management of research and development, and regulation of energy supply, where market imperatives were taking a far more prominent position.[13]

SOFC Development: A Review of Existing Literature

The technical development of the SOFC has been well documented in the literature of materials science and electrochemistry. There are numerous technical papers covering the progress of the development of the SOFC over time: however, many of these papers do so from a focused, technical standpoint. While the chronology of developments is discussed, these are often to establish technological precedent and

[12] Mirowski, Philip and Esther-Mirjam Sent, 'The Commercialisation of Science and the Response of Sts', in *The Handbook of Science and Technology Studies 3rd Edition,* ed Edward J Hackett, et al. (Massachusetts: MIT Press, 2008), pp. 635-689.
[13] Mirowski, Philip, *Science-Mart: Privitizing American Science,* (Cambridge Massachusetts: Harvard University Press, 2011); Press, Eyal and Jennifer Washburn, 'The Kept University.(U.C. Berkeley's Recent Agreement with a Swiss Pharmaceutical Company Has Raised Concerns over Who Ultimately Directs Research)', *Atlantic,* 285 (2000).

rarely linked to wider social and contextual events.[14] One significant text which covers aspects of the historical development of the SOFC is the substantive volume by Behling, published in 2013.[15] This book covers all types of fuel cell, but has a significant chapter on the SOFC. Although it mentions some work in the 1980s, outlining the emergence of Westinghouse as the main corporate actor in SOFC over this time, a significant portion of this chapter covers the 1990s and beyond. Starting with a review of DOE sponsorship of SOFC development, Behling goes on to give a comprehensive listing of companies involved in SOFC development, grouping these by geographical location and discussing each company's SOFC programme in turn in alphabetical order. This has provided a valuable and instructive reference of SOFC actors and has been useful in this research for checking and cross-referencing those companies and institutions covered in this dissertation.

As with the other technical reviews, Behling focussed very much on the technological approaches of the various actors. It did list the various funding agencies involved and the various demonstrations undertaken, however gave less consideration to wider contextual issues, such as political, economic or societal influences occurring over this time, how these externalities were changing with time and what effects these could have on the development of the SOFC. In this respect it could be suggested that Behling's account had an internalist feel, focussing on the world of fuel cells as a seemingly closed system.[16] One example of this is when Behling describes the US losing its lead in SOFC technology across the decades of the 1960s to the 2000s.[17] Little account is taken of the profound changes in the socio-

[14] For example see; Brandon, N. and S. Skinner, 'Recent Advances in Materials for Fuel Cells', *Annual Review of Materials Research,* 33 (2003)., Steele, Brian and Angelika Heinzel, 'Materials for Fuel-Cell Technologies', *Nature,* 414 (2001)., Möbius, H. H., 'On the History of Solid Electrolyte Fuel Cells', *Journal of Solid State Electrochemistry,* 1 (1997)., Menzler, Norbert, et al., 'Materials and Manufacturing Technologies for Solid Oxide Fuel Cells', *Journal of Materials Science,* 45 (2010). Singhal, Subhash C., 'Solid Oxide Fuel Cells, History', in *Encyclopedia of Applied Electrochemistry,* (Springer New York, 2014), pp. 2008-2018; Kendall, K., 'History', in *High Temperature Solid Oxide Fuel Cells for the 21st Century,* ed K. Kendall and M. Kendall (London: Academic Press - Elsevier, 2016), pp. 25-50.

[15] Behling, Noriko Hikosaka, *Fuel Cells : Current Technology Challenges and Future Research Needs / [Internet Resource],* (Amsterdam]: Amsterdam : Elsevier, 2013).

[16] In this case I take my definition from the lines of historical enquiry outlined in Staudenmaier, John, *Technologies Storytellers: Reweaving the Human Fabric (Paperback Edition 1989),* (Cambridge Massachusetts: MIT Press, 1985), pp. 9-12.

[17] Behling, *Fuel Cells : Current Technology Challenges and Future Research Needs / [Internet Resource]*, p. 395.

political landscape in the US over this time and what this meant for large corporations like General Electric or Westinghouse. Such changes had significant implications for the management of scientific and technological innovation which, in turn, as will be argued in this thesis, influenced development activities of SOFC in particular, and fuel cells more generally.[18]

With respect to more contextually informed histories of fuel cells, one significant contributor over recent years has been Matthew Eisler, with several journal papers and a book *Overpotential: Fuel Cells, Futurism and the Making of a Power Panacea*.[19] Eisler discussed fuel cells with respect to the political economy of the need for continued supply of energy to sustain an increasingly power hungry world, linking this to utopian futurism based around visions of abundant clean energy constructed by technology actors to maintain validity and currency in their promissory technology. Eisler has linked the fuel cell to wider electrochemical technologies such as batteries, especially where these have been used either as part of the wider imaginaries around environmentally friendly futures or as tool to create contested visions of the route to a zero-emission future which worked to serve the status quo. Across these discussions one significant theme were fuel cell applications in transportation.

The trials and tribulations of the search and development for an electric vehicle have been a focus of historians and technology scholars for many years.[20] An early account was by French sociologist of science Michel Callon in 1980, who used the French electric car programme and their fuel cell efforts as a lens through which to study the social relations between the state and other partners in technical innovation.[21] Callon would later use this to develop concepts around Actor Network

[18] Mirowski, *Science-Mart*.
[19] Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*. Eisler, M.N., 'Fuel Cell Research and Development and the Pursuit of the Technological Panacea, 1940-2005', in *IEEE Conference on the History of Electric Power,* (2007), pp. 171-191; Eisler, M.N., 'The Carbon-Eating Fuel Cell [Blueprints for a Miracle]', *IEEE Spectrum,* 55 (2018); Eisler, ""A Modern 'Philosopher's Stone"': Techno-Analogy and the Bacon Cell"; Eisler, Matthew N., 'Getting Power to the People: Technological Dramaturgy and the Quest for the Electrochemical Engine', *History and technology,* 25 (2009).
[20] Mom, Gijs, *The Electric Vehicle: Technology and Expectations in the Automotive Age*, (Baltimore: John Hopkins University Press, 2004); Eisler, Matthew N., *Age of Auto Electric : Environment, Energy, and the Quest for the Sustainable Car* (Cambridge, Massachusetts : The MIT Press, 2022).
[21] Callon, M., 'The State and Technical Innovation: A Case Study of the Electrical Vehicle in France', *Research Policy,* 9 (1980).

Theory to describe the sociological relations involved in the shaping of the technology. Callon's work emphasised the large cast of actors that needed to be recruited in these collaborative programmes, and that, in order to satisfy the often-disparate requirements of all partners, various levels of simplification of the device description and operation were required. Such simplifications often led to loss of the underlying complexities inherent in the device, leading to misplaced expectations.[22] The high profile of transportation in this zero emission discussion in turn created a focus on the lower temperature polymer exchange membrane (PEM) fuel cell as this was the type of fuel cell most commonly associated with transportation applications.[23] Tom Koppel presented a significant description in the development of the PEM and its potential transportation applications with his account of the history of the Canadian company Ballard. This company became prominent in the development of the PEM fuel cell across the 1990s and would be highly influential in shaping popular visions of the fuel cell, and reinforcing its relationship with hydrogen and zero emission vehicles.[24]

As well as transportation applications, Eisler has also discussed the promotion of the fuel cell as a "universal power convertor" effortlessly and efficiently turning any fuel into electricity with little or no emissions, and so forming the basis of the "power panacea" of the book's title. Eisler traced several development paths for the technology, including portable power for the military running on a variety of logistical fuels, space and automotive applications, and expanding the use of the natural gas grid to enable the virtual delivery of electricity through the localised conversion of natural gas in distributed fuel cell power plants.[25] However, throughout this discussion, the SOFC, whose developers would claim was the fuel cell type best positioned to deliver the multifuel capability required by Eisler's "panacea", only gets fleeting mention throughout the book. Eisler focussed

[22] Ibid.; Callon, M., 'Society in the Making: The Study of Technology as a Tool for Sociological Analysis', in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology: Anniversary Edition*, ed W. E. Bijker, T.P. Hughes, and T. Pinch (Cambridge MA.: MIT Press, 2012), pp. 77-97.
[23] Eisler, Matthew, 'Materials Research, Super Batteries, and the Technopolitics of Electric Automobility', *Historical Studies in the Natural Sciences,* 46 (2016). Eisler, Matthew N., 'Public Policy, Industrial Innovation, and the Zero-Emission Vehicle', *Business History Review,* 94 (2020).
[24] Koppel, Tom, *Powering the Future : The Ballard Fuel Cell and the Race to Change the World*, (New York: Wiley, 1999).
[25] Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*.

on the more mature versions of the fuel cell such a alkaline, phosphoric acid, and polymer, and how different alliances were formed around the expectation of these various devices in relation to how their specific affordances related to the political economies of energy, and research and development. As such, Eisler's work sets a firm foundation from which to focus more specifically on the SOFC, and to build further investigations into how these social, political and economic effects have influenced those involved in the development of the SOFC, and the promises and expectation constructed around it.

In a similar vein to Eisler, Harold Wallace traced the events around several points in history where fuel cells, despite high levels of expectation to do so, did not emerge from the laboratory into wide deployment.[26] Wallace emphasised the importance of the changing social, political or economic contexts which he suggested altered the landscape against which the technology was viewed, pushing it back to the laboratory for further development. However, while Wallace stressed that such changing contexts can help explain the different reasons why fuel cells remained a laboratory based technology, he also emphasised why people and the power of their imaginations are a crucial part in the tenacity of the fuel cell, constructing optimistic scenarios for the technology in the minds of scientists, engineers and policymakers.[27] Like Eisler, Wallace takes a broadbrush approach to the subject covering all types of fuel cell which again provides scope to develop a focussed study on the SOFC.

Science and Technology Studies (STS) scholars have engaged with socio-technical aspects of fuel cells, often from the perspective of the sociologies of expectation.[28] Again, these have frequently focused on lower temperature variants in conjunction with hydrogen as a fuel, automotive applications, or have focused on a very specific time frame such as the hype and excitement around fuel cells of the late 1990s and early 2000s. Further, many of these studies have had tight geographical

[26] Wallace, "Fuel Cells: A Challenging History".
[27] Ibid. pp. 94-95.
[28] Borup, Mads, et al., 'The Sociology of Expectations in Science and Technology', *Technology Analysis & Strategic Management,* 18 (2006); Brown, Nik and Mike Michael, 'A Sociology of Expectations: Retrospecting Prospects and Prospecting Retrospects', *Technology Analysis & Strategic Management,* 15 (2003).

limits, focussing on single European countries or comparative regions.[29] While some of these studies have considered the SOFC as an example of a potential stationary electrical generation system, they do so against the context of the fuel cell hype of the late 1990s and early 2000s. I contend that the story of the SOFC is more than this period of hype, and that the technology has a far richer history in the future energy imaginaries of policymakers, sustaining its early development well before of the turn of the century hype.

In some respects, these STS studies do echo many of the attributes highlighted by Eisler, Wallace and before them Callon, in that, the development of the fuel cell has been sustained over time by the desire of policymakers for simple technical solutions to the complicated social issues around the continued need for clean, plentiful energy. This constructed a collective expectation around the fuel cell where its value was judged around what the technology could potentially achieve, rather than its actual level of development.[30] I therefore situate my own thesis within the context of this technological optimism, and I argue that the long development programme of the SOFC has been sustained by the promise of advanced materials and new manufacturing processes, and the expectation that these would solve the problems of earlier embodiments of the technology and lead to rapid deployment and returns on investment.

Energy Transitions and "the Technological Fix"

Philosopher Max Oelschlaeger described the expression "technological fix" as "the idea that technology can solve social problems".[31] Historian of science and

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[29] For example see Konrad, Kornelia, et al., 'Strategic Responses to Fuel Cell Hype and Disappointment', *Technological Forecasting & Social Change,* 79 (2012). Budde, Björn, Floortje Alkemade, and K. Matthias Weber, 'Expectations as a Key to Understanding Actor Strategies in the Field of Fuel Cell and Hydrogen Vehicles', *Technological Forecasting & Social Change,* 79 (2012). Ruef, Annette and Jochen Markard, 'What Happens after a Hype? How Changing Expectations Affected Innovation Activities in the Case of Stationary Fuel Cells', *Technology Analysis & Strategic Management,* 22 (2010). Hultman, Martin and Christer Nordlund, 'Energizing Technology: Expectations of Fuel Cells and the Hydrogen Economy, 1990-2005', *History and Technology,* 29 (2013). Bakker, Sjoerd and Bjorn Budde, 'Technological Hype and Disappointment: Lessons from the Hydrogen and Fuel Cell Case', *Technology Analysis & Strategic Management,* 24 (2012).
[30] Budde, Björn and Kornelia Konrad, 'Tentative Governing of Fuel Cell Innovation in a Dynamic Network of Expectations', *Research policy.,* 48 (2019).
[31] Oelschlaeger, Max, 'The Myth of the Technological Fix', *SOUTHWEST J PHILOS,* 10 (1979), p. 43.

technology Sean Johnston attributed the popularisation of the expression to Alvin Weinberg, physicist and director of the Oak Ridge National Laboratory, through Weinberg's essays and articles in the mid-1960s.[32] In this context it related closely to the increasing dominance of American science and technology during and after the Second World War, and the association of this with visons of progress towards high technology futures.[33] However, as Segal pointed out, "the technical fix", while coined in the Cold War 1960s, represents a longer tradition in America to look towards technology for progress. Matthew Eisler also referred to this in his PhD thesis, where he characterised American notions of progress as "a series of technical fixes".[34]

In *American Technological Sublime*, David Nye describes this view of technology as an allegory for progress as being associated with notions of modernity and statehood, something which has long been established in the US political and public imagination.[35] From the massive hydro projects, the establishment of the electrical grid, oil pipelines and the associated infrastructure that arose around centres of production, the increasing need for energy has played a central role in developing and sustaining the national idea of technology as progress.[36] Where these ideas present visions of how technology and society will interact to create potential futures they can be described as "sociotechnical imaginaries".[37]

To be considered as a sociotechnical imaginary Jasanoff stated that the future visions had to be collectively held, she described this communality as being "institutionally stabilised", initially described as being at a level of nation states but

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[32] Johnston, Sean F., 'Alvin Weinberg and the Promotion of the Technological Fix', *Technology and Culture,* 59 (2018); Johnston, Sean F., 'The Technological Fix as Social Cure-All: Origins and Implications', *IEEE Technology and Society Magazine,* 37 (2018).
[33] Segal, Howard P., 'Practical Utopias: America as Techno-Fix Nation', *UTOPIAN STUD,* 28 (2017).
[34] Eisler, Matthew N., 'Fueling Dreams of Grandeur: Fuel Cell Research and Development and the Pursuit of the Technological Panacea, 1940-2005', (University of Alberta, 2008), p. 332.
[35] Nye, David E., 'American Technological Sublime', (1994).cited in Winner, Langdon, 'Sow's Ears from Silk Purses: The Strange Alchemy of Technological Visionaries', in *Technological Visions: The Hopes and Fears That Shape New Technologies*, ed Marita Sturken, Douglas Thomas, and Sandra J. Ball-Rokeach (Philidelphia: Temple University Press, 2004), pp. 34-47 (p. 38).
[36] Hughes, Thomas Parke, *Networks of Power : Electrification in Western Society, 1880- 1930,* (Baltimore: Baltimore : Johns Hopkins University Press, 1983); Jones, Christopher F., 'Building More Just Energy Infrastructure: Lessons from the Past', *Science as Culture,* 22 (2013); Jones, Christopher F., *Routes of Power*, (Cambridge Massachusetts: Harvard University Press, 2014).
[37] Jasanoff, Sheila and Sang-Hyun Kim, *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power*, (Chicago, IL: Chicago, IL: University of Chicago Press, 2015).

later extended to other organized groups for example "corporations, social movements and professional; societies." Jasanoff further extends the argument to suggest that any collective vision need not be universally held and several contested visions can exist within multiple groups across a society.[38] However, it is in the identification and definition of these differing societal groups, the social level at which they exist, the contested views that they possess and the visibility of these contested views, where many of the criticisms of sociotechnical imaginaries lie.[39] It has been suggested that the many interpretations of the social level where the imaginary exists can lead the idea of the imaginary becoming ambiguous and difficult to articulate, leading to abstraction and methodological inconsistencies.[40] Jasenoff and Semmet have responded to criticisms of methodological vagueness by arguing that the notion of the sociotechnical imaginary is not a blanket theory to be bluntly applied, rather it is an "interpretive concept" forming "tools for sense-making." In this perspective ambiguities are reflective of the "background values," which "illuminate the important features of a social landscape."[41] This could be argued to be the context in which the imaginaries are being contested and the discourse within a society attempting transition.

Historian Langdon Winner suggested that the sociopolitical edge of imaginaries based around technological optimism presented technology as moving society to a "utopian social order" where the "technological fix" would provide solutions from the problems "associated with the previous age of technology."[42]

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[38] Jasanoff, Sheila, 'Future Imperfect: Science, Technology and the Imaginations of Modernity', in *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power,* ed Sheila Jasanoff and Sang-Hyun Kim (Chicago: University of Chicago Press, 2015), pp. 1-33 (p. 4); Levy, David L. and André Spicer, 'Contested Imaginaries and the Cultural Political Economy of Climate Change', *ORGANIZATION,* 20 (2013).
[39] Smith, J. M. and A. S. D. Tidwell, 'The Everyday Lives of Energy Transitions: Contested Sociotechnical Imaginaries in the American West', *Social Studies of Science,* 46 (2016); Tidwell, H.J. and A. S. D. Tidwell, 'Energy Ideals, Visions, Narratives, and Rhetoric: Examining Sociotechnical Imaginaries Theory and Methodology in Energy Research', *Energy Research & Social Science*, 39 (2018); Kuchler, Magdalena and Gubb Marit Stigson, 'Unravelling the 'Collective' in Sociotechnical Imaginaries: A Literature Review', *Energy Research & Social Science*, 110 (2024).
[40] Sismondo, Sergio, 'Sociotechnical Imaginaries: An Accidental Themed Issue', *Social Studies of Science,* 50 (2020); Smith and Tidwell, "The Everyday Lives of Energy Transitions"; Rudek, Tadeusz Jozef, 'Capturing the Invisible. Sociotechnical Imaginaries of Energy. The Critical Overview', *Science and Public Policy,* 49 (2022); Kuchler and Stigson, "Unravelling the 'Collective'".
[41] Jasanoff, Sheila and Hilton Simmet, R., 'Renewing the Future: Excluded Imaginaries in the Global Energy Transition', *Energy Research & Social Science,* 80 (2021).
[42] Winner, "Sows Ears", p. 34.

Such optimistic visions of future utopianism can be encapsulated by the statement of Lewis Strauss the Chair of the US Atomic Energy Commission, who in 1954 declared that power of the atom would one day provide electricity that was "too cheap to meter."[43] Such optimistic visions around technological solutions are not always universally shared and policymakers have been criticised for unquestioned reliance on technological optimism.[44]

Winner linked the imaginaries of technological optimism to what he called "the triumph of the will", how "these things will happen".[45] This linked the imagination of what can happen to how technology can achieve that aim, so connecting sociotechnical imaginaries with sociologies of expectation.[46] As many scholars of expectation point out, a promissory technology is not judged "on what it can do now," but rather "what it will be able to do in the future," for this future promise to gain validity, a "collective expectation" must be developed, not just around the future performance of a technology, but also its position in any wider sociotechnical system.[47] David Nye describes these as "little narratives", stories that are constructed about how a promising technology will exist within wider visions of utopian futures.[48]

These "little narratives" do not in themselves form the broad-ranging sociotechnical imaginaries used to underpin national ideas of progress through science and technology.[49] Rather the "little narratives" can exist within these larger frames with each drawing from the other to reinforce their legitimacies and

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[43] Strauss, L.L., 'Remarks Prepared by Lewis L Strauss, Chairman, United States Atomic Energy Commission, for the Delivery at the Founders Day Dinner, National Association of Science Writers, 16 September 1954', (1954) <www.nrc.gov/docs/ML1613/ML16131A120.pdf>.
[44] Harrabin, R., 'Climate Change: Technology No Silver Bullet, Experts Tell P.M.', *BBC News - Science & Environment,* (2020) <https://www.bbc.co.uk/news/science-environment-54662615>; Harrabin, R., 'John Kerry: Us Climate Envoy Criticised for Optimism on Clean Tech', *BBC News - Energy & Environment,* (2021) <https://www.bbc.co.uk/news/science-environment-57135506>.
[45] Winner, "Sows Ears", p. 37.
[46] van Lente, Harro, 'Imaginaries of Innovation', in *Handbook on Alternative Theories of Innovation* ed Benoît Godin, Gérald Gaglio, and Dominique Vinck (Cheltenham: Edward Elgar, 2021), pp. 23-36 (p. 27).
[47] Borup, et al., "The Sociology of Expectations in Science and Technology"; Konrad, et al., "Strategic Responses to Fuel Cell Hype and Disappointment"; Budde and Konrad, "Tentative Governing of Fuel Cell Innovation in a Dynamic Network of Expectations".
[48] Nye, David E., 'Technological Prediction a Promethean Problem', in *Technological Visions the Hopes and Fears That Shape New Technologies*, ed Marita Sturken, Douglas Thomas, and Sandra J. Ball-Rokeach (Philadelphia: Temple University Press, 2004), pp. 159-176 (p. 160).
[49] Jasanoff and Kim, *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power*.

validities.[50] Nye suggested that for the emerging technology such validation of the "little narrative" is vital to secure funding and mobilise resource with advocates positioning it as part of the wider vision.[51] At the same time, promising results from the new technology can be extrapolated by proponents of wider imaginaries to construct routes to the future utopia. Winner describes such routes as "comforting illusions" through which,

> "- we relinquish our ability to engage with the urgent decisions at hand. Transfixed by supposedly optimistic dreams… leaving key decisions to others, people who may not have our best interests or the long-term well-being of the planet anywhere in their plans." [52]

In other words, the promise of new technologies which may become available in the near term allows business as usual to continue and avoids the need to directly confront difficult underlying social problems.

Another potential critique of sociotechnical imaginaries is their close association with technological approaches which provide the vison for the future and expert technical voices playing a significant role in defining the imaginary, often through association with national technology projects or programmes.[53] This potentially leads to a risk that discussing technology as a key element on which future imaginaries are constructed or enabled moves towards notions of determinism, where the technology itself can be presented as an agent of change with the power to shape futures. Indeed, Sismondo described the concept of imaginaries as having "more or less determinism built into them."[54] However rather than imaginaries being a source of potential determinism, the concept can be utilised to interrogate sociotechnical relations between groups of actors where ideas of the technological fix may predominate in the construction of future visions and better reveal the role of policy, political and social agendas at play within the technical discourse.[55]

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[50] Moezzi, Mithra, Kathryn B. Janda, and Sea Rotmann, 'Using Stories, Narratives, and Storytelling in Energy and Climate Change Research', *Energy Research & Social Science,* 31 (2017); van Lente, "Imaginaries of Innovation", p. 26.
[51] Nye, "Technological Prediction a Promethean Problem", p. 160.
[52] Winner, "Sows Ears", p. 38 and 41.
[53] Tidwell and Tidwell, "Energy Ideals"; Kuchler and Stigson, "Unravelling the 'Collective'", p. 11.
[54] Sismondo, "Sociotechnical Imaginaries: An Accidental Themed Issue", p. 505.
[55] Levidow, Les and Sujatha Raman, 'Sociotechnical Imaginaries of Low-Carbon Waste-Energy Futures: Uk Techno-Market Fixes Displacing Public Accountability', *Social Studies of Science,* 50 (2020).

Merritt Roe Smith has outlined that while such notions and ideas around technological determinism may have been prevalent in earlier discourse around the role of technology in history, they have long been problematised by more recent historians and few, if any, would suggest technology as a prime causal agent in history.[56] The cultural turn towards social constructivism of the 1980s and 1990s saw a shift towards accounting for technological change in social terms, where the complex roles of social relations in the construction and realisation of technological artifacts, through conceptual programmes such as social construction of technology (SCOT) and actor network theory (ANT).[57] While these ideas became increasing popular, some scholars felt that they still did not provide a satisfactory account, sometimes being over-theorised, over-socialised or lacking in contextualisation.[58] Historian Thomas Hughes remarked that, just as he could not accept technological determinism as the single driving force in history, neither could he accept the flip side, social determinism, which he argued that some interpretations within SCOT tended towards.[59]

Despite arguments around representation, the important roles of social and contextual relations are well accepted by historians. The same is not the case across wider communities such as policymakers, technological actors and indeed wider society. In these communities, notions around the role of technologies in enabling change remain powerful and prevalent. Merritt Roe Smith described this as "technocratic thought" and suggested it is built on the deeply embedded cultural ideas of technology as progress.[60] Historian Thomas Turnbull recently cautioned that

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[56] Smith, Merritt Roe, 'Technological Determinism in American Culture', in *Does Technnology Drive History? The Dilema of Technological Determinism,* ed Merritt Roe Smith and Leo Marx (Cambridge, Massachusetts: MIT Press, 1994), pp. 4-35.

[57] Bijker, W. E., T.P. Hughes, and T. J. Pinch, *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology,* Anniversary ed.. edn (Cambridge, Mass. ; London: MIT Press, 2012); Latour, Bruno, 'Aramis, or, the Love of Technology', (1996).

[58] Winner, Langdon, 'Upon Opening the Black-Box and Finding It Empty - Social Constructivism and the Philosophy of Technology', *Science, technology, & human values.,* 18 (1993); Edgerton, David, 'Tilting at Paper Tigers -- Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance by Donald Mackenzie', *The British Journal for the History of Science,* 26 (1993); Hughes, Thomas Parke, 'Technological Momentum', in *Does Technology Drive History? The Dilema of Technological Determinism,* ed Merritt Roe Smith and Leo Marx (Cambridge, Massachusetts: MIT Press, 1994), pp. 101-113; Lécuyer, Christophe and David C. Brock, 'The Materiality of Microelectronics', *History and Technology,* 22 (2006).

[59] Hughes, "Technological Momentum", pp. 103-104.

[60] Smith, "Technological Determinism", p. 34.

energy and energy transitions are topics where deterministic and "technocratic thinking" can be seen to be especially prevalent and deeply rooted.[61] In part, this has been ascribed to the embedding of the large-scale infrastructures required for extraction, distribution and consumption of energy within society.[62] Such infrastructures appear immutable and rigid, shaping the way society functions: however closer reflection on the nature of the systems reveal this is an erroneous assessment.

Hughes suggested that this system rigidity is a result of what he termed "technological momentum", where a "large technological system" has gained a certain set of characteristics which allow the effective and efficient management and operation of that system, such as the voltage and frequency of the electrical grid or the track gauge of a railway network.[63] These large systems can appear to shape society in a number of ways: for example wider access to electricity resulted in social and cultural changes as new appliances became available.[64] Any technologies utilising these large technical systems had to match the basic requirements of the large system, so appeared to be shaped and governed by the large system giving this a deterministic character. However, Hughes suggests that to characterise this as determinism is not correct and represents the viewing of a mature system, where it has moved beyond the technical and formed a social construct which includes politics, policy, regulation, finance, science, industry and cultural behaviours and values.[65] Both Hughes and Nye suggest that looking purely at this mature system does not consider, or downplays, historical aspects where the current form of the system had been constructed and shaped by human agency, negotiation and the wider social contexts into which the system was emerging during its early development.[66] Nye describes Hughes's idea of technological momentum as providing "the

[61] Turnbull, Thomas, 'Energy, History, and the Humanities: Against a New Determinism', *History and Technology*, 37 (2021).
[62] Nye, David E., *Consuming Power: A Social History of Americal Energies*, (Massachusetts: MIT Press, 1998), p. 4.
[63] Hughes, "Technological Momentum".
[64] Cowan, Ruth Schwartz, *More Work for Mother : The Ironies of Household Technology from the Open Hearth to the Microwave*, (New York: New York : Basic Books, 1983).
[65] Hughes, "Technological Momentum", p. 102.
[66] Ibid.; Nye, *Consuming Power*.

contextualist argument with an explanation of the rigidities often mistaken for determinism."[67]

In his book *American Genesis*, Hughes further emphasised the social aspects still present in the mature system by invoking Karl Marx's ideas that social relations around capital and control of labour are a shaping force in history through creation of vested interests and hegemonies. Here Hughes characterises the individuals and groups who have heavily invested in mature technical systems as representing "powerful vested interests" looking to protect both the political and financial capital within the system by reinforcing regulatory, political and social practices across the system.[68] As David Nye succinctly summarises, "the hegemony of large systems is culturally shaped."[69] Nye goes on to state that even with this cultural hegemony, continued momentum of any technical system is not a given and can be lost as other favourable systems emerge.[70]

In many ways this characteristic of shifting momentum can be seen across energy transitions as a new energy source becomes dominant. Turnbull argues that historians have long presented the notion of a "smooth transition" from one fuel to another as an erroneous perception, suggesting that the evidence shows the history of energy transitions to be a better represented by accumulation rather than replacement, with the new energy source capturing an increasing proportion of ever-increasing energy consumption, which Canadian historian Sean Kheraj characterises as a "story of more."[71] While technological momentum shifted from coal to oil as the dominant energy source across the twentieth-century, coal use did not stop: in the US production remained strong and increased over time, with peak production occurring in the early 2000s.[72]

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[67] Nye, *Consuming Power*, p. 4.
[68] Hughes, Thomas Parke, *American Genesis : A Century of Invention and Technological Enthusiasm, 1870-1970*, (Chicago: Chicago : University of Chicago Press, 2004), p. 460.
[69] Nye, *Consuming Power*, p. 5.
[70] Ibid.
[71] Turnbull, "Energy, History, and the Humanities: Against a New Determinism", p. 3; Kheraj, Sean, 'More: The History of Energy and Humanity', (2019) <https://www.seankheraj.com/more-the-history-of-energy-and-humanity/>.
[72] Smil, Vaclav, *Energy and Civilization : A History*, (Cambridge, Massachusetts : The MIT Press, 2017), p. 298; Podobnik, Bruce, *Global Energy Shifts, Fostering Sustainability in a Turbulent Time*, (Philadelphia, PA: Temple University Press, 2006), p. 161; Ritchie, H. and M. Roser, 'Fossil Fuels', *ourworldindata.org [online resource]*, (2020) <https://www.ourworldindata.org/fossil-fuels>.

In his wide-ranging survey *Energy and Civilisation: A History*, energy scholar Vaclav Smil traces the changing use of energy across the broad sweep of human history.[73] By detailed analysis of both production of energy sources and the consumption of energy he attempts to address many of the myths and assumptions that have built up or persisted around the nature of the changing nature of energy sources and how these have been consumed. In concert with other energy historians such as Bruce Podobnick and Timothy Mitchell, Smil has sought to show that rather than being a driving force in history, energy transitions have come about through multifaceted interactions of politics, statehood, finance, trade, labour, regulation and all of the complex social relations these entail.[74]

As Turnbull summarised, while it may be easy to suggest that the more concentrated energy contained in coal determined the transition to this substance from wood and resulted in the industrial revolution, there were also a number of social, political and regulatory changes which occurred over the sixteenth and seventeenth centuries. These concerned issues of land ownership, mineral rights and state taxes, which Turnbull suggests were prerequisites that then allowed nascent industrialists to exploit coal as a resource to reorganise labour and production, creating a route to accumulate capital over future decades.[75] As Christopher Jones describes in *Routes of Power,* such energy transitions were more than just the discovery of a new energy source. They required a wide range of visionaries willing to invest capital in associated infrastructure such as canals and railways, not only to move a bulky energy source such as coal, but also to distribute the goods and materials manufactured, creating more complex social relations as a Hughesian "large technical system" emerged.[76]

Timothy Mitchell discussed how the social relations around coal were a key component in the later transition to oil and it could be argued that these relations were in some way related to its bulk. As the use of coal grew so the labour needs around its extraction and distribution increased. In the early twentieth-century workers in coal extraction and distribution such as railway and shipping began to

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[73] Smil, *Energy and Civilization : A History*.
[74] Ibid.; Podobnik, *Global Energy Shifts, Fostering Sustainability in a Turbulent Time*; Mitchell, Timothy, *Carbon Democracy: Political Power in the Age of Oil*, (London: Verso, 2011).
[75] Turnbull, "Energy, History, and the Humanities: Against a New Determinism", p. 9.
[76] Jones, *Routes of Power*.

organise through unionisation, which placed pressure on industrialists and governments through unrest resulting from union disruption. At the same time the liquid nature of oil was proving far more transportable, requiring less labour to extract and transport resulting in fewer labour disputes and higher profits. The advantages of oil were further legitimised through acts of statehood, when in the early twentieth century the Royal Navy switched to oil to power its warships. While this fuel allowed larger, faster ships with increased range, it also reduced the reliance of strategic military operations on domestic labour relations.[77] Such moves reinforced the place of oil as a global energy source, but it also shifted pressures of maintaining energy supply from localised labour relations to issues of a geopolitical nature where domestic and international government policies would become key instruments of energy supply and transition.[78]

Recently, Jones has commented that Mitchell's reference to the bulk of coal and the liquidity of oil as important shaping factors in energy history, in concert with his own work on infrastructures, and that of others such as Hughes and Nye on the large technical systems, shows the importance of the materiality of energy in discussing the history around it.[79] In many ways, Jones's focus on the material forms around energy reflects the wider materials turn across history and science and technology studies, where the limitations of analyses based on highly relativistic accounts of social and cultural perspectives were becoming apparent and analysis turned to more explicitly consider the role of artifacts and things in shaping cultural and social practices.[80] Here Jones is concerned with investigation not only of the material form of the energy source itself, from the bulk of coal, the liquidity of oil and the more ethereal nature of electricity, but also the material nature of the systems build to extract, distribute and consume it. Jones also links this idea around the

[77] Mitchell, *Carbon Democracy*, pp. 59-65.
[78] Podobnik, *Global Energy Shifts, Fostering Sustainability in a Turbulent Time*, pp. 65-67.
[79] Jones, Christopher F., 'The Materiality of Energy', *Canadian journal of history,* 53 (2018).
[80] Latour, B., 'Can We Get out Materialism Back, Please?', *ISIS,* 98 (2007); Trentmann, Frank, 'Materiality in the Future of History: Things, Practices, and Politics', *J. Br. Stud,* 48 (2009); Lécuyer and Brock, "The Materiality of Microelectronics"; Mody, Cyrus and Michael Lynch, 'Test Objects and Other Epistemic Things: A History of a Nanoscale Object', *British Journal for the History of Science,* 43 (2010).

increasingly abstract nature of energy, especially from the perspective of the end user in the developed nations.[81]

With wood and coal, the user was intimately involved with the material, gathering wood, or stoking furnaces and fire grates. With oil, this link became one step removed. The liquid material being encased in pumps, pipes and tanks, although the user would pump gasoline into a car, the physical contact with the medium was reduced. This this was even more so with gas. While the energy source would still be present at the user location, interaction was turning a stopcock and pressing an igniter button. At present, perhaps the ultimate embodiment of this energy abstraction is electricity. Here, electricity is only a vector for the distribution of energy, the end user is completely divorced from the primary fuel and its conversion and needs only to "flick a switch". The externalities of fuel extraction, distribution and conversion "recede into the background".[82] Jones argues that much of the material nature of current energy systems are embedded and represented within the infrastructure for their extraction, conversion and distribution, the varying nature of which can shape "the distribution of social goods and ills" and that the pipelines and wires of oil gas and electricity result in different social outcomes than the railroads and canals of coal. [83]

He also noted that transitions between energy sources did not occur as a given. It required considerable effort on the actors promoting the new system, to invest in new infrastructure or to shift cultural practices of consumers, all of which created complex social interactions between the material form of energy, and finance regulation politics and practice.[84] However, all share characteristics of long-term investments, sunk costs and embedded cultural practice which together have resulted in the powerful vested interests and hegemonies to which both Hughes and Nye refer.[85] Nye suggests that transitions occurred when new energy systems offered corporations competitive advantages through reorganisation of labour, increased

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[81] I stress the developed nations here, as access to energy is not universal and in many parts of the world populations still rely on wood for fuel and therefore retain their close material link to energy having to gather fuel and build fires. This also highlights the inequalities around energy and energy transitions where considerable distributional injustices remain.
[82] Jones, "The Materiality of Energy", p. 379.
[83] Ibid. p. 387.
[84] Ibid. p. 391.
[85] Hughes, "Technological Momentum", p. 460; Nye, *Consuming Power*, p. 5.

profits or both.[86] This suggests that the Marxian imperatives of control of the means and relations of production were at the heart of historical energy transitions and so hints at underlying pressures and apparent sluggishness around the current need to transition to low carbon energy where the imperative is the wider social good of the environment, rather than accumulation of capital and power.[87]

It is within these shifting and growing tensions around the continued supply of energy that the SOFC has sat. Framed as one of several "technical fixes" with expectation constructed around promises to deliver highly efficient, low pollution energy conversion within existing energy infrastructures of coal and gas. However, I will argue that the promise for change that the SOFC offered lay within the materials of its construction rather than the wider materiality of the systems and infrastructures described by Jones. This expectation was built on successes of materials from the early postwar period, from semi-conductors to jet engines, where new materials had been presented by influential advocates as the gateway to a new technological age.[88]

The shared expectations around the SOFC were constructed around multiple notions of the efficacy of electrochemical energy conversion within the cell. This in turn focussed attention on cell materials and privileged metrics of energy conversion and transfer, such as "voltage", "current density" and "area specific resistance" as arbiters of progress and success. I will further contend that such expectation around materials placed the materials scientists at the heart of SOFC development, shaping agendas through their worldview, constructed from the affordances of the materials they worked with. However, the SOFC was not just a laboratory project: it was also embedded with social and cultural concerns about future energy supply. It represented the visions and imaginaries of a society that looked for pollution-free energy within existing practices and structures, leaving the fuel cell developers to

[86] Nye, "American Technological Sublime", p. 9.
[87] Hardin, Garrett, 'The Tragedy of the Commons', *Science (American Association for the Advancement of Science),* 162 (1968).
[88] Baker, W.O., 'The National Role of Materials Research and Development, Address Delivered at the Materials Science Luncheon, Astm Materials Science Division Symposia [1961]', (1961); Baker, W.O., *Advances in Materials Research and Development*, (Washington D.C.: National Academy Press, 1987); Mody, Cyrus C. M. and Hyungsub Choi, 'From Materials Science to Nanotechnology: Interdisciplinary Center Programs at Cornell University, 1960–2000', *Historical Studies in the Natural Sciences,* 43 (2013), p. 126; Eisler, M.N., "The Ennobling Unity of Science and Technology': Materials Sciences and Engineering, the Department of Energy, and the Nanotechnology Enigma', *Minerva,* 51 (2013), p. 230.

attempt to deliver the contradictory promise of a world that is both changed and unchanged at the same time.

Sources & Methodologies

The Self in Research

I was actively involved in solid oxide fuel cell (SOFC) research for almost twenty-five years, as an active laboratory researcher developing processing methods between 1993 and 2017. Therefore, my positionality within the historical research that I am conducting is important. It is impossible for me to claim that I am a neutral or passive observer. During my time as an active participant in SOFC research, I have constructed my own assumptions, prejudices and worldviews based on my own lived experiences along with my interactions with other colleagues, collaborators and research participants in the field. Therefore, rather than trying to ignore these experiences and claiming some form of false objectivity, I felt it was better to embrace them.

The use of autobiographical or similar approaches where the self is put more to the centre is beset with challenges. Such works, especially in fields such as autoethnography, are sometimes cast as unscientific and lacking in objectivity.[89] These criticisms can extend to suggest that the self-focus in such writing borders on the narcissistic.[90] This can especially be the case where the autoethnographic writing centres around the "evocative" such as that espoused by Carolyn Ellis and similar scholars.[91] However, in this work, while I will draw on some aspects of autoethnographic methodologies I will tend more towards the methodological characteristics of "analytic autoethnography" as described by Leon Anderson.[92] While Anderson's analytic approach shares some common traits with evocative auto-ethnographic approaches such as "full member status" of the ethnographic or cultural group in question and narrative visibility of the self, Anderson also stipulates that there must also be an analytical reflexivity with a commitment to an analytical

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[89] Ellis, Carolyn, Tony E. Adams, and Arthur P. Bochner, 'Autoethnography: An Overview', *Historical Social Research / Historische Sozialforschung,* 36 (2011), p. 283.
[90] Atkinson, Paul, *Writing Ethographically,* (London: Sage, 2020), p. 143.
[91] Ellis, Adams, and Bochner, "Autoethnography: An Overview".
[92] Anderson, Leon, 'Analytic Autoethnography', *Journal of Contemporary Ethnography,* 35 (2006).

agenda and dialogue beyond the self. This last criterion is an attempt to minimise the criticisms of being too inward-looking that are often laid at the door of autoethnographic work.

Ethnographic insight is often gained be gained through observation of practice, such as was the case in Latour's classic study *Laboratory Life*.[93] As the observer becomes more familiar with the language of the group under study, the nature of the interaction may change from interview through discussion and eventually to conversation. Collins and Evans termed this "interactional expertise", which is attained as the analyst becomes familiar with the vocabulary and conventions of the group.[94] When the analyst and participants are from the same member group, as is the case in my research, such familiarity and rapport may be enabled by shared cultural perspectives and worldviews. This can lead to issues of the intersubjectivity between the researcher and the participant, which can have positive and negative outcomes, both during the interview and later analysis of the data, and is discussed in more detail in the oral history methodology,

Another potential risk of such close identification between the analyst and the group being studied is what ethnographer Paul Atkinson termed in his book *Writing Ethnographically* as "going native", which he described as when the work that is being observed becomes inseparable from observations of the work.[95] Latour also commented that "analysis of a tribe couched entirely in the concepts and language of the tribe would be both incomprehensible and unhelpful to all non-members of the tribe".[96] To overcome this, the analyst requires some level of "reflective ability," which allows them to discuss the group under study in a manner that those outside of the group can comprehend. This reflection should also provide some level of "translation" so that the discussion is pitched in analytical terms from which social and cultural interpretation and meaning can be constructed.[97]

[93] Latour, Bruno, *Laboratory Life : The Social Construction of Scientific Facts*, (Beverly Hills: Beverly Hills : Sage Publications, 1979).
[94] Collins, H. M. and R. Evans, *Rethinking Expertise*, (Chicago, Ill. : Bristol: Chicago, Ill. : University of Chicago Press ; Bristol : University Presses Marketing distributor, 2007), pp. 32-34.
[95] Atkinson, *Writing Ethnographically*, p. 51.
[96] Latour, *Laboratory Life : The Social Construction of Scientific Facts*, pp. 38-39.
[97] Collins and Evans, *Rethinking Expertise*, p. 37.

It could also be argued that my use of the self as an entry point to explore influences acting on SOFC development in 1993 is not in fact an ethnographic exercise, at least in the explicit meaning of the methodological approach. While others have used their own membership of a group to explore the cultures and practices within that group, they did so explicitly from the outset.[98] Their work would develop copious field notes and reflections contemporaneously with their observations: they set out to undertake an autoethnographic enterprise, or at least to write their ethnographic account from a position of close engagement and participation with their own peer group.[99] However, in this work no defined ethnographic field notes were taken at the time. It was not the intention to be observing the group while interacting with them. Rather, at the time, my aim was just to be a functioning and contributing actor within this group.

In this case, the ethnographic reflection has taken place in a post hoc manner. Therefore, in place of field notes taken and reflected on at the time, there are recollections and memories which are being reflected on many years after the fact. In this respect, it probably owes more to a self-history, analogous to the oral history interviews that provide input throughout this thesis. However, in this case the interviewer and narrator could be considered as one and the same, recalling events over a certain time and reflecting on these against accounts of wider social and cultural interpretations of what was occurring in science and technology. This self-reflective activity also carried value into the oral history programme; by identifying uncertainties or gaps in my own memories or understanding of events, it helped inform a number of the questions I would ask of oral history participants.

Oral History

Oral History has a long tradition of aiming to capture otherwise marginalised or unheard voices. Much of this tradition stems from social history and efforts to document this uncaptured history that represented the actual lived experiences for much of a working population outside of the hegemonic class, or other disenfranchised groups.[100] This is due to many archival sources privileging "official

[98] Anderson, "Analytic Autoethnography", p. 380.
[99] Atkinson, *Writing Ethnographically*, p. 138.
[100] Abrams, Lynn, *Oral History Theory*, (Abingdon UK: Routledge, 2016), pp. 4-6.

accounts", or shaped by what happens to have been preserved officially or privately. Interpretations of these events from unofficial or unrecognised sectors of society were largely unheard. In the context of this study the "official account", could be considered the publication in a learned journal, conference proceedings or government report, where their collective reductive nature has removed the authors own voice. Groups, such as scientists, were trained to remove their voice from many facets of communication, with social and contextual influences considered superfluous, except maybe for a short acknowledgement of the threat of climate change in the introduction of a paper. [101] Therefore, in this respect the oral histories collected from scientists, engineers and developers can help in reconnecting with the people behind the work and bring their social relations more to the foreground.

The majority of participants for the oral history interviews were drawn from a materials science and engineering background and reflects the prominence of this community across SOFC development. They were selected because of their prominence within the community. All of the participants interviewed measure their involvement in the field in decades. The majority have significant levels of publications in SOFC research, design and development, and all are recognised for their active engagement in work to bring the SOFC from the laboratory towards real world deployment. Although they come from within the SOFC community they represent different institutional backgrounds. Some are academics, some industrially based, some have moved between the two. There are also engineers who have sought to use the SOFC, as well as participants from economics and policy making backgrounds. The community around the SOFC is tightly knit and many of the participants in this study are still active within the community, so while some of the participants were happy to be identified within this work, a number preferred to remain anonymous, this allowed them to speak with greater candour about their recollections. In these cases, contributions from these participants are referred to as "anonymous interview" in the footnotes.

While prominent within the SOFC community, on a global scale, regarding wider energy transitions, my participants were not senior politicians making national

[101] Doel, Ronald E., 'Oral History of American Science: A Forty-Year Review', *History of Science*, 41 (2003).

energy policy: however, neither were they graduate students working away in the depths of the laboratory with little or no influence. In his 2016 book *The Long Arm of Moore's Law*, historian of science Cyrus Mody described such actors as "meso-level."[102] My participants did possess considerable agency in the development of the SOFC and were respected leaders within their field whose opinions were sought, listened to and in many cases acted upon. They would write papers, articles and books. They would give keynote speeches at conferences and were involved in multiple funding cycles both as applicants and as assessors. In many ways, they have they have been instrumental in constructing the discipline, the community around it and the narratives which are embedded within it. Therefore, within the close community of the SOFC they could be considered "elites," something which was an important consideration with respect to the intersubjectivity of the interview process, especially considering my own positionality as a member of the community.[103]

Many oral histories initially looked to give voice to those previously unheard or marginalised in official accounts: however, it was quickly realised that such attempts to widen the historical narrative from oral accounts was not so straightforward. The researcher was intimately involved in the process both from shaping the questions asked, to selecting how to use the answers given by participants in later reports or papers.[104] This resulted in an imbalance of power between the researcher and the participant, with the power tending towards the researcher, especially in terms of how the final narrative was constructed. A further imbalance was often identified when interviewing participants who were from nonhegemonic groups, those perceived to hold little in the way of power to influence the events that they were discussing. In these situations, the presence of the researcher, often an academic from a respected institution, presented a social imbalance between the researcher and the participant. This again potentially created perceived social imbalances weighted in favour of the researcher.[105]

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[102] Mody, Cyrus C. M., *The Long Arm of Moore's Law: Microelectronics and American Science*, (Cambridge: MIT Press, 2016), p. 17.
[103] Odendahl, Teresa and Aileen M. Shaw, 'Interviewing Elites', in *Handbook of Interview Research*, ed Jaber F. Gubrium and James A. Holstein (Online Resource: SAGE Publications, Inc., 2001), pp. 299-316.
[104] Portelli, Alessandro, 'The Peculiarities of Oral History', *History Workshop*, 12 (1981), pp. 103-104.
[105] Thompson, Paul and Joanna Bornat, *The Voice of the Past: Fourth Edition*, (Oxford: Oxford University Press, 2017), p. 21.

In the case of my research, it could be argued that such imbalances were not only less likely to exist but, in many cases, may have reversed. Firstly, all of the participants in this research were senior academics, industrialists or of similar standing. This, therefore negated the perceived power imbalance of, for example, the academic researcher interviewing a shop floor worker. Secondly, due to my own previous research activities in this field many participants were known to me, either personally or through reputation. We were therefore at least peers within the community, many of the participants were senior figures in the field whom I held in high respect for their work and on a few occasions, some had actually held management responsibilities over me.

Therefore, in many cases we were equals and in some it could be argued that the power imbalance between participant and interviewer was reversed. Where such power existed, it could be exercised in terms of controlling time and duration of any interview, even granting an interview or dictating the terms under which an interview was conducted.[106] While such issues did not present themselves as my research proceeded, it was still something that I had to remain aware of in designing and conducting my interviews.

A further consideration related back to the relatively close community of SOFC research. Many of the participants knew one another or had worked and collaborated together for many decades. Therefore, there was a significant chance that my research programme would be discussed between participants. This created a couple of potential issues. The first was how my research was viewed by the various participants: was it seen as valuable to the field or an unnecessary intrusion? If their view was unfavourable, it could have had negative implications for recruiting further participants or influenced the manner in which participants engaged with the interviews. Second, invitations to participate were sent out over an extended period of time, was there a chance that if a participant was aware that they had not been invited earlier in the process they could take this as a slight on the value of their contribution, thereby making it difficult to recruit them at a later date.

Several oral historians have also commented on the relationship between researcher and participant being a vital factor in determining the type of information

[106] Odendahl and Shaw, "Interviewing Elites".

that was revealed by a participant. As I was considered an insider to the community it could shape the direction of the interview in profound ways. In certain circumstances this could be considered a good thing, leading to more insightful enquiry from the researcher and correspondingly reflective answers from the participant. However, this familiarity could also lead to issues with the inter-subjectivity between the observer and participant leading to omissions of information due to the shared assumptions, or a researcher who may be highly invested in the topic experiencing feelings during an interview that distract from following up a comment or avoiding a line of enquiry as they do not want to put the participant into an uncomfortable situation. The researcher may also feel pressure from participants to "do the story justice" or tell the story in a particular light.[107]

Most interviews were conducted over an eighteen-month period across 2021 and 2022, with some later ones in 2023 and 2024. Over this period nineteen individuals were interviewed, mainly over the Zoom web-based meeting platform, but some by telephone, and towards the end of the project a few interviews were conducted face-to-face. While remote interviewing techniques can have limitations in terms of reading body language and reacting to nonverbal cues, they also had the advantage of allowing the interviews to have a far further geographical reach than potentially would have been possible if they were all conducted face-to-face. Interviews were semi-structured, and ahead of the interview participants were given a sheet containing some outline points for discussion, which was termed a "reflective outline". Each participant was given an individual reflective guide based on my initial research and my own knowledge of their individual positioning within the field and looked to bring out their own unique journey in the SOFC community. It was highlighted to the participant that this was mainly a guide to assist their own reflections or help guide the discussion and was not a questionnaire to be rigidly followed. Digression to other interesting points which they felt were important in telling their story was encouraged.

[107] For differing perspectives on the issues of interviewing peers and members of their own community see Murphy, Amy Tooth, 'Listening in, Listening Out: Intersubjectivity and the Impact of Insider and Outsider Status in Oral History Interviews', *Oral history (Colchester),* 48 (2020); Yow, Valerie, '"Do I Like Them Too Much?": Effects of the Oral History Interview on the Interviewer and Vice-Versa', *The Oral History Review,* 24 (1997); Platt, Jennifer, 'On Interviewing One's Peers', *The British Journal of Sociology,* 32 (1981).

Interviews lasted around one hour with the shortest being around 45 minutes and some longer ones running to two hours. In addition to interviews conducted directly for this work, participants from a 2018 science and technology studies (STS) focussed study undertaken to investigate learning pathways in SOFC graciously allowed me to reuse these interviews for this historical research.[108] This gave access to a collection of seven further interviews which although carried out for a more STS orientated project, still contained significant historical content and participant reflection. Therefore, relistening to these interviews from the perspective of an oral history would potentially yield fresh interpretations and further insights.[109]

The interviews were analysed by a mixture of repeated listening, summarising and transcription. I approached the interview data in a grounded manner, trying to avoid the imposition of any pre-existing theories and letting the text speak for itself. Special attention was paid to looking for cross cutting themes which emerged from multiple participants. Where such themes were identified further consideration would be given to the source of such shared understandings: for example, was this from a common institutional background or other shared experience? Attention was also given to how participants described or discussed their experiences and exposure to the wider contextual changes of the time period. One feature of speech which could be useful here was if a participant switched between describing events in personal or more formalised terms. The latter suggested more collective and shared understandings of the community, while the former potentially pointed to a more personal relationship to the events being described.[110] Another aspect of speech where close listening of the recording proved useful was identifying times where dialogue between myself and the participant would adopt a more conversational tone, mostly when discussing events where we were both present or personally involved.

The aim of the oral history programme was to get underneath the reductive and formulaic structure of the academic paper or government report, where social and contextual influences are often minimised and the text reflects a more idealised

[108] Cassidy, Mark, 'The Long and Winding Road: A Study of the Innovation Dynamics & Learning Pathways in Solid Oxide Fuel Cell Development ', (University of Edinburgh, 2018).
[109] Bornat, J., 'A Second Take: Revisiting Interviews with a Different Purpose', *Oral History,* 31 (2003).
[110] Portelli, "The Peculiarities of Oral History", p. 99.

logical sequencing of information, rather than the messy, non-linear processes that actually occur in the laboratory or industrial research department. It looked to gain better understanding as to how the influences of wider macro level events across energy landscapes and science and technology management were experienced or perceived by the participants who were undertaking SOFC development and what effects these wider contextual influences had on development decisions within the SOFC community.

Archival Sources

The data collection and analysis engaged with both primary and secondary documentary sources. I drew from a number of different types of sources to attempt to gain access to a number of different actor perspectives on SOFC strategy and development, such as government bodies, funding agencies, private investors, industrial SOFC developers, academic laboratories and potential end users. These documents also represented a variety of modes of communication including (but not limited to) academic papers and reviews, company reports and brochures, government agency updates and investor profiles. As well as these established sources of information, I also looked to utilise more general media outputs such as popular scientific stories in the press and public perceptions via websites and online comments and discussions. These latter sources were important in positioning the technology within wider socio-political contexts and debates such as air quality and climate change.

As well as primary research papers detailing technical aspects of SOFC development, I also searched for primary data in on-line governmental archives such as the US federal archives database, the US Dept. of Energy, Office of Science and Technical Information (OSTI) database and the Central Intelligence Agency (CIA) online reading room.[111] I used these to elucidate general US energy research and development policy and where possible relate this to SOFC developments. Where these wider archives did not refer directly to SOFC, I searched other potential primary sources which were closer to SOFC research, such as archival sources and

[111] https://www.archives.gov/research/alic/reference/govt-docs.html; https://www.osti.gov; https://www.cia.gov/library/readingroom/home.

press releases around the National Labs and academic research groups directly involved in SOFC research.

It may be noted that I specifically refer to on-line archives above, this reflects the global context under which this research was undertaken. I commenced my PhD in September 2019 and in March 2020, just six months in, the world came to a standstill with the COVID-19 pandemic. The travel restrictions that remained in place for the following two years rendered original plans to undertake a US archival fieldtrip untenable within the funding window of my PhD. Fortunately, the on-line databases of the organisations above contained digital copies of many of the original progress reports that various groups such as the Westinghouse team had prepared for the various US government agencies funding their work. Close historical reading of these technical reports combined with my “insiders” technical knowledge allowed a great deal of information to be gleaned from these reports, which when used in conjunction with other contemporaneous primary and allied secondary sources still revealed much detail, such as the early SOFC work at Westinghouse.

While these digital records, allied with the detailed accounts from my oral history participants still permitted a rich account of early SOFC development to be written, it cannot be ignored that access to physical archives, for example the Westinghouse records held at the Hienz History Center, Pittsburgh, Philadelphia, run by the Historical Society of Western Pennsylvania, would have been of additional value.[112] Here I hoped to find records of communications and discussions not captured within the official reports which may have shed further light on the issues and concerns shaping the decisions of the Westinghouse SOFC team, particularly any discussions and tensions across the wider corporate landscape of Westinghouse

[112] This archive has been cited in several histories relating to technoscientific development at Westinghouse, Lassman, Thomas C., 'Industrial Research Transformed: Edward Condon at the Westinghouse Electric and Manufacturing Company, 1935-1942', *Technology and Culture,* 44 (2003); Kline, Ronald R. and Thomas C. Lassman, 'Competing Research Traditions in American Industry: Uncertain Alliances between Engineering and Science at Westinghouse Electric, 1886—1935', *Enterprise & Society,* 6 (2005). and of particular interest to me in this work was a Box176-Folder 6 labelled “SOFC”.

during the 1960s and 1970s, This would have helped further increase the richness of this part of the account. This potentially provides an avenue for future study.

Another important source of primary data were the various avenues of communication from the different commercial organisations involved in SOFC development. Of particular interest was how the discourse varied between that intended for technical consumption (e.g., reports to funders and presentations to peers at technical conferences) and that intended for wider consumption (e.g., press releases, statements relating to investment opportunities, etc). Therefore, databases archiving articles in both the popular and technical press were a useful source of such information.[113] These more popular or general pieces were of considerable interest as they represent the interface between communities. Whereas more technical articles, for example in specific disciplinary journals, could be said to be a community discussing or debating within itself, articles in more general trade journals or popular press could be said to be the SOFC community, or advocates for the community, trying to convince other relevant communities of the utility of the SOFC. Conversely, these general articles may also be the documentary locations where barriers to a new technology are constructed - where uncertainties around the operational viability, interoperability of technological systems or just costs are used to reinforce and protect existing regimes based on established technologies, practices and the social relations of the two.

One further interesting source of contextual data, that I drew from was on-line message boards such as "siliconinvestor.com."[114] This particular web resource provided a specific link to the message board relating to comments of small private investors in the SOFC company Global Thermoelectric. This company adopted SOFC technology in the mid-1990s and were caught in the cycles of growth and expectation described by Konrad and others as being typical of the second half of that decade.[115] Webpages such as "siliconinvestor.com" provided some insight into the social aspects of energy investing which played an important part in the

[113] https://advance.lexis.com
[114] Available at https://www.siliconinvestor.com/subject.aspx?subjectid=17464
[115] Konrad, et al., "Strategic Responses to Fuel Cell Hype and Disappointment"; Ruef and Markard, "What Happens after a Hype? How Changing Expectations Affected Innovation Activities in the Case of Stationary Fuel Cells".

expectation and excitement around smaller fuel cell companies emerging during the late 1990s.

Structure of Thesis

Following on from this introductory chapter the remainder of the thesis is composed of seven further chapters. In Chapter 2 I begin by discussing materials science and the cultures and practices of the materials scientists and engineers, a community who I identified as being most directly involved in SOFC development. In this chapter, I also aim to develop and justify the analytical lens thorough which the events described in subsequent chapters will be observed and discussed. I outline the notion of technoscience, where the boundaries of science technology and engineering practices are blurred and difficult to define and how various successes in the years following Second World War engendered a belief in technoscientific practice and the power of materials to deliver solutions. From this premise I further explore the culture, values and practices of the technological community around the SOFC and contend that the very nature of materials science promotes technoscientific practices, and what this means for the type of knowledge produced within the community. This discussion is expanded to consider how the culture of materials transitions from within a technical community to wider contexts by discussing the materiality of an artifact such as the SOFC, and how it moves beyond its technical function to perform wider social roles. This leads on to the way the physical form of the artifact can give further clues to the values and practices of the technological community. It suggests how the different forms reveal some of the decision-making processes at work and what they say both about the ambitions for the SOFC, but also the material affordances and changing contexts of any given time which acted to rein in these ambitions.

In Chapter 3, I outline the early history of the SOFC and go on to describe how one of the first attempts to create a practical SOFC system emerged from the needs of the political backers of the US coal industry looking to secure the place of coal in the changing contexts of US energy, where continued consumption of coal for electricity generation was being placed under pressure from growing utilisation of oil, natural gas and nuclear. These initial attempts, while not resulting in a practical system, were important for establishing basic the materials sets and arrangements of the device, along with identifying initial operational parameters and areas for further development. I then discuss how this knowledge was used by SOFC developers to rekindle interest in the SOFC by reframing it as part of a range of solutions to the energy crises of the 1970s, with narratives focussed on increased use of US domestic coal reserves drawing on political imperatives to be seen to be minimising the countries increasing dependence on foreign oil. These political imperatives, of maintaining the supply of energy against an ever-increasing demand, were also at the heart of several reorganisations of US energy R&D management over this time, and I describe how these new organisations, such as the Department of Energy (DOE), looked towards technologies such as the SOFC as a means of offering technical solutions to problems whose roots were embedded within social, cultural and political dimensions.

In Chapter 4, I build on the emerging relationship between the DOE and Westinghouse and how this developed into a longstanding sponsorship which shaped US SOFC development over the next two decades. While DOE funding was relatively modest, the steady stream of funding combined with the culture of the large US corporate research laboratory gave the Westinghouse SOFC scientists latitude to explore different cell arrangements resulting in significant improvements in performance, reliability and an encouraging demonstration of SOFC promise. This helped legitimatise the technology so securing further funding.

Chapter 4 also engages with the enthusiasm of the new Reagan Administration for market-led technological solutions which led to other profound changes in the US such as the beginnings of deregulation in energy markets and changing practices of R&D. I begin to explore these changes from the perspective of SOFC development, and how contexts of deregulated energy markets began to stimulate notions of smaller distributed nodes of electrical generation distinct from the established ideas of large, centralised facilities built by the corporate giants linked to government backed infrastructure projects.[116] I describe how SOFC developers began to reframe the SOFC as a smaller unit to match these new contexts and how this attracted new sets of actors to SOFC development, which brought new approaches to the design and manufacture of the SOFC. I contend that these new groups, together with Westinghouse, laid the foundations for the rapid expansion in SOFC activity which was to be seen in the 1990s.

An account of this rapid expansion of SOFC development activity in the 1990s forms the basis of Chapter 5. I argue that the adoption of thick-film processing technology which appeared to simplify the fabrication processes and drastically reduced the cost of entry to new developers was a key enabler of this expansion. No longer was SOFC manufacture the preserve of the large corporate research institute: it could now be accomplished by a single researcher in the corner of a laboratory, which led to a surge in research and design activity. I also outline how, at the same time, changes in the management of established US corporate entities were incorporating more market-oriented thinking and that this led to a short-termism in company management which eventually resulted in the dissolution of the large corporate lab. This precipitated a shift in the centre of knowledge production from the large corporate R&D centres towards university laboratories and small companies looking to rapidly capitalise on new knowledge, which I argue reinforced how the new SOFC actors were beginning to reframe the device as part of a deregulated energy framework.

This more market-oriented landscape, allied with manufacturing shifts, attracted the attention of entrepreneurs looking for new speculative investment opportunities. Buoyed by recent rapid successes in digital technologies, investors superimposed these investment models onto energy technologies which led to overly ambitious expectations of returns on investments. I describe the formation of a knowledge community centred around promissory materials for the SOFC which privileged the discovery, processing and application of new materials, and how

[116] The US federal government was involved in several large electrical utility and infrastructure projects such as the Tennessee Valley Authority and Bonneville Power Administration. Further, due to its costs and complexity the US civil nuclear project also created many close ties between government and the corporate giants of US industry such as Westinghouse and General Electric. For an account of the government involvement in civil nuclear see Lowen, Rebecca S., 'Entering the Atomic Power Race: Science, Industry, and Government', *Political Science Quarterly,* 102 (1987).

encouraging laboratory results reinforced expectation and created misunderstandings around the difficulties in translating smaller tests and demonstrations in controlled settings into a fully commercial device. I suggest this confluence of events, both technical and contextual, was an important factor in the SOFC part of the fuel cell hype cycle of the late 1990s and early 2000s.

In Chapter 6, I focus on the case study of a single company, Global Thermoelectric. This company embodied many of the issues discussed in Chapter 5 with respect to the expectation built by early laboratory successes and the challenges of delivering these as a commercially viable product. Over the space of five years, the company went from just entering SOFC technology, to becoming one of the world leading companies in the field at that time, to suffering share price collapse and eventual sale. While Global Thermoelectric has many traits in common with other fuel cell start-up companies, it also had a key differentiator: before engaging on SOFC development it was already a successful small company working in another area of energy technology, that of the thermoelectric generator.

Through interviews with key technical actors working within the company over this time and reviewing the contemporaneous views of small shareholders in the company, I follow the increasing influence of fuel cell activities on the company identity. This chapter aims to give a fine-grained account of how this identity changed, from a company whose value was based on a portfolio of energy products to one based solely on the perceived value of a promissory fuel cell product. This delivered dynamic capital spurred by powerful imaginaries of new distributed energy frameworks and new materials technologies. However, building on assumptions constructed from experiences in digital technologies resulted in profound misalignment of expectation against delivery: this led to delays, loss of confidence and eventually sale of the company. Despite these events, future owners were able to reframe the underlying promise of their SOFC technology to align it with ongoing and future US government energy policy imperatives, so maintaining its legitimacy to secure funding for continued development activities.

In Chapter 7, I return to a wider account of US SOFC development priorities over the early 2000s. Here, I discuss how the events of the 1990s led to the US DOE restructuring its SOFC development programme to better reflect the trends towards smaller SOFC systems based on thick-film manufacture. This account segues with the reframing of the former Global Thermoelectric who became an integral part of this new programme. This repositioning of US SOFC towards smaller systems did not last long, activities quickly became interlocked into wider US government policies around the development of large-scale facilities for hydrogen production and “clean coal”, again couched around rhetoric of energy security and insulation from geopolitical energy supply shocks, but now with the addition of achieving these goals with reductions in carbon dioxide emissions. This brought US SOFC development into close association with hydrogen imaginaries, which was instrumental in its brief cancellation as the incoming Obama Administration moved against hydrogen.

I then describe how US SOFC development was resurrected by the framing of the SOFC as compatible with existing hydrocarbon energy frameworks and presented as potential “technological fix” which could help the US meet many energy policy goals. I also remark on how a further reframing of these devices, as energy convertors for storage of renewable energy via hydrogen, closely mirrors the original conception of the technology as envisaged by the inventor of the alkaline fuel cell Francis Bacon when he first proposed it in the 1930s and how from some perspectives it could be argued that the technology has come full circle. These examples reveal how, through multiple reframing of the SOFC to appeal to multiple energy constituencies, developers became bound up in two very different energy imaginaries, one based in electrochemical conversion of hydrocarbon fuels as a route to helping maintain existing energy infrastructures and the other based around the use of hydrogen and electricity as vectors for storage and transmission vectors of green energy from renewable energy. Together these apparent contradictions which promise both changed and unchanged worlds have simultaneously complicated the development of the SOFC and sustained interest by maintaining expectations of its role as a “technical fix”.

The conclusion looks to distil the main elements of the history of the SOFC and connect these to the wider ideas of technological optimism and the need for a “technological fix” discussed in Chapters 1 and 2. Here I aim to argue that over its long development the SOFC has been able to be reframed to maintain its promise against the changing expectation of policymakers. A promise whose validity was, to a large extent, embedded in the belief that new materials and processes would deliver solutions to the problems experienced by earlier examples.

Chapter 2: Technoscience, Materials and Materiality

> "the material was the device"[1]
>
> "…materials seem to vanish, swallowed up by the very objects to which they have given birth"[2]

The SOFC is a device, or object, which is inseparable from materials. Materials are important to this story, as not only are they directly linked to the SOFC, but they were also central to the technological optimism in the postwar US. With new analytical techniques, materials could be understood at the atomic level, enabling "materials by design" the results of which pushed progress in sectors such as aerospace, electronics and biotechnologies.[3] The inherent interdisciplinary of materials development also became a blueprint for science and technology expansion in the US in the 1950s and 1960s.[4] The ongoing successes of "Silicon Valley", based around semiconducting materials, in turn laid the foundations for models of innovation based around disruptive start-up companies in the 1990s.[5] Materials science and technology also dominates SOFC activities: a quick look at any SOFC conference proceedings will show this, with many future promises for the technology being predicated on the "next materials breakthrough". However, the SOFC is more than a single material. It is an assembly of materials, where the selection, processing, arrangement, and design of the material layers define the device and ultimately, how it is seen and interpreted and utilised by different sociotechnical groups within wider energy systems. Therefore, the SOFC does not exist at a single level, but is a multifaceted device which can be considered across several, with each conferring differing values and affordances depending on the position of the observer.

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[1] Lécuyer and Brock, "The Materiality of Microelectronics", p. 307.
[2] Ingold, Tim, 'Materials against Materiality', *Archaeological Dialogues*, 14 (2007), p. 9.
[3] Bensaude-Vincent, Bernadette, 'Das Konzept Von Werkstoffen in Historischer Perspektive', *NTM-J HIST SCI TECHN*, 19 (2011), p. 117.
[4] Baker, "The National Role of Materials Research and Development, Address Delivered at the Materials Science Luncheon, Astm Materials Science Division Symposia [1961]".
[5] Berlin, Leslie, *The Man Behind the Microchip: Robert Noyce and the Invention of Silicon Valley*, (New York: New York: Oxford University Press, 2005); Lécuyer, Christophe, *Making Silicon Valley : Innovation and the Growth of High Tech, 1930-1970*, (Cambridge, Mass.: Cambridge, Mass. : MIT Press, 2006); Riordan, Michael and Lillian Hoddeson, *Crystal Fire : The Birth of the Information Age*, (New York: New York : Norton, 1997); Mody, *The Long Arm of Moore's Law: Microelectronics and American Science*.

With the centrality of materials science to the development of the SOFC it would be easy to assume that all knowledge creation in the field derives from fundamental studies in physics and chemistry and disseminates in a hieratical structure to technology, engineering and processing. However, such a view, that technology and engineering are applied science, has long been problematised in the history of technology and engineering, and it is now well recognised that technology and engineering are distinct forms of knowledge with their own epistemologies, cultures and practices.[6] Historian of the philosophy of science and technology Ann Johnson discussed how actors from these distinct and different knowledge bases, such as electrical engineering or mechanical engineering, come together to form "knowledge communities" around specific engineering problems. Here a community can form around the solution of a technological or engineering problem with the composition of the community representing the main challenges to be addressed. However, she also suggested that such communities are dynamic with the composition of technological backgrounds changing with time as the nature of the problem at the centre of the community changed.[7]

Therefore, it could be expected that the design of a multifaceted device such as the SOFC, spanning many academic, engineering and systems design disciplines, would result in a highly dynamic community with changing composition encompassing all of these disciplines reflecting the changing nature of the development challenges. However, across the more than 60 years of development materials science and chemistry remain the most prolific of the disciplines associated with the SOFC. This is not to suggest that other disciplines are not involved in the development of the SOFC, rather that the distinction between the epistemological practices of the disciplines appears more difficult to discern. With respect to developing the core SOFC stack (the electrically connected array of individual cells required for a practical fuel cell system), materials scientists need to consider engineering implications, while engineers need to be aware how the chemical and compositional sensitivities of the materials impact their work. Such practices espouse

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[6] Vincenti, Walter G., *What Engineers Know and How They Know It : Analytical Studies from Aeronautical History*, (Baltimore: Baltimore : Johns Hopkins University Press, 1990).
[7] Johnson, Ann, *Hitting the Brakes: Engineering Design and the Production of Knowledge*, (Durham: Durham: Duke University Press, 2009).

the ideas put forward by both Layton and Hughes of scientists acting as engineers and engineers doing science and creates a diffuse boundary between science, technology and engineering which is difficult to define.[8] The difficulty in defining such boundaries and not being able to easily to identify the flow of ideas, methods and epistemological basis were at the heart of what some defined as “technoscience”, especially as these boundaries extended beyond the laboratory into wider networks of actors and institutions.[9]

One of the aspects of SOFC history this thesis seeks to explore are the effects of the dominance of materials science thinking and cultures in SOFC research and development. Did this create dominant narratives from the SOFC technical community about the primacy of materials and that solutions to problems would be predicated by new, novel and breakthrough materials? [10] If this was the case, did such narratives influence other technical actors and policymakers in the community when deciding directions for support and future development? Then in turn did this reinforce and further strengthen frames and narratives about the “next breakthrough” material?

In order to enable these questions to be addressed across the remainder of this thesis, this chapter aims to develop an analytical framework through which the history of the development of the SOFC can be interpreted. Such a framework seeks to move beyond the extensive but reductive technical reviews in the literature and attempts to bring into consideration the cultures and practices underpinning those actors making the decisions in the design and development of the device. Geertz suggests that culture is not something which in itself causes behaviours or social actions: rather, it is a context in which these actions take place, and it is observing these actions within this context that forms the basis of what he termed “thick

[8] Layton, Edwin, 'Mirror-Image Twins: The Communities of Science and Technology in 19th-Century America', *Technology and Culture*, 12 (1971); Hughes, Thomas Parke, 'The Seamless Web - Technology, Science, Etcetera, Etcetera', *Social studies of science*, 16 (1986).
[9] Latour, Bruno, *Science in Action : How to Follow Scientists and Engineers through Society*, (Milton Keynes: Milton Keynes : Open University Press, 1987), pp. 174-175; Pickstone, John V., *Ways of Knowing : A New History of Science, Technology and Medicine*, (Manchester: Manchester : Manchester University Press, 2000), p. 163.
[10] Wachsman, E. D., C. A. Marlowe, and K. T. Lee, 'Role of Solid Oxide Fuel Cells in a Balanced Energy Strategy', *Energy and Environmental Science,* 5 (2012).

description".[11] Therefore this chapter will discuss the cultural context for the materials scientists and provide a lens through which to observe and describe the actions and practices of the actors involved in the history of SOFC development.

Materials and Technoscience

Technoscience embodies the idea that science and technology do not exist as a linear progression from fundamental, through applied then onto technology. Rather they are intertwined with both science and technology driving one another similar to the "seamless web" espoused by Hughes.[12] While the focus of this chapter is on the development of materials science in a postwar environment, mixed communities of scientists and engineers employing technoscientific practices were already well established. Such communities were evident in the emerging corporate research and development centres of the early twentieth century. The growth of the influence of corporate research and development centres such as those of General Electric, Westinghouse and Bell Labs were part of a changing locus for the generation of science as industrialisation began to increase in pace.[13] This shifted knowledge production away from the stereotypical imagery of the dusty basement laboratory inhabited by the lone Victorian scientist indulging their curiosity and into the large corporate complex of heavily staffed and copiously equipped teams, all working towards shared corporate goals which Mirowski and Sent describe as the first regime of twentieth century science organisation.[14]

It could be argued that the foundation for the discipline of modern materials science that emerged in second half of the twentieth century were the large interdisciplinary projects of the Second World War, most famously the Manhattan Project to develop the atomic bomb. These projects influenced many individuals as to the critical importance of scientific and technological development in the years

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[11] Geertz, Clifford, *The Interpretation of Cultures 3rd Edition (2017)*, (New York: Basic Books, 1973), p. 15.
[12] Hughes, "The Seamless Web - Technology, Science, Etcetera, Etcetera".
[13] Wise, George, 'A New Role for Professional Scientists in Industry: Industrial Research at General Electric, 1900-1916', *Technology and Culture*, 21 (1980); Smith, John Kenly, 'The Scientific Tradition in American Industrial Research', *Technology and Culture,* 31 (1990); Kline and Lassman, "Competing Research Traditions ".
[14] Mirowski and Sent, "Commercialisation of Science", pp. 640-649.

following Second World War and importantly, the role of interdisciplinarity in achieving these goals. Much of the rapid technological development taking place in the US in the 1950s, 1960s and beyond revolved around the specific area of materials. Advances in sectors such as aerospace, electronics, defence and many allied areas all relied heavily on improving not only fundamental understanding of the science of materials but also, importantly, how to process them into viable technological devices. Leaders in the materials arena was AT&T's Bell Labs.[15] In particular, the ideas and writings of Vice President and later President of Bell Labs, William O. Baker, were highly influential in shaping the thinking of successive US governments with respect to the place of materials in national security and later the wider technological prowess of the nation.[16]

Baker served as both vice-president (1955-1973) and president (1973-1979) of Bell Labs, arguably one of the most archetypal industrial research labs of the immediate postwar era, the framework of which many have tried to emulate as a model to produce innovative and impactful technoscience. A physical chemist by training, Baker had been part of the effort developing synthetic rubber during the Second World War.[17] In all his writings, spanning over 4 decades, the achievements of postwar interdisciplinarity in fields such as electronics, aerospace, biotechnologies, polymers are sold as positive outcomes in no uncertain terms. Taking these achievements as his baseline, Baker believed that academic research and development focused on government needs, in close collaboration with industry, was the way to continue developing new materials which would impact many of the technological issues at a national (and therefore, one could imply, societal) level. Baker called for interdisciplinarity to be enshrined at a national level through the creation of government-led programmes and new interdisciplinary institutions. This drew heavily on activities within emerging military-industrial complexes established

[15] Gertner, Jon, *The Idea Factory : Bell Labs and the Great Age of American Innovation*, (New York: New York : Penguin Press, 2012).
[16] For example see; Baker, "The National Role of Materials Research and Development, Address Delivered at the Materials Science Luncheon, Astm Materials Science Division Symposia [1961]"., Baker, W.O., 'Science and Technology', *Daedalus,* 109 (1980)., Baker, W.O., 'Using Materials Science', *Science (New York, N.Y.),* 211 (1981)., Baker, *Advances in Materials Research and Development*.
[17] Baker, W.O., 'Microgel, a New Macromolecule', *IND ENG CHEM,* 41 (1949).

during the Second World War and which gained traction during the immediate postwar and cold-war years.

Baker was keen to link the emergence of materials science and technology with earlier epochs of human development such as the Stone Age, Bronze Age and Iron Age. He referred to the current time as the “materials era” or “solid state era” and was keen to contrast the interdisciplinary practice he promoted as part of this materials era in contrast to those of “academic science…as engendered by the great European traditions”, where disciplinary silos had organised knowledge with “little change in them for centuries”. [18] The language used in the second quotation is somewhat rhetorical as it implied nothing had changed in the academia for hundreds of years, whereas the late eighteenth century and the nineteenth century had actually been times of great change in academia, with the initial disciplines, as we would recognise the concept today, only emerging from the 1830s.[19] Growth of the disciplines continued since that time with emergence of new disciplines through division, coalescence or refinement of existing disciplines. Indeed, the emergence of Materials Science as a discipline in its own right could be considered to be a continuation of this process: however, the establishment of the discipline of Materials Science proved to be more complex.[20] While many materials science departments did indeed appear in universities in the 1960s and 1970s, in many cases the management and administration of the research within these departments was very different from that of a traditional academic discipline. The knowledge creation was no longer being sought for its own sake, but rather focused towards national goals and entrepreneurial ambitions, and the direction of research was no longer instigated by the curiosity of the individual academic but by the milestones and targets required to satisfy the programme manager.[21]

[18] Baker, *Advances in Materials Research and Development*, p. 4; Baker, "The National Role of Materials Research and Development, Address Delivered at the Materials Science Luncheon, Astm Materials Science Division Symposia [1961]", p. 2.
[19] Weingart, P, 'A Short History of Knowledge Formations', in *The Oxford Handbook of Interdisciplinarity*, ed R Frodeman, J.T Klein, and C Mitcham (Oxford: Oxford University Press, 2010), pp. 3-14 (p. 6).
[20] Bensaude-Vincent, Bernadette and Arne Hessenbruch, 'Materials Science: A Field About to Explode?', *NAT MATER*, 3 (2004).
[21] Channell, David F., *A History of Technoscience: Erasing the Boundaries between Science and Technology*, (Abingdon: Routledge, 2017), p. 257.

Some have suggested that this change in how research is structured and managed represents an epochal break in scientific practice.[22] With the frequent linking of the "materials age" to the other epochal ages of human technological development in his writings it would certainly seem that William Baker also saw it in this light.[23] Others have suggested that the realm of technoscience has become part of a postmodern era of science where advances in technology may no longer be seen by some to guarantee "progress" in a modernist sense.[24] If this later view is correct, how does this postmodern position relate to the post-industrial condition where knowledge rather than manufacturing is seen as the driver for economic growth? This has interesting implications for how materials have been considered across history. For example, how does the worldview of materials in Baker's materials age differ from that of the great engineers of the industrial revolution, as the development and application of materials were central to both. In both the iron forge of industrial revolution and the microfabrication facility of the semiconductor "ways of making" play a central role.[25] The main difference is the length scale over which the material is both considered and understood. Therefore, one can consider if the current materials age is indeed an epochal shift or rather just another "way of knowing" with respect to materials?[26]

For much of the historical record materials were seen as different "substances" or "bodies" which were often classified and grouped with respect to readily observable physical appearances, behaviours and properties creating a "zoology of materials".[27] This cataloguing approach resonates strongly to the "natural history" way of knowing as proposed by Pickstone.[28] These substances were hewn, extracted, fashioned and distilled from nature with the skills to work the substances tacit and undocumented, firmly within the realms of craft, the artisan and even the alchemist. However, over the eighteenth and nineteenth centuries the

[22] Nordmann, A., H. Radder, and G. Schiemann, 'Science after the End of Science? An Introduction to the "Epochal Break Thesis"', in *Science Transformed? Debating Claims of an Epochal Break*, ed A. Nordmann, H. Radder, and G. Schiemann (Pittsburgh: Pittsburgh University Press, 2011), pp. 1-15.
[23] Baker, *Advances in Materials Research and Development*, p. 13.
[24] Forman, Paul, 'The Primacy of Science in Modernity, of Technology in Postmodernity, and of Ideology in the History of Technology', *History and Technology*, 23 (2007).
[25] Baker, "Using Materials Science", p. 359.
[26] Pickstone, *Ways of Knowing : A New History of Science, Technology and Medicine*.
[27] Bensaude-Vincent, "Das Konzept Von Werkstoffen in Historischer Perspektive", p. 110.
[28] Pickstone, *Ways of Knowing : A New History of Science, Technology and Medicine*, p. 60.

emergence of chemistry as a discipline and the ascendance of analysis and rationalisation as ways of knowing substances saw attempts to reduce natural substances to their basic components in an attempt to understand how they were composed from these basic "elements".[29] This developed a chemist's "style of thinking", which revolved around and evolved from the early modernist "laboratory style" which Ian Hacking derived from Alistair Crombie's "styles of scientific thinking", in particular the "experimental argument".[30] Echoes of this "laboratory style" are still evident in today's materials research and development facilities and it will be argued across this thesis that it has had a significant influence on the culture of research and development in the SOFC community and has impacted, and continues to impact the dynamics, priorities and directions of SOFC development.

While the reductive approach of the "laboratory style" began to unravel some mysteries of how various substances were made up, utilisation of these was still very much in the hands of the craft artisan. It was not until the twentieth century and the emergence of ideas such as atomic theory and quantum theory, supported by new instrumental techniques such as X-ray diffraction, electron microscopy and associated compositional spectroscopies, that the "generic notion of a material" began to form.[31] This allowed any material to be defined by the spatial arrangement of its constituent atoms, with the materials structure and properties being defined both by this arrangement and the nature of the bonds holding them together.[32] This understanding of "structure-property-process-performance" relationships revealed the underlying "abstract knowledge" of materials and the notions of being able to manipulate these relationships very precisely at the atomic level, leading to "materials by design" and the emergence of "materials thinking".[33]

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[29] Ibid. pp. 83-130; Bensaude-Vincent, "Das Konzept Von Werkstoffen in Historischer Perspektive", p. 111.
[30] Hacking, Ian, "Style' for Historians and Philosophers', *Studies in History and Philosophy of Science,* 23 (1992). Bensaude-Vincent, Bernadette, 'The Chemists' Style of Thinking', *BER WISSGESCH*, 32 (2009), p. 367.
[31] Bensaude-Vincent, "Das Konzept Von Werkstoffen in Historischer Perspektive", p. 115.
[32] Pauling, Linus, *The Nature of the Chemical Bond and the Structure of Molecules and Crystals : An Introduction to Modern Structural Chemistry*, 2nd ed.. edn (Ithaca, N.Y.: Ithaca, N.Y. : Cornell University Press, 1945).
[33] Bensaude-Vincent, "Das Konzept Von Werkstoffen in Historischer Perspektive".; Bensaude-Vincent and Hessenbruch, "Materials Science: A Field About to Explode?".

The idea of “materials thinking” has been associated with a “systems approach”, required by the multi-agency interactions involved in the interdisciplinary endeavours of materials-based technoscience.[34] These interactions included government, industry and academic actors, with the military-industrial-complex as a key component in the new organisation of materials technoscience as proposed by Baker.[35] However, while many defence and aerospace projects carried national security or national prestige importance, there were budget limitations and not all technological options could be pursued. Therefore, government sponsoring agencies would, to a certain extent, have to “pick winners” from the various options.[36] Although such approaches went against the notion of free market-based ideologies, especially those which gained dominance during the 1980s and 1990s, the market itself would not take the financial risks associated with such long-term and uncertain developments without government support. This created an environment where government intervention could promote development of favoured energy technologies as had been seen previously such as the case of the nuclear industry.[37]

Over the postwar decades interdisciplinary research laboratories (IDLs) began to appear at universities across the US, many of these instigated from the 1957 recommendations of President Eisenhower’s science advisory committee.[38] These were based partly on the nuclear research laboratories of the Manhattan Project (which emerged as the US National Laboratories) and looked to emulate models of the exemplar corporate research laboratories such as Bell Labs. However, what was often enacted did not replicate the actual laboratory and social practices of Bell Labs. These practices have been outlined as extensive facilities and the ability of researchers to “roam free” with limited bureaucracy or accountability.[39] The more closely controlled and monitored government and commercially focused initiatives

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[34] Bensaude-Vincent and Hessenbruch, "Materials Science: A Field About to Explode?", p. 346.
[35] Baker, *Advances in Materials Research and Development*, pp. 19-22., see also Leslie, Stuart W., *The Cold War and American Science : The Military-Industrial-Academic Complex at Mit and Stanford*, (New York : Columbia University Press, 1993). For a detailed history of the role of the Military, Industrial, Academic complex in the creation of multidisciplinary materials technoscience.
[36] National Research Council (US), *Energy Research at Doe, Was It Worth It? : Energy Efficiency and Fossil Energy Research 1978 to 2000 / [Internet Resource]*, (Washington, D.C.: Washington, D.C. : National Academy Press, 2001).
[37] Lowen, "Entering the Atomic Power Race: Science, Industry, and Government".
[38] Bensaude-Vincent, "Das Konzept Von Werkstoffen in Historischer Perspektive", p. 115.
[39] Gertner, *The Idea Factory : Bell Labs and the Great Age of American Innovation*, p. 152.

relied more on the assumptions of how Bell Labs operated rather than the actual practices. Indeed, folk theories of how Bell Labs innovated have arguably emerged over the years which have had a long lasting effect not only on the theories of innovation but on how we have tried to stimulate and manage innovation in the recent past.[40] It could be asked whether such theories of innovation have emerged to support current paradigms and imaginaries of the innovative process rather than the theories being built upon around what the actual practices were in facilities such as Bell Labs.

The report of engineer Vannevar Bush, director of the US Office of Scientific Research and Development during and after the Second World War is often seen as a key document in defining the postwar vision of science and technology.[41] This has often been linked to the emergence of the much problematised “linear model” of science, technology and engineering. The linear model suggested that knowledge stems purely from fundamental science and that technology and engineering activities are derivative in that they apply that fundamental knowledge to solve real world problems.[42] However, Bush was not overtly proposing such a model: he was lobbying for funding for fundamental research. It suggested he was worried that with the success of these large projects, the roles and direction of fundamental research would become increasing shaped by the needs of technologists, engineers and managers running these programmes and that government support for undirected “blue sky” research would be under threat. [43]

His report argues for the importance of funding such undirected research, arguing that new technologies would emerge from the reservoir of basic scientific knowledge it would produce. The existence and function of this so-called linear model in science and technology has been widely contested with various

[40] Rip, A., 'Folk Theories of Nanotechnologists', *Science as Culture*, 15 (2006).
[41] Bush, V., *Science - the Endless Frontier*, (Washington DC: US Government Printing Office (Office of Scientific Research and Development), 1945).
[42] Godin, Benoît, 'The Linear Model of Innovation: The Historical Construction of an Analytical Framework', *Science, Technology, & Human Values*, 31 (2006); Balconi, Margherita, Stefano Brusoni, and Luigi Orsenigo, 'In Defence of the Linear Model: An Essay', *Research Policy*, 39 (2010); Edgerton, David, '‘The Linear Model’ Did Not Exist: Reflections on the History and Historiography of Science and Research in Industry in the Twentieth Century', in *The Science-Industry Nexus: History, Policy, Implications.*, ed Karl Grandin and Nina Wormbs (2004), pp. 1-36.
[43] Godin, "The Linear Model of Innovation: The Historical Construction of an Analytical Framework", p. 640; Edgerton, "‘The Linear Model’ Did Not Exist: Reflections on the History and Historiography of Science and Research in Industry in the Twentieth Century", p. 11.

interpretations existing around the nature of linearity in the actual practice of science and technology.[44] While Edgerton may have claimed that the linear model was purely a construct of historians looking to develop a strawman against which to argue that linearity did not represent scientific practice, it must be remembered that linear representations of the development process do exist at the level of policymaking and project management heuristics such as "Technology Readiness Levels" (TRLs).[45]

To gain funding or to visualise progress and manage complex projects, scientists, engineers and project managers may have to present an idealised and simplified pathway from scientific conception through technological development to commercial deployment. This avoids the messy, complex and uncertain "truths" of their scientific and engineering practices that closer study has shown to exist.[46] This suggests how simplified narratives of practice and progress could potentially lead to the construction of misplaced expectation in the minds of funders, investors or entrepreneurs who may not themselves be practicing scientists and therefore profoundly underestimate the nature and scale of developing the proposed technology.[47] This thesis will explore the argument that much of this misplaced optimism was built around the promise of new materials or processes to solve whatever messy or complex problems were blocking the technology development at that time, which in the case of the SOFC could be issues such as reducing operating temperatures or improving durability all with the overall aim of reducing costs. This optimism attached to new materials were not just confined to technical issues, as upon the foundations of these new technologies were built the future imaginaries

[44] For example see; Scranton, Philip, 'Technology-Led Innovation: The Non-Linearity of Us Jet Propulsion Development', *History and Technology,* 22 (2006). Edgerton, "'The Linear Model' Did Not Exist: Reflections on the History and Historiography of Science and Research in Industry in the Twentieth Century"; Channell, *A History of Technoscience: Erasing the Boundaries between Science and Technology*.

[45] Mankins, John C., 'Technology Readiness Assessments: A Retrospective', *Acta Astronautica,* 65 (2009).

[46] Balconi, Brusoni, and Orsenigo, "In Defence of the Linear Model: An Essay", p. 8.

[47] The impacts of such simplifications lay at the heart of Callon's critique of the French electric car programme Callon, "The State and Technical Innovation: A Case Study of the Electrical Vehicle in France".

solving societies "wicked problems" such as harmful emissions or climate change, while permitting, to a large extent, business as unusual.[48]

Communities, Culture and Practice in Materials Science

As has been previously suggested, multifaceted nature of the SOFC leads to the potential for different groups to see the artifact of the SOFC from their own perspectives, taking different meanings and values from this singular object. Therefore, this leads to the need to better understand where the relative viewing points are for the solid oxide fuel cell, who inhabited them and what assumptions and worldviews are they constructed from. Ann Johnson's book, *Hitting the Brakes* took the notion of the "knowledge communities" that form around a technological problem and how these changed over the course of the development of a technoscientific artifact as the focus of her analysis of the social and cultural dynamics of engineering design.[49] Johnson described these communities as forming from groups or individuals from different traditions of knowledge production and that as the development of the artifact progressed so the composition of the community changed and in turn so did the values and practices of the community.[50]

In this work it will be suggested that the dominance of the cultures, values and practices of the materials scientists have played a significant role in influencing and shaping the cultures, values and practices of those actors from other disciplines working in the SOFC field. It will also be argued that there appeared to be a far messier and greyer defining line between scientific and engineering knowledges. It was often not clear where one finished and the other started, and this becomes highly relevant in materials processing where it could be argued that scientific and engineering knowledges were being applied concurrently. This also reflected Edwin Layton's ideas of "scientists who do engineering and engineers who act as scientists"

[48] Such technological optimism amongst politicians and policymakers remains strong, for recent examples, along with criticism of the position see; Harrabin, "Technology No Silver Bullet"; Harrabin, "Kerry Comments Criticised"; Peeters, Paul, et al., 'Are Technology Myths Stalling Aviation Climate Policy?', *Transportation Research Part D: Transport and Environment,* 44 (2016); Lamb, William F., et al., 'Discourses of Climate Delay', *Global Sustainability,* 3 (2020), pp. 3-4.
[49] Johnson, *Hitting the Brakes: Engineering Design and the Production of Knowledge*.
[50] Ibid. pp. 4-5.

and his notions of “Mirror Image Twins”.[51] It also reflected the proposition that this messy interface defined the solid oxide fuel cell as an archetypal “technoscientific object”.

Johnson also appeared to suggest a singular community forming around an artifact or problem, in this case the development of ABS braking systems, where the members of this community come and go, and the composition of the community changes as the foci of different problems to be solved change and evolve. This could be thought of as similar in manner to Hughes’s “reverse salients” where resource coalesces around defined specific problems seen to be holding back the development front.[52] However, the solid oxide community could be viewed in a different light. While it could be argued that in the case of the SOFC, a “central knowledge community” of actors formed focussed on the design and development of the cell, stack, and fuel cell system, I contend that the composition of this community became established and consolidated around materials science, rather the composition of the community changing as different problems to be solved emerged. Therefore, in studying the history of the interactions of the solid oxide community, it is not so much how this group formed and changed membership (although this is of interest) but more how the cultures and values of the materials scientists influenced the social interactions both within the materials science community and with other wider communities, those with looser links to the solid oxide fuel cell.

These wider communities may view the solid oxide fuel cell in their own image, using different cultural and sociotechnical frames or references. This builds on Pickstone’s different “ways of knowing” and on Susan Leigh Star’s ideas of “boundary objects” in that these allow for relativistic interpretations of a material artifact.[53] These other wider communities may not be involved in direct knowledge making within the solid oxide fuel cell or related components insofar as developing

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[51] Layton, "Mirror-Image Twins: The Communities of Science and Technology in 19th-Century America".

[52] Hughes, *Networks of Power : Electrification in Western Society, 1880- 1930*, p. 79.

[53] Pickstone, *Ways of Knowing : A New History of Science, Technology and Medicine*. Star, Susan Leigh and James R. Griesemer, 'Institutional Ecology, `Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39', *Social Studies of Science,* 19 (1989).

physical artifacts or solutions. However, they play an important part in shaping perceptions around the technology. Therefore, they perform critical social roles.

Consideration of the influence of these wider communities in shaping the development of a technology brings in consideration of the roles of socio-technical "regimes" in shaping the social context in which the technology must exist. In this case, I take socio-technical regimes to derive from Frank Geel's idea of the "Multi-Level Perspective" (MLP).[54] Here, regimes are large socio-technical constructs of technical, regulatory, financial, governmental and social interests which form around an incumbent technology: in this respect they share a lot in common with Thomas Hughes's “Large Technical System”. [55] It could be argued they are the same, just viewed from a sociologist's or historian's perspective respectively (i.e., Geels tries to form a far more defined generalisable theory than does Hughes, who focuses more on the historical context).[56] The self-reinforcing nature of the interests across the regime or large technical system forms part of the "technological momentum" described by Hughes which may, from certain perspectives be perceived as being deterministic in character.[57]

However, as discussed in Chapter 1, David Nye suggests that this deterministic character or appearance may stem from looking at the regime or system in its present, mature, form and the apparent inevitability does not consider, or downplays, historical aspects where the current form has been constructed and shaped by human decisions and agency in the early stages of the system development.[58] This reflects one criticism levelled at MLP by some scholars: the apparent “monolithic nature” that can be ascribed to the regime giving the

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[54] Geels, Frank W. and Johan Schot, 'Typology of Sociotechnical Transition Pathways', *Research Policy*, 36 (2007).
[55] Hughes, Thomas Parke, 'The Evolution of Large Technical Systems', in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed W. E. Bijker, T.P. Hughes, and T. Pinch (Cambridge Massachusetts: MIT Press, 2012), pp. 45-76.
[56] David Edgerton commented on the potential parallels between sociological theorisation and historical contextualisation through critique of the approaches of social construction of technology and the society for the history of technology in Edgerton, "Tilting at Paper Tigers -- Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance by Donald Mackenzie" and further discussed in Fox, Robert, *Technological Change: Methods and Themes in the History of Technology*, (Abingdon, UK: Routledge, 1996). I suggest that similar comparisons can be made between the regime aspect of MLP and Hughes's large technical system.
[57] Hughes, "Technological Momentum".
[58] Nye, David E., *Technology Matters : Questions to Live With*, (Cambridge, Mass.: MIT Press, 2006), pp. 101-113.

impression that they are stable, coherent, rules based uniform entities, rather, than the constructs of social relations, with alliances and tensions which will likely change over time depending on internal stresses across these relations.[59] Some suggest that the "operationalisation" of these shifts in the dynamics within regimes are not clearly defined within MLP.[60]

Within the Multi-Level Perspective new technologies, such as fuel cells, exist within niches which form protected spaces for their early development. This relates to a further critique of MLP where some say that there has been a prevalence of studies focussing on the dynamics between niche and regime interactions leading to a privileging of "bottom-up change models", where transitions occur from niche developments finding their way into modified regimes, with the landscape acting as a "residual" location for other factors not easily located within niche or regime levels.[61] However while the prevalence of niche-regime dynamics is criticised, further criticisms of MLP refer to poor representation of the power imbalances that exist within these dynamics. Such imbalances could influence discourse around new technologies and their reception with respect to the incumbent regime, leading to the acceptance or undermining of the particular new technology and whether or not it transitions from its niche and into wider deployment within the regime.[62] Such changing dynamics can provide opportunities for technologies to move from a niche to find a position within a modified regime. An example of this could be changing relations between the electrical grid and renewable energies over time.[63]

Another significant concern from several scholars, which is particularly relevant for this thesis, suggested that the "everyday practice" and "dynamic processes" of various actors involved in innovations were not well captured within

[59] Smith, Adrian, Andy Stirling, and Frans Berkhout, 'The Governance of Sustainable Socio-Technical Transitions', *Research Policy,* 34 (2005); Smith, Adrian, Jan Peter Voss, and John Grin, 'Innovation Studies and Sustainability Transitions: The Allure of the Multi-Level Perspective and Its Challenges', *Research Policy,* 39 (2010).
[60] Genus, Audley and Anne-Marie Coles, 'Rethinking the Multi-Level Perspective of Technological Transitions', *Research Policy,* 37 (2008).
[61] Berkhout, Frans, Adrian Smith, and Andy Stirling, 'Socio-Technological Regimes and Transition Contexts.', in *System Innovation and the Transition to Sustainability: Theory, Evidence and Policy,* ed Boelie Elzen, Frank Geels, and Ken Green (Cheltenham: Edward Elgar, 2004), pp. 48-75; Markard, Jochen and Bernhard Truffer, 'Technological Innovation Systems and the Multi-Level Perspective: Towards an Integrated Framework', *Research Policy,* 37 (2008).
[62] Smith, Stirling, and Berkhout, "The Governance of Sustainable Socio-Technical Transitions".
[63] Sovacool, Benjamin K., 'The Intermittency of Wind, Solar, and Renewable Electricity Generators: Technical Barrier or Rhetorical Excuse?', *Utilities Policy,* 17 (2009).

MLP and incorporating viewpoints from other analytical traditions could improve "concern for the actors".[64] This lack of visibility of individual actors and the agency and constraints around their material practice could also be linked to criticism towards MLP that in developing a generalisable midrange theory, less attention has been addressed to the contextual untidiness and complexity of individual technology cases.[65]

The criticisms highlighted (while not exhaustive) suggest that although MLP remains a powerful theory through which to engage with SOFC technology development and its potential positions in future energy regimes, it may not be the most applicable for all such analyses. In this thesis I consider the macro and meso-level influences (landscape and regime respectively in MLP terminology) from a perspective of "historical contextualisation" rather than the "sociological theorisation" of MLP. This positioning reflects the specific critiques of MLP around "actor agency" and "everyday practice", which in his response to these critiques, Geels does acknowledge that specific agencies such as "rational choice", "power struggles" and "cultural discursive activities" are not well resolved.[66] This suggests fine grained consideration of agency and actions within actor groups in niche activities is not best served within MLP. In this thesis, a central focus is given to just such accounts of agency and practice, in this case amongst SOFC materials scientists and engineers, and how these related to constructing and maintaining promise and expectation over many decades of development, which suggests that MLP, while useful, may not be the most effective analytical lens in this case.

While other approaches to actor relations, such as "actor network theory" (ANT) have also been widely applied, these often focus on the social and there has been criticism that many accounts of technological development have become "over-socialised" and neglect the importance of materials as an analytical frame. [67] Such concerns about the place of material relations in History of Technology and Science

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[64] Shove, Elizabeth and Gordon Walker, 'Governing Transitions in the Sustainability of Everyday Life', *Research Policy,* 39 (2010); Genus and Coles, "Rethinking the Multi-Level Perspective of Technological Transitions".
[65] Berkhout, Smith, and Stirling, "Socio-Technological Regimes and Transition Contexts."; Genus and Coles, "Rethinking the Multi-Level Perspective of Technological Transitions".
[66] Geels, Frank W., 'The Multi-Level Perspective on Sustainability Transitions: Responses to Seven Criticisms', *Environmental Innovation and Societal Transitions,* 1 (2011).
[67] Lécuyer and Brock, "The Materiality of Microelectronics".

and Technology Studies can be seen the “materials turn”, where relationships of materials and artifacts have shifted to become far more central in analytical considerations.[68] Therefore, in this thesis I look to centre my analytical frame around the place of materials and the artifact and the roles these had in shaping the agency and practice of the materials scientists developing the SOFC.

Bringing the Artifact into View

It will be argued that the development of the SOFC represents the very notion of technoscience, with multi-disciplinary groups of likeminded technical communities, institutions, companies and policymakers simultaneously collaborating and competing as the political economies of R&D and energy both changed with time. As Ann Johnson suggests, creating frameworks to describe such complex and dynamic sociological relations is a key challenge when looking at histories involving both science and technology and that, “individuals tend to fade in such frameworks”.[69] Therefore, while my research may draw from the histories and experiences of individuals I do so not so much to extol the roles of these individuals, though they were noteworthy, but rather to present vignettes and perspectives which illustrate the formation of a technical community around the SOFC in the late 1980s and early1990s, and how the focus of this community around materials science played an important role in how the development agendas and priorities around the technology were both framed and reframed to align with wider changing notions of research and development management, and energy regulation. .

One potential difficulty that presents itself in attempting to write about the history of the SOFC is that many of the material practices involved in the technological development may be undocumented, involving tacit knowledges. Michael Mahoney used the phrase “creativity is cloaked in anonymity” to describe the hidden nature of the many innovations and creative practices in technological

[68] Latour, "Can We Get out Materialism Back, Please?"; Jones, "The Materiality of Energy"; Trentmann, Frank, 'Materiality in the Future of History: Things, Practices, and Politics', *J BRIT STUD,* 48 (2009); Ingold, "Materials against Materiality".
[69] Johnson, Ann, 'What If We Wrote the History of Science from the Perspective of Applied Science?:Making Silicon Valley: Innovation and the Growth of High Tech, 1930–1970;Nylon and Bombs: Dupont and the March of Modern America;into the Black: Jpl and the American Space Program 1976–2004', *Historical studies in the natural sciences,* 38 (2008), p. 619.

development.[70] Mahony also suggests that the historian may need to use "informed speculation" in trying to understand these hidden practices. To help bridge this gap in textual or literary sources Mahoney suggests we "read the machine", by which he means,

> "determining what the artifact says about the people who designed it, the process of its design, the assumptions made about its purposes, the expectations held of its putative users, and the ways it could actually be used." [71]

Such an approach could attempt to encapsulate the zirconia used in the SOFC as a "social" material, trying to understand the properties of this material as actors understood it at the time and how this understanding has changed with time. As well as zirconia this line of thinking could be extended to the other materials in the SOFC and indeed the artifact of the SOFC itself. This would involve problematising the idea of determining properties exhibited by the artifact and the materials from which it is constructed. Which of these properties are socially defined, are they measured because they are important or is their importance shaped by what can be measured? How did the actors involved use this materials knowledge to define the artifact and its place in the wider context?

One example of this could be the high operation temperature of the earlier SOFCs, 1000°C, described as "ferociously hot".[72] Initially, this operating temperature was defined by the need to allow the ions to conduct through the zirconia at rate which minimised resistive losses across the electrolyte. While this operating regime had advantages to those sets of actors who saw its utility in processing a broad range of carbonaceous fuels such as gasified coal, it created other issues such as potential for degradation, component corrosion and complications around interfacing the cell to parts of the device outside of the "hot box". The difficulties associated with the high temperatures suggested to other sets of actors that there was a need to search for ways in which the operating temperature could be reduced. This led them to look to modify the design of the artifact and to

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[70] Mahoney, Michael S., 'Reading a Machine', (2008) <http://www.princeton.edu/~hos/h398/readmach/modeltfr.html>., paragraph 5 [last accessed 9th Nov 2021]

[71] Ibid., final paragraph [last accessed 9th Nov 2021]

[72] I thank Matthew Eisler for this evocative description of SOFC operating temperature.

manipulations of the constituent materials, which in turn altered how the SOFC was viewed and reshaped to fit changing contexts around notions of energy provision and the organisation of technologically focussed R&D. The emergence of these changing contexts during the 1980s and 1990s, and their impact on how different sets of actors reframed the SOFC to take account of them will be a significant aspect of Chapters 4 and 5.

This introduces an interesting perspective on how different actors may view the SOFC. Some may be focussed on the chemistry of the materials through the culture of the laboratory, others may see the stack and system as a standalone device looking to emerge from its niche to disrupt the existing sociotechnical regime, while others still may see it as a component of a wider energy network, part of a "large technical system".[73] In the same way that by passing white light through a prism it can be separated out into its constituent colours related to their wavelengths, all of these perspectives are embodied within the singular artifact of the SOFC, which if viewed through a conceptual prism, can be imagined as separating out on a spectrum from the fundamental science of the materials chemist to the wider engineering and energy systems of the energy engineer or policy maker. Each of these groups of actors will confer differing values and affordances on the device depending on the position of the actor. However, I will make a case for considering materials scientists as the central community of actors at the heart of SOFC development and, from this, how their changing relationships with the device itself and with the other wider communities around sociotechnical energy regimes influenced the development of SOFC technology.

Following the materials-focused community around the development of the SOFC is a key analytical consideration in understanding the history of this device, as it will be argued that the development activities around the SOFC have been sustained through the power of promissory materials. The SOFC is often discussed as a device which is inseparable from materials, and a quick review of the agenda for any SOFC conference will reveal this. Materials science and processing have dominated activities in the field throughout its history, with many future promises

[73] For background to each of these potential views see Bensaude-Vincent, "The Chemists' Style of Thinking"; Geels and Schot, "Typology of Sociotechnical Transition Pathways"; Hughes, "Evolution of Large Technical Systems".

being predicated on the "next materials breakthrough". However, the notion of a more continuous spectrum from materials chemistry through to development of a viable prototype creates a blurred distinction between materials science and engineering, and who performs or directs those roles. Both the materials making up the SOFC and the SOFC as an artifact itself, blend not only scientific, technical and engineering knowledges, but are also embedded with policy, political and societal concerns. Therefore, if this relationship between the technical and cultural, the objective and the subjective, is through its constituent materials and their fabrication, on some level, should the SOFC not be considered as having some degree of materiality?

Materials and Materiality

The term "materiality" and its meaning are contested and mutable, and as such it could be described as a "slippery term". It is also apparent that when dealing with a technology such as the SOFC, which is so centred on materials, which, will be argued, performed social as well as technical functions, then the notion of materiality could not be ignored. It needs to be engaged with in some way. This section attempts to come to terms with some interpretations of the concept and ideas of materiality across anthropology, archaeology, and material culture, and how this relates to history of technology, materials science and technology and in particular to the development of the SOFC itself.

It could be argued that improving understanding or at least further interpretation, of what is meant by materiality and how to incorporate it into analytical frameworks is an ongoing issue in the history of technology. A recurring theme within some of the papers appearing around the theme of materials and materiality is an exploration of the relationship between the two.[74] Of these papers, one that had had an important influence on my thinking around this relationship was Lécuyer and Brock's "The Materiality of Microelectronics", where they argue for the importance of materials as an analytical category in the history of technology,

[74] For example see, Lécuyer and Brock, "The Materiality of Microelectronics".; Latour, "Can We Get out Materialism Back, Please?".; Ingold, "Materials against Materiality".

suggesting that many previous accounts were "device design centred".[75] This study focussed on the development of the solid state semiconducting transistor, a device where the material and the device could effectively be considered one and the same, exemplified by the phrase "the material was the device".[76] However while materials are central to the SOFC story, the device is more than a material, it is composed of several materials and the selection, arrangement , design and processing of these material layers are all critical.

This brings into question the relationship between a device (or artifact) and the materials from which it is composed. Around the same time as Lécuyer and Brock were bringing questions of materiality in the history of technology, Anthropologist Tim Ingold was asking similar questions with respect to the place of materials in studies of materials culture within anthropology and archaeology.[77] In his paper he suggested that the focus on objects and artifacts was privileged over the stories of the materials from which they are made. Rather than suggesting that one could be conflated with the other, as with Lécuyer and Brock's suggestion around the very specific case of the semiconducting transistor, Ingold claimed that the focus on objects consumed the materials, "materials appear to vanish, swallowed up, by the very objects to which they have given birth".[78]

In the development of his arguments about the importance of materials in materiality Ingold draws on the ideas of design theorist David Pye, from which Ingold postulated the notion of two worlds, "the materials world" and the "world of materials".[79] The first is the world of physical properties: density, hardness, conductivity, co-efficient of expansion, crystal structure. Properties which are objective and for a given material independent of place or person measuring them. The second world is more subjective, related to the tacit knowledge of the artisan, for example a skilled blacksmith can work a piece of steel into an ornate object or sword without knowledge of the atomic theory of matter or the iron - iron carbide phase diagram. However, such objects will be very much linked to both place and person. In a response to Ingold's paper, archaeologist and anthropologist, Christopher Tilley

75 Lécuyer and Brock, "The Materiality of Microelectronics", p. 302.
76 Ibid. p. 307.
77 Ingold, "Materials against Materiality".
78 Ibid. p. 9.
79 Ibid. p. 14.

suggested that what is important between the two worlds is that “brute material properties” of the materials world do not convey any “human significance” of the material within a “broader social or historical context”.[80] A quote from Ingold’s response to Tilley, regarding an anecdote regarding the materiality of mud bricks, is to suggest Tilley’s position on materiality as “a shorthand for understanding bricks in the social and historical context of the use of mud by humans”.[81] Is this therefore what materiality means for the history of the SOFC? Could Ingold’s response be rewritten for the SOFC as, the materiality of the SOFC is a shorthand for understanding the SOFC in the social and historical context of the use of energy by humans?

Staying with the notion of these two worlds, that of “the materials world” and that of “the world of materials”, does this idea help understand the interplay of these objective and subjective worlds on the development of a technoscientific artifact such as the SOFC? It could be considered that these are different ways of knowing the materials at play and are therefore not exclusive but rather complementary.[82] The case for the coexistence of the two worlds could certainly be argued in the development of the SOFC. For example, creating a screen-printed electrode that performs well involves a considerable amount of tacit knowledge, from powder preparation and dispersion of that powder in the carrier fluids, to the printing process itself.[83] Much of this process required craft and artisanal knowledge of the ink behaviour, as it did objective knowledge about the crystal structure of the ceramic powders and their effects on the electrocatalytic activity of the electrode. This roots a significant portion of the materials practice involved within the contextual development and undocumented knowledge that Mahoney refers in his invitation to “read the machine”.[84] In the terms of the notion of materiality as described by Tilley, that there is human significance in a broad social and historical context, the subjective actions of the ink maker may not seem all that significant in the grand

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[80] Tilley, Christopher, 'Materiality in Materials', *Archaeological Dialogues,* 14 (2007), p. 17.
[81] Ingold, Tim, 'Writing Texts, Reading Materials. A Response to My Critics', *Arch. Dial,* 14 (2007), p. 32.
[82] Pickstone, *Ways of Knowing : A New History of Science, Technology and Medicine*.
[83] I draw from my own experiences here, with much of my laboratory practice in SOFC development revolving around the development of such printing inks.
[84] Mahoney, "Reading a Machine".

scale. Nevertheless, in employing these tacit knowledges, built up over time working with the material rather than information lifted from a database of objective, measured properties, perhaps the ink maker is operating as a "skilled practitioner participating in the world of materials", engaging with the "qualities" of the material, as opposed to its measured, objective properties within the "materials world".[85]

How these two worlds are treated and privileged in materials culture studies is the heart of Ingold's argument. He commented that the objective properties of matter are opposed to the subjective qualities, suggesting that the latter reside more in the imagination and the mind, "the physical world versus the world of ideas" and that in material culture too much focus has been given to the latter.[86] It is not the intention here to try to decide whether Ingold's argument is correct or not, rather to use his contention of the two worlds as an entry point for unpacking the tacit and undocumented knowledge and practice embedded in SOFC development and the artifacts themselves. Such a position would look to build from Mahoney's evocation of R.W. Hammond's call to follow "the contextual development of ideas, rather than merely listing names, dates, and places of "firsts".[87] This would employ Mahoney's ideas of "reading the machine" and link these to wider notions of material culture as a way of unpacking the undocumented practices, values and cultural contexts of the SOFC actors.

Alan Mayne suggests the "study of material culture is ultimately less about things than the practices, relationships and value systems that produced them".[88] However "reading the machine" in isolation is not sufficient as Richard Grassby suggested: "Artifacts cannot reveal underlying cultural values without other evidence [and] the most effective method of reconstructing material culture is to combine written evidence … with the physical evidence".[89] This suggests taking material culture as an entry point to engage and reengage with the wider textual sources could yield fresh perspectives by trying to minimize the risk of repeating existing rhetorics

[85] Ingold, "Materials against Materiality", pp. 13-14.
[86] Ibid. p. 14.
[87] Mahoney, "Reading a Machine"., opening paragraph
[88] Mayne, A., 'Material Culture', in *Research Methods for History,* ed S. Gunn and L. Faire (Edinburgh: Edinburgh University Press, 2016), pp. 49-67 (p. 62).
[89] Grassby, Richard, 'Material Culture and Cultural History', *Journal of Interdisciplinary History,* 35 (2005), pp. 599-602.

and interpretations of the textual sources by allowing the object to speak.[90] This may suggest new questions which must then be reconciled by the textual sources: "Detailed consideration of the chosen thing(s) leads to a set of questions that would not arise in any other way".[91] Adding to this Hood further suggested that it is when combining the knowledge from the artifact with relevant documentary evidence that the deeper issues can be addressed.[92]

Taking the notion of Ingold's two worlds, that of the "materials world" and the "world of materials" further, it could be suggested that the latter represents what some actors would like to be able to achieve with materials, a world of ideas (or ideals). This "world of materials" represents the technological optimism and promissory futures that are built on the back of new materials and the potential technologies these suggest. In contrast, the "the materials world" represents what can physically be achieved within the affordances of the materials available, together with existing process capabilities, these constrain the realisation of the ideal device. This imposed a defined set of choices or options on any actor engaged in developing the application of a specific material in any device or artifact.

I aim to show how technical actors viewed their options through the affordances of the materials they worked with. These affordances demanded compromise across their decision-making processes, what might work and what might not, shaping their development agendas. The choices that could be made related to the current state of the art with respect to materials knowledge, synthesis and processing capabilities. These factors privileged some choices while closing others off. It has been suggested that by studying the choices and decisions enforced onto actors by materials affordances and their processing techniques an analyst's category is created, labelled by Lécuyer and Brock as "material logic".[93]

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[90] Pursell, C, 'The History of Technology and the Study of Material Culture', *American Quarterly*, 35 (1983), p. 305.
[91] Hood, A.D., 'Material Culture:The Object', in *History Beyond the Text*, ed S. Barber and C.M. Peniston-Bird (Abingdon: Routledge, 2009), pp. 176-198 (p. 178).
[92] Ibid. p. 187.
[93] Lécuyer, Christophe and David C. Brock, *Makers of the Microchip : A Documentary History of Fairchild Semiconductor / [Internet Resource]*, (Cambridge, Massachusetts : MIT Press, 2010); Brock, David and Christophe Lécuyer, 'Digital Foundations: The Making of Silicon-Gate Manufacturing Technology', *Technology and Culture*, 53 (2012).

While the notion of material logic may sound deterministic in nature, it does not in any way predetermine any particular outcome. Rather, Lécuyer and Ueyama propose it provides a framework to analyse the decisions made by actors in the field, based around what was known at that particular time about materials properties and behaviours, and how this was understood by those actors (the “logic” referred to by Lécuyer and Ueyama).[94] The material itself is not afforded any agency of its own: however, it impacts the agency available to any actor working to employ this material. Further, this logic or any affected agency is not static. It could be argued that invention and innovation in materials development is an effort to increase or modify the logics around particular materials to increase the agency afforded to technical actors in developing new devices. A processing method adopted from another research or development field, or a new material compound emerging from the laboratory may open up new pathways previously restricted by material or process limitations.

By studying the changing designs and approaches of the materials science community, it is hoped to identify where and how these “logics” were used by developers shaping the development of the SOFC and how through the acquisition of new knowledge or knowhow these “logics” were modified or manipulated. In turn the paths of these changing “logics” can be followed to reveal how they allowed various actor groups to reshape and reframe the SOFC to retain relevance against changing contexts of energy provision, political policy and social awareness of the environmental impacts of energy generation.

I will aim to show how it was the promise of new materials or processing that allowed SOFC developers to construct new frames for their technology, retaining relevance and sustaining support. These reflected the ethos of the “technological fix” where the new materials would allow fresh development which would solve the issues of previous embodiments and create the underlying optimism that underpins and sustains the powerful idea embedded within the notion of the fuel cell, that vision of plentiful clean energy.

[94] Lécuyer, Christophe and Takahiro Ueyama, 'The Logics of Materials Innovation: The Case of Gallium Nitride and Blue Light Emitting Diodes', *Historical studies in the natural sciences,* 43 (2013).

This chapter has looked to give an overview of accounts of how materials have been considered within the history of technology and the technoscientific nature of the practices of various actor groups involved in materials development, highlighting the indistinct boundaries between the practices of engineers, scientists and technologists. In the case of the SOFC, these practices were linked to the physical materials under development, whose affordances were closely tied to the agency available to the development community. This in turn was used to justify the adoption of an analytical framework based around “material logics”, which reflected the constraints of “the material world” and promissory futures offered by “the world of materials”. This framework will be used as a lens through which to consider the accounts of SOFC development described in the following chapters.

Chapter 3: Born of Coal and Crises

By the 1960s, America's transition to an economy dominated by oil was in full swing. While coal remained a critical source of primary energy for electricity generation, some such as Robert Byrd the long-standing senator for the coal state of West Virginia could see it coming under pressure from other sources, not only through the growth of oil, but also the promise of nuclear and growing poor perceptions around the cleanliness of coal as a combustion feedstock. What Byrd saw as necessary was a new technology, something that could transform the embedded energy of coal into electricity in a way that was clean and efficient. The solid oxide fuel cell appeared to fit this need. With its high operating temperature, it promised to convert coal to electricity cleanly and silently through its highly efficient electrochemical reactions. There was only one issue: as yet no practical system had ever been produced. However, in the heightened optimism that existed in postwar America of the 1950s and early 1960s such issues were not seen as any sort of barrier to realising the promise of technology.

Much of this optimism revolved around the increasing perception that science, technology and engineering would deliver the advances and progress that society craved. By the middle of the twentieth century the United States had become a country that revolved around the automobile. In the postwar era new ostentatious vehicles of chrome, fins and leather reflected this growing optimism. In the home too, technologies were multiplying as refrigerators, dishwashers and air-conditioning all fed growing demand for a technologically based way of living.[1] The ability to embrace these technologies also reflected social station, both individually and collectively with aspiration and optimism fuelling increasing consumption of goods and services. Much of this optimism was underpinned by one thing, low cost, plentiful supply of energy. In the 1950s and 1960s this supply seemed assured: American "big science" was going to harness the power of the atom to deliver unrivalled electrical power with the apparatus of the Manhattan project being

[1] For history of the increasing prevalence of technology and consumerism in domestic America see Cowan, *More Work for Mother : The Ironies of Household Technology from the Open Hearth to the Microwave*, pp. 192-196. and Cohen, Lizabeth, 'A Consumers' Republic: The Politics of Mass Consumption in Postwar America', *Journal of Consumer Research,* 31 (2004).

repurposed into a network of National Laboratories focused on this delivery.[2] Simultaneously, American oil companies controlled much of the Middle East oil reserves creating hegemonic relationships with oil states with the goal of continuing to feed Americans' voracious appetite for oil.[3]

It was in this environment that some energy technology developers began to consider the use of the solid oxide fuel cell (SOFC) as a potential fuel-flexible energy conversion technology. Running fuel cells on readily available logistical fuels has been a persistent dream of fuel cell supporters at the institutional and policy level. The military had long seen the requirement for flexible and portable sources of electrical power as increasingly sophisticated and power-hungry electronic communications and surveillance equipment was beginning to become central to efficient military battlefield operations.[4] The high operating temperature of the SOFC (1000°C) suggested a route to fuel flexibility that had been problematic to achieve in other fuel cell types with lower operating temperatures. This higher temperature provided favourable conditions for utilisation of carbon-based fuels such as coal. This was promoted by those developing the SOFC as offering simplified engineering around fuel processing, avoiding what could be construed as a miniature refinery that was required to be attached to the lower temperature fuel cell designs.[5]

The potential for a fuel cell that could utilise coal, the country's most abundant primary energy reserve, was also beginning to emerge in the minds of some such as Robert Byrd who could see this as a way to maintain coals prevalence in the US energy mix and protect the jobs and economics of his home state. Issues around the high level of emissions from burning coal were perceived as potentially threatening the position of this fuel within the US primary energy mix when compared to other fuels with relatively lower emissions, such as oil, gas and nuclear. The electrochemical conversion of the SOFC presented the promise of far lower

[2] Strauss, "Remarks Prepared by Lewis L Strauss, Chairman, United States Atomic Energy Commission, for the Delivery at the Founders Day Dinner, National Association of Science Writers, 16 September 1954".
[3] Podobnik, *Global Energy Shifts, Fostering Sustainability in a Turbulent Time*, pp. 94-100.
[4] For more detailed account of early military interest in fuel cells see Chapter 2 of Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*.
[5] Steele, "Running on Natural Gas". Fickett, Arnold P. , 'Fuel-Cell Power Plants', *Scientific American,* 239 (1978).

levels of the harmful flue gasses that were responsible for the poor air quality in industrial and densely populated areas.[6]

This chapter discusses the initial US development of the solid oxide fuel cell through the 1960s and 1970s. It will focus on the origins of the long-running Westinghouse Tubular SOFC programme, which, through government sponsored programmes in the 1960s, emerged as the first major industrial actor in the field. The chapter places the discussion of the early Westinghouse programme against the wider context of growing concerns about meeting the ever-increasing energy needs of the US, and the changing nature of US government organisation of energy research and development policy in an attempt to meet these needs.

This chapter will also set out the position that this early part of SOFC development was an important period for the wider development of the SOFC over the years. In this period, the values and cultures of the materials-based communities would come to the fore, which would have significant influence the viewpoints and directions of future SOFC developers. Significant advances in knowledge around materials had emerged in the early-mid-twentieth century. The improved understanding around the chemistry and structure of materials were allowing better links to be made between the properties and the performance of materials. Combined with new advanced fabrication techniques, such new knowledge was allowing novel materials to be tailored for function, “materials by design”.[7]

The research and deployment of such advanced materials had been at the heart of many of the US postwar technological advances, from the development of nuclear power, the jet engine, aerospace advances and the emergence of the nascent semiconductor industry.[8] These successes had placed advanced materials at the heart of US science and technology policy.[9] It will be argued that the SOFC actors of the 1960s and 1970s were in a position to capitalise on many of these developments, to utilise new materials knowledge to invent materials and structures that were unattainable to previous generations of solid-state fuel cell developers thereby

[6] Wallace, "Fuel Cells: A Challenging History", p. 87.
[7] Bensaude-Vincent, "Das Konzept Von Werkstoffen in Historischer Perspektive".
[8] For example, see Lécuyer and Brock, "The Materiality of Microelectronics". Scranton, "Technology-Led Innovation: The Non-Linearity of Us Jet Propulsion Development".
[9] Baker, "The National Role of Materials Research and Development, Address Delivered at the Materials Science Luncheon, Astm Materials Science Division Symposia [1961]".

opening up new avenues for investigation. In the case of Westinghouse, it will also be argued that working in the well-resourced environment of a corporate R&D centre of large a vertically integrated company created conditions to allow the pursuit of certain developmental pathways which had major implications later in the life of that project.

The SOFC Comes to America

The solid oxide fuel cell is often described in fuel cell literature as the least mature of the fuel cell technologies, which is in turn often taken by some to imply that it is the newest of the fuel cell technologies. For example, in the *Fuel Cell Handbook*, an influential resource for many entering the field of fuel cells in the late 1980s and 1990s and co-authored by A.J. Appleby, a leading and highly respected fuel cell researcher of the time, describes the solid oxide fuel cell as a “third generation” technology with respect to other types of fuel cell such as the molten carbonate fuel cell, which Appleby describes as “second generation” which implies some form of temporal progression.[10] However the application of the general scientific mechanisms which take place in the solid oxide fuel cell can be traced back to the late 1800s with the use of a zirconia rod in the Nernst Glower, patented by German physicist Walter Nernst in 1899, a competitor to the early incandescent light bulbs.[11]

In the incandescent light bulb, the light is emitted from a metal filament which is heated to glowing heat by the resistance to the current of electrons flowing through it. In the Nernst glower the light was emitted from a zirconia rod as opposed to the metal filament. Resistance to conduction through the rod provided the heat energy that resulted in the emitted light in a similar manner to the filament, however, rather than the flow of electrons, Nernst suspected that the conduction mechanism in his glower was due to a flow of oxygen ions, which would be confirmed by later research.[12] It is this flow of oxygen ions which is central to the operation of the

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[10] Appleby, A.J. and F.R. Foulkes, *Fuel Cell Handbook*, (New York: Van Nostrand Rheinhold, 1989), p. 590.
[11] Nernst, W., "Material for Electric-Lamp Glowers", United States Patenet Office, Westinghouse, George, 1901.. Also, for a description of the competition between the Nernst Glower and Incandescent Bulb see Hughes, *Networks of Power : Electrification in Western Society, 1880- 1930*, p. 166.
[12] Möbius, "On the History of Solid Electrolyte Fuel Cells", p. 4.

zirconia electrolyte in the SOFC and therefore the glower and the SOFC work on very similar principles. While the glower was more efficient than early carbon filament bulbs, complexity of construction, and materials led to higher costs, which when allied with a longer start up time than incandescent bulbs meant that the glower eventually lost out to competing technologies.[13] In this respect it could be argued that the similarities between the glower and the SOFC were more than just the operational principles.

Research into the ionic conduction behaviour and properties of zirconia and other oxides continued throughout the early twentieth century, with much of this work taking place in Germany. Experimental focus was often based around the search for stable electrolyte materials with suitable conduction properties. Carl Wagner's 1943 paper in *"Naturwissenschaften*" ("*Science in nature*"), published while he was Professor of Physical Chemistry at Darmstadt University, described the advantages of negatively charged oxygen ion (anion) conduction in solid electrolytes which were to be considered for fuel cell applications.[14] The preference for zirconia-based materials such as those used by Walter Nernst in his glower was also established in this paper, due to their tendency to be almost pure ionic conductors with very low levels of electrical conduction the presence of which would effectively short circuit the cell. [15]

After the Second World War, Wagner moved to the US first as a scientific adviser at Fort Bliss, Texas, before moving to Massachusetts Institute of Technology (MIT) in 1949. In 1957, while at MIT, he published a significant paper with fellow scientist, Kalevi Kiukkola, which detailed the use of solid-state galvanic cells in the measurement of fundamental thermodynamic values of electrochemical processes. Published in the US *Journal of the Electrochemical Society*, this paper was instrumental in helping to underpin the emerging field of solid state ionics, its

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[13] Ibid. p. 3.
[14] An anion is a negatively charged ion, in this case a negatively charged oxygen ion. The hopping of these anions between vacancies in the crystal lattice in doped fluorite crystals such as yttria-stabilised-zirconia electrolytes forms the ionic conduction mechanism in such oxides.
[15] Wagner, Carl, '□Ber Den Mechanismus Der Elektrischen Stromleitung Im Nernststift', *Die Naturwissenschaften*, 31 (1943)., while the original paper is in German the broad content and influence of this paper can be seen by referring to Martin, M, 'Life and Achievements of Carl Wagner, 100th Birthday', *Solid State Ionics*, 152-153 (2002), p. 16. and Möbius, "On the History of Solid Electrolyte Fuel Cells", p. 5..

associated applications such as sensors and fuel cells and importantly bringing the technology to the eyes of American scientists.[16] This work was paralleled with continued work in Germany by Peters and Möbius who published several papers on the use of zirconia membranes related to oxygen concentration measurements for gas analysis.[17]

The Corporate Crucible of the SOFC

The first appearance of explicit solid oxide electrolyte fuel cell development in the United States occurred in the early 1960s with publications and patents from both the research and development centres of the General Electric Company and the Westinghouse Electric Corporation, two classic vertically integrated industrial enterprises with large in-house laboratories.[18] Both utilised zirconia-based electrolytes citing Wagner's work and both also looked to the utilisation of carbon-based fuels. The early General Electric design utilised liquid electrodes and looked to dissolve carbon species in a liquid anode of iron or cobalt-tin.[19] While such liquid electrodes may have had some advantages in directly utilising solid carbon-based fuels, the containment and management of the liquid electrodes created extra complexities not seen in the completely solid state fuel cell approaches adopted by Westinghouse.

Although the General Electric patents appear to predate the earlier Westinghouse fuel cell publications, it was the latter which appeared to be more committed to the design and development of a potential SOFC system, with a

[16] Kiukkola, Kalevi and Carl Wagner, 'Measurements on Galvanic Cells Involving Solid Electrolytes', *Journal of The Electrochemical Society,* 104 (1957). for the influence of this paper again see Fergus, Jeffrey W., et al., 'Jes Classics: Ecs Science at Its Best: Impact of Kiukkola-Wagner Paper on the Development of Electrochemical Probes and Tools for Fundamental Studies and Industrial Applications', *The Electrochemical Society Interface,* 18 (2009)., Möbius, "On the History of Solid Electrolyte Fuel Cells", p. 6. and Martin, "Life and Achievements of Carl Wagner, 100th Birthday", p. 16.

[17] Möbius, "On the History of Solid Electrolyte Fuel Cells", p. 6.

[18] Weissbart, Joseph, 'Report of the New England Association of Chemistry, Teachers Fuel Cells - Electrochemical Converters of Chemical to Electrical Energy', *Journal of Chemical Education,* 38 (1961); Weissbart, J. and R. Ruka, 'A Solid Electrolyte Fuel Cell', *Journal of the Electrochemical Society,* 110 (1963). Tragert, William E., "Fuel Cell", United States Patent, 3,138,488, General Electric Company, 1964. Tragert, William E., Robert L. Fullman, and Ralph E. Carter, "Fuel Cell", United States Patent, 3,138,490, General Electric Company, 1964.

[19] Giddey, S., et al., 'A Comprehensive Review of Direct Carbon Fuel Cell Technology', *Progress in Energy and Combustion Science,* 38 (2012).

significant research project from the Office of Coal Research allowing for sustained development over several years.[20] General Electric did have ongoing solid oxide fuel cell activity over the 1960s, as patent and publication activity across the decade shows continued output.[21] Some of this included significant and enduring contributions to the field, such as Spacil's patent for a mixed nickel zirconia anode, regarded as the origin of the cermet anode which has become a standard component material in the solid oxide fuel cell. This composite material (ceramic and metal) continues to be the most widely used anode in SOFC despite some significant technical issues, with decades of research yet to produce a widely preferred alternative.[22] However, despite this activity and contribution to the field, no singular, sustained SOFC programme appears to have gained the same momentum in General Electric as the activities at Westinghouse.

These later GE innovations showed a move away from the liquid anode concepts of Tragert's earlier patents with a move towards tubular designs similar to those being investigated by Westinghouse. This underscored both the difficulties in managing the liquid electrodes and the material affordances around the ceramic processing of the time. Due to the way mechanical stresses interact, tubular forms are often stronger and more robust than other geometric forms. This led to early popularity of tubular designs as it was easier to fabricate shapes in this form, either through pressing, casting or extrusion. It is not clear what the source of funding was for the General Electric Projects. However, as few if any funding acknowledgements appear on their papers or patents, it could be suggested that this indicates that General Electric's initial work into SOFC was possibly funded through in-house channels. Apart from describing carbonaceous fuels in such a way as to suggest that

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[20] Sverdrup, E. F., 'Project Fuel Cell Final Report- Prepared by Research & Development Center Westinghouse Electric Corporation', *Research and development report (United States. Office of Coal Research)* (Washington DC: 1970).

[21] Tragert, William E., "Fuel Cell with Stabilized Zirconia Electrolytes and Nickel-Silver Alloy Anode", United States Patent, 3,296,030, General Electric Company, 1967; Spacil, Henry S. and C. S. Tedmon, 'Electrochemical Dissociation of Water Vapor in Solid Oxide Electrolyte Cells', *Journal of The Electrochemical Society,* 116 (1969).

[22] Spacil, Henry S., "Electrical Device Including Nickel Containing Stabilized Zirconia Electrode", United States Patent, 3,503,809, General Electric Company, 1970. subsequent technical reviews of SOFC anode development have cited this patent as the emergence of the nickel-zirconia cermet anode which remains the most widely used anode composition in spite of its weaknesses and a search for alternatives spanning many decades of research Atkinson, A., et al., 'Advanced Anodes for High-Temperature Fuel Cells', *Nature Materials,* 3 (2004), p. 19.

utilisation of these were central to the final application of the design, there is very little context given with respect to wider energy landscapes.

A 1963 review of "practical fuel cell technology" does refer to the General Electric design as consuming natural gas and refers to publicity articles published by General Electric in "*Chemical Engineering News*" and "*Machine Design*", the latter of which is entitled "Fuel Cell "Burns" Natural Gas", suggesting the cell could have been focused towards the natural gas market.[23] Both of these publications were positioned to provide more news-oriented updates, analysis and opinion on new engineering directions. They targeted an industry readership that while focussed on engineering, leaned very much towards the engineer as scientist rather than mechanic. Similarly, in keeping with Layton's idea of "mirror image twins," the readership would also encompass scientists who practiced or at least needed to be aware of engineering.[24] Therefore, as well as giving some indication of where General Electric SOFC developers saw the positioning of the SOFC in a wider energy context, it also reveals an early example of the positioning of the SOFC at the technoscientific border between science and engineering, potentially setting the foundations of a community who would draw membership from both fundamental scientists and scientifically orientated engineers.

These articles suggested General Electric looked to position the SOFC towards using natural gas as a fuel. Existing as a gas in its natural state, it offered potential for direct use in the high temperature SOFC, avoiding the additional chemical steps required to turn solid coal into a gas, further natural gas use was increasing across the US in the postwar years.[25] Together these attributes made natural gas a potentially popular choice for fuelling an SOFC. Such thinking within General Electric is given further weight by a series of papers and publications over the early 1960s by Herman A. Liebhafsky, then the manager of the physical chemistry section at the General Electric Research Centre at Schenectady, New York. He repeatedly states that a fuel cell for central generation stations would be the hardest application to develop and deploy, and would be closely linked to the

[23] Peattie, C.G., 'A Summary of Practical Fuel Cell Technology to 1963', *Proceedings of the IEEE,* 51 (1963), p. 804.
[24] Layton, "Mirror-Image Twins: The Communities of Science and Technology in 19th-Century America".
[25] Podobnik, *Global Energy Shifts, Fostering Sustainability in a Turbulent Time,* p. 101.

fortunes of natural gas as a fuel, with coal being mentioned as a particularly difficult fuel to utilise due to the need to both gasify it and remove potentially damaging impurities.[26] It could also be suggested that Liebhafsky's opinions of the future of SOFC development were also shaped by his views on General Electric's positioning within the wider context of more general fuel cell development activities of the time. His favouring of space and military applications as the most probable avenues for the immediate development of fuel cells could be considered to reflect the heavy commitment of General Electric to the development of the polymer exchange membrane (PEM) fuel cell for the NASA Gemini programme. This commitment which would lead to increased focus on this aspect of this technology in preference to solid oxide development over the course of the following decades. It also gives an early presentation of what became an enduring and contested question in fuel cell commercialisation, that of, would commercialisation come about through focus on early high value niche markets or through large, mass market penetration as a commodity technology.

Some of Spacil's papers in the later 1960s also suggest a change in focus of his research, from using the solid electrolyte device as a fuel cell in generating electricity towards looking at it as a means to electrolyse water to generate hydrogen.[27] It is interesting to speculate whether this move towards electrolysis is linked to GE being more invested in PEM systems, especially terrestrial applications of the Gemini programme, which would require a source of hydrogen and moreover, whether this approach was linked to continued visions of utilisation of excess electricity and heat from nuclear power stations producing hydrogen via a solid oxide electrolyser.[28] The changing focus does suggest that the position of the solid oxide electrolyte technology in General Electric was not well established, with its principal

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[26] Douglas, David L. and Herman A. Liebhafsky, 'Fuel Cells: History, Operation, and Applications', *Physics Today*, 13 (1960). Liebhafsky, H. A., 'Fuel Cells and Fuel Batteries‐an Engineering View', *IEEE Spectrum*, 3 (1966).

[27] Spacil, Henry S., "Solid Oxide-Ion Electrolyte Cell for the Dissolution of Steam", United States Patent, 3,635,812, General Electric Company, 1972. Spacil and Tedmon, "Electrochemical Dissociation of Water Vapor in Solid Oxide Electrolyte Cells".

[28] For example of the use of nuclear heat in hydrogen production see Salzano, F J and C Braun, 'Hydrogen Energy Assessment', (Office of Scientific and Technical Information (OSTI), 1977); Winsche, W. E., K. C. Hoffman, and F. J. Salzano, 'Hydrogen: Its Future Role in the Nation's Energy Economy', *Science*, 180 (1973).

developers looking to find a position which fitted with wider company directions and thereby find greater internal support.

The approach at Westinghouse appeared very different from that at General Electric. The initial Westinghouse publications link their early interest in ionic conduction not with fuel cells, but with the work on oxygen sensors, as shown by a 1961 paper by Weissbart and Ruka, the initial Westinghouse developers in solid state ionics, citing the work by Kiukkola and Wagner, and Peters and Möbius on sensors.[29] Sharing the same technoscientific mechanisms of operation, oxygen sensors and SOFC shared an overlapping research space during the 1960s and 1970s, with a number of scientists who would later become prominent figures and leaders in the SOFC community, such as Brian Steele from the UK, conducting their initial research activities on sensors.[30] Many of the large vertically-integrated energy companies such as Westinghouse in the US and ABB in Europe also had interests in metallurgy and manufacturing steel-based components within their energy equipment businesses. Monitoring oxygen levels during manufacture and heat treatment processes was vital in producing high-quality components. Further, as more demanding operating conditions pushed the limits of metallic components, thermal barrier coatings began to be developed, in many cases based on zirconia, providing further technical links between the materials sets of the SOFC and those being used elsewhere in the organisation.[31]

However, it is also clear from early on that developers in Westinghouse saw the potential of the SOFC as a means of efficiently generating electricity within the existing hydrocarbon energy frameworks, as opposed to the hydrogen-focused fuel cells being developed for the space programme. In addition to their sensor paper, Weissbart also published a fuel cell-related paper in 1961. While this was a wide-ranging paper describing the various types of fuel cell to a more general audience, it did discuss the behaviour and performance of fuel cells with various carbon-based fuels and made some reference to preliminary work ongoing at Westinghouse into

[29] Weissbart, J. and R. Ruka, 'Oxygen Gauge', *Review of Scientific Instruments,* 32 (1961).
[30] Interview with John Kilner, Conducted by Author on 30th March 2022
[31] Interview with Subhash Singhal Conducted by Author 21st June 2022; Interview with Ulf Bossel, Conducted by Author on 28th June 2022

fuel cells based on solid oxide electrolytes.[32] In 1962, Weissbart and Ruka published again, in a paper that for the first time specifically described work ongoing at Westinghouse into the development of a solid oxide fuel cell.[33] In both of their fuel cell papers, Weissbart and Ruka refer to the work of Bauer and Preis, who carried out early experimental work into carbon fuelled solid oxide fuel cells in Germany during the 1930s.[34] Their discussions emphasised the thermodynamics and performance of cells when running on carbon based fuel feed-stocks. Through the content of both papers there is a strong indication that Weissbart and Ruka saw the SOFC as running on carbon-based fuels.

The Westinghouse programme attracted some early government sponsorship: firstly in the form of a US Air Force project which ran from February 1962 until April 1963.[35] Although direct documentary evidence as to the aims of this project have not been uncovered, publications of the time referred to "initial performance data" being discussed with reference to "evaluation of its [solid oxide fuel cell] potential as a space power source".[36] A far more significant project, and the one which would effectively set the path for SOFC development in Westinghouse, was to follow in December 1962. This was sponsored by the Office of Coal Research, an arm of the US Department of the Interior, and ran until April 1970. The final report lists 37 members of the Westinghouse Research and Development Center as having made a significant contribution to the work, with further input from subcontractors over the course of the project.[37] This list of actors also reveals that, although they represented a wide range of backgrounds, many, in fact the majority, of the roles revolved around development, characterisation, measurement and processing of materials.

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32 Weissbart, "Report of the New England Association of Chemistry, Teachers Fuel Cells - Electrochemical Converters of Chemical to Electrical Energy".
33 Weissbart and Ruka, "A Solid Electrolyte Fuel Cell".
34 For a description of the work of Bauer and Preis see Möbius, "On the History of Solid Electrolyte Fuel Cells", pp. 4-5.
35 Archer, D.H. and W.G. Carlson, 'An Investigation of Solid Electrolyte Fuel Cells Contract No. (Af33(657)-8251)', (Westinghouse Electric Corporation, 1962).
36 Peattie, "A Summary of Practical Fuel Cell Technology to 1963", p. 804. See also comments in Austin, L.G., 'Fuel Cells: Review of Government-Sponsored Research, 1950-1964', (Washington DC: NASA, 1967). also Archer, D.H., et al., 'Westinghouse Solid Electrolyte Fuel Cell', in *Advances in Chemisty 47: Fuel Cell Systems,* ed G. J. Young and H.R. Linden (Washington DC: ACS, 1969), pp. 332-342 (p. 341).
37 Sverdrup, "Project Fuel Cell Final Report", pp. i-iv.

The Case for a Coal SOFC

The Office of Coal Research was established in 1961. It was formed by splitting out responsibility for developing and promoting new uses of coal away from the regulatory functions of the Bureau of Mines another agency of the Department of the Interior. A major actor in driving its creation was Senator Robert E. Byrd, the Democratic politician from West Virginia who served the state first as a member of the House of Representatives from 1953 to 1959, then as US Senator from 1959 until his death in 2010 at the age of 92, then the longest serving senator in US History with over 51 years of service.[38] West Virginia was a strong coal mining state, so it is natural that Byrd would have promoted increased use of coal through different technological applications as part of the overall drive of expanding energy availability to the USA and to benefit the economy of the state. He also saw the increased use of coal through a prism of energy security against a context of tensions in the Middle East and the growing reliance of the US on foreign oil. In 1955, Senator Byrd had taken part in a visit to the Middle East and Europe.[39] On visiting Egypt he was concerned about some Middle Eastern countries increasing reliance on Soviet aircraft and other military equipment. In his travel diaries Byrd wrote that Egypt's President Nasser assured him that Egypt saw the weapons purchases as required to deter against what it saw as potential aggression from a US-backed Israel but that this in no way put Egypt under any influence from Moscow.[40]

This visit alerted Byrd to the inherent and growing instabilities in the Middle East along with the risks this carried for assured supply of oil into the future. This convinced him to further promote the place of coal in the US energy portfolio. A member of the Department of the Interior Sub-committee for Appropriations, Byrd was well placed and became instrumental in creating the legislation that led to the foundation of the Office of Coal Research in 1961.[41] The mission of the Office of

[38] United States Senate, 'Longest Serving Senators', <https://www.senate.gov/senators/longest_serving_senators.htm>.
[39] Byrd Centre, 'Senator Byrd's 1955 International Delegation Trip', <https://www.byrdcenter.org/senator-byrd-1955-delegation.html >.
[40] Byrd Centre, 'Senator Robert C. Byrd's Response to the Energy Crisis ', (2020) <https://www.byrdcenter.org/draft-blog/robert-c-byrd-and-the-energy-crisis>.
[41] Department of Energy, 'Early Days of Coal Research', <https://www.energy.gov/fecm/early-days-coal-research>.

Coal Research was based around the idea of Byrd's "Project Bootstrap" which involved finding innovative ways to increase coal utilisation and reduce reliance on oil based products.[42] The research covered a wide range of projects and technologies many of these early projects are outlined in a paper by George Lamb, the first Director of Coal Research.[43]

In keeping with Byrd's concerns over the increasing reliance on foreign oil, production of synthetic liquid fuels formed a prominent goal of the Office of Coal Research remit, with gas predominantly seen as a by-product from this process.[44] While manufactured gas from coal had been popular both in Europe and the US in the 1800s, the discovery of oil and natural gas deposits across the US in the later 1800s and the expansion of electrification in the early 1900s had rendered chemically manufactured gas from coal as more expensive and squeezed it out from the US energy mix. The programmes proposed by the OCR in the early 1960s still presented such significant economic challenges. The liquefaction or gasification of coal required huge chemical processing infrastructure if it was to be carried out on a scale which would have a measurable impact the energy mix of the US.

Such large and complex plant would require significant capital investment and need to compete economically with imported oil or domestic natural gas. This economic balance was further complicated by the variability of different coals and the need to remove different mineral impurities which could negatively affect the gasification reactions and the economic calculations. While the bulk of the OCR's activities focussed on these questions, the programme also ranged wider than that and included the embryonic Westinghouse SOFC developments with the programme known as "Project Fuel Cell". The main aim of this project was as part of a wider range of programmes looking at more efficient ways to utilise coal in the generation

[42] Byrd, Robert C, 'Research Makes Coal Industry Look Bright', *Byrds Eye View Collection 1961-1970,* 2 (1962).
[43] Lamb, George A., 'The Office of Coal Research and Its Activities - Remarks by George A. Lamb Director of Coal Research', in *Annual Meeting of the American Institute of Mining, Metallurgical and Petroleum Engineers,* (Dallas, Texas: SPE, 1963).
[44] Ibid. pp. 4-5.

of electricity.[45] The underlying premise was to create "substantial economic progress in the coal industry". [46]

Despite this focus of the OCR and Westinghouse on coal utilisation, it was not universally seen as the fuel of choice for fuel cells, including the SOFC. Others shared Liebhafsky's views that smaller portable units would be the first applications for fuel cells and that central power generation was a long way off.[47] Even where central power generation was envisioned as a fuel cell application, it was often with a fuel feed which was fluid in its natural state, such as natural gas or oil products as a fuel, rather than fuel which needed to be pre-processed from solid feedstock, such as gasified coal. Irrespective of the type of fuel being discussed these articles and discussions begin to set the foundations around which the future promises of both the fuel cell in general, and the SOFC in particular, were constructed. Those promises revolved around extending existing primary fuel reserves, high efficiencies leading to reduced energy costs, multiple fuel capabilities, integration with other energy systems and, importantly, initial market penetration in the next five years. These promised advantages, or combinations of them, with differing emphases on particular characteristics and promises depending on the intended application or market being addressed or courted, would be used to maintain the expectation of the device over the coming decades of ongoing development.

Project Fuel Cell

The Office of Coal Research "Project Fuel Cell" (Contract Number 14-01-001-303) appears to be the first significant SOFC project sponsored by a government agency. While other previous projects had existed, such as the Air Force project, Project Fuel Cell was far in excess of these, both in terms of duration, scope and ambition. Whereas the Air force project was of short duration, only one year, and focused on specific aerospace applications, Project Fuel cell ran for seven and a half years, from December 1962 to August 1970. It pulled in significant contributions from 37

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[45] Ibid. p. 7.

[46] Byrd, Robert C, 'Development of a "Fuel Cell" Could Spur West Virginia's Economy ', *Byrds Eye View Collection 1961-1970,* (1963).

[47] Young, G. J., 'Fuel Cell Panel Discussion', *Industrial & Engineering Chemistry,* 52 (1960).

members of staff from the Westinghouse research laboratories as well as further effort from the Institute of Gas Technology (IGT). IGT was a non-profit organisation founded in 1941 to support development of gas industries across the US and were also involved in other OCR coal gasification programmes.[48] IGT and their subcontractor Cameron and Jones Engineers, were focused on design and evaluation of a 100kW demonstration system incorporating coal gasification and associated chemical engineering equipment where the SOFC itself was only one small part. This contrasted with the main effort at Westinghouse which focussed on the development of the SOFC itself, with the majority of staff accredited with efforts on design, development, processing and testing of materials for the electrochemical cells.[49]

If realised, the aims of the project would have far wider reach than the focused and niche applications in the space programme. The main aim was the development of an increased efficiency coal-fuelled fuel cell power generation system which would be “cost competitive with conventional central station power plants.”[50] However, rather than looking to replace general generation capacity on the grid at large, early advocates for the SOFC described the technology being co-located with power-hungry chemical process industries such as aluminium plants or oil refineries, where there was a high demand for local direct current (DC) electricity which is the form of the electrical output from a fuel cell .[51] The grid used alternating current (AC) as this was better for longer distance transmission due the easier stepping up and down of voltages between long distance transmission and local distribution networks. Therefore, fuel cell output needed to be converted to AC for the grid, while grid AC electricity needed to be converted to DC for some industrial processes, both steps leading to efficiency losses. By placing the SOFC DC output adjacent to the industrial processes, designers sought to minimise these losses further enhancing the high efficiency credentials of the technology. Such visions also began to create a link between the SOFC and ideas around distributed power generation, where electricity was generated close to point of use rather than centrally generated before distribution.

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[48] Lamb, "The Office of Coal Research and Its Activities - Remarks by George A. Lamb Director of Coal Research", p. 5.
[49] Sverdrup, "Project Fuel Cell Final Report", pp. i-iii.
[50] Ibid. p. iv.
[51] Ibid. p. 7.

Specific objectives for Project Fuel Cell were the design and evaluation of a 100kW SOFC plant fuelled by a gasified coal from an integrated fluidised bed. In this design, the coal was gasified internally by-passing steam through beds of finely crushed coal powder which was suspended in the gas flow, taking on the properties of a fluid. The steam and coal would react to form a mixture of carbon monoxide and hydrogen (both fuels for the SOFC). Through this approach, designers also hoped they could also thermally integrate the processes of electrical generation of the SOFC with that of the gasification of coal, with the excess heat produced by the fuel cell reaction being used in the gasification of the coal, which required heat for this reaction to take place. In this design, banks of the tubular SOFC cells would be interspersed throughout multiple fluidised beds with the fuel gas from the coal flowing around the outer fuel electrodes of the fuel cell tubes with air passing through the inside of the tubes.

Initial cell tests were conducted using smaller laboratory-based bench top trials to investigate and improve basic cell materials, evaluate cell and stack design concepts and develop manufacturing approaches.[52] The structure of the final report from 1970, whose primary author was the then Westinghouse SOFC project manager, Edward Sverdrup, reveals how some of these activities were split amongst various technical communities, from conceptual design of the 100kW system, the detailed engineering design of this, fundamental materials development, cell and stack testing, and manufacturing and process development. This shows how such endeavours are highly interdisciplinary affairs, where decisions taken in one aspect of the project by one group can profoundly influence the nature of the problems that need to be addressed or solved by another group. It may also suggest how some decisions can be taken by particular groups to address a short-term issue or problem to allow the meeting of immediate milestones or present progress, but which in themselves may not be applicable to the overall goal and require further effort to bridge the disconnect created by the short-term fix.

One such example of how these disconnects can occur can be identified in the report by following the arrangement of fuel and air supplies in the system. Westinghouse researchers quickly established that their system would be based on a

[52] Ibid. p. 4.

tubular arrangement. While cells based on a flat plate zirconia electrolyte with the air and fuel electrodes on either side (known as the planar design) had been used for some initial trials and continued to be used for fundamental cell materials characterisation throughout the project, building a larger system based on planar cells presented issues around sealing and bulk of the stack.[53] For a fuel cell to work, the fuel and air gasses must be kept separate. In the planar design, this required sealing around the edge of the plate. In the hot environment of the SOFC this was a technically tricky proposition. Moving to a tubular design simplified the sealing, as the fuel and air could be kept separate by running one on the inside and the other on the outside. Further, by extending the tube outside of the hot areas connections to the tube could be made using polymer-based sealing materials. The tube also imparted further advantages around mechanical stability of the ceramic cell components with the stress distributions around the circumference of a tube resulting in a more robust form when compared to a flat plate.[54]

The report described two different types of tubular cell arrangements, one with air on the inside of the tube and another with the fuel on the inside of the tube. The former arrangement was arrived at through an engineering rationale to interface with the gaseous output from the integrated fluidised beds of ground coal. This, therefore, represents the arrangement envisaged by the designers of the conceptual 100kW system. This arrangement was also used in the initial small-scale benchtop tests of early potential cell designs. However, the report also describes an alternate design with fuel on the inside of the tube. This latter arrangement was only mentioned with respect to cells manufactured from new methods developed during the project, which were required to overcome shortcomings in the new fabrication techniques which were revealed in the initial benchtop tests.[55] And it is this change that suggests the need to overcome problems with cell performance and materials manufacture were seen as key to maintaining the promise of the SOFC.

An individual fuel cell does not produce enough power to be useful. In order to build a useful voltage and power output cells must be stacked together, electrically

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[53] Ibid. p. 206.
[54] Interview with Kevin Kendall, Conducted by Author on 9th March 2022
[55] For examples of the co-existence of these two different approaches see Sverdrup, "Project Fuel Cell Final Report". Figures 8.8, 11.1 and 11.31 show fuel gas on the inside of the tube whereas Figures 9.1, and 10.18 give examples where fuel is on the outside.

connected in series to build up the voltage produced. This presents two potential problems: sealing the cells to prevent unwanted mixing of fuel and air and creating a good electrical connection (interconnection) to minimise losses due to electrical resistance across the interface. The scale up and stacking has proven challenging for the low temperature variants, but in the high temperature fuel cells such as the SOFC it has proved an order of magnitude harder. As will be discussed throughout this thesis, taking the performance often exhibited by a single cell in a laboratory test jig and maintaining this into a stack of multiple interconnected cells has proven one of the most challenging and elusive tasks across the developmental history of the SOFC. While many promising materials and designs have been tested successfully at the single cell level, far fewer have made it through to successful demonstration in a stack.

The first attempts at Westinghouse to make this jump from single cell to stack testing was based on a design known as the “bell and spigot”. The bell and spigot design was based on small individual cells in the shape of a conical frustum, a broad cone with the tip cut off. The body of the cone was made from the zirconia electrolyte, with the air electrode on the inside surface and the fuel electrode on the outside. The narrower nose of one cone fitted into the tail of another such that the fuel and air electrodes made contact, resulting in a stack of cells connected in electrical series.[56] In the first half of the project, between 1962 and 1965, the cell and stack materials development team at Westinghouse ran a series of bench level tests based on stacks of 20 interconnected bell and spigot cells which culminated in the bringing several of these stacks together in the demonstration of a 100 Watt generating system running on coal gas.[57] These tests would provide data to demonstrate the technical feasibility of the system and provide a basis for the design of the conceptual 100kW system.[58]

[56] Ibid. p. 223.
[57] Ibid. p. 265.
[58] Ibid. p. 223.

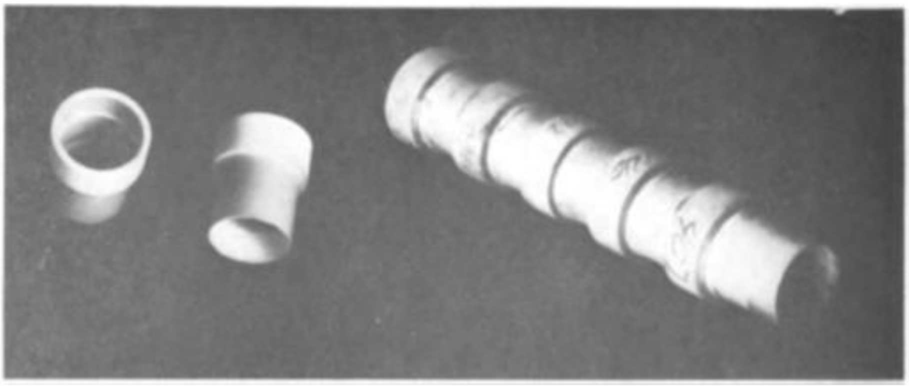

Figure 2; Early Westinghouse bell and spigot cell design. Source DOE Report: Sverdrup, E. F., 'Project Fuel Cell Final Report- Prepared by Research & Development Center Westinghouse Electric Corporation', Research and development report (United States. Office of Coal Research) (Washington DC: 1970).

However, these cells were fabricated from bulk ceramic pieces which required careful machining to create the seal and contact, increasing materials waste and costs. Production of these cells was also limited by the bulk ceramic processing constraints of the early 1960s and the minimum thickness which could be attained for the electrolyte was around 0.4 mm. Such a thickness would lead to unacceptable electrical resistance across the electrolyte for a commercially viable system.[59] Therefore, a cell arrangement with thinner layers deposited on a supporting tube was going to be required. This led to the development of what was termed the “thin-film cell”.[60] This thin-film cell required the development of new processes which would facilitate the deposition of ceramic films with thicknesses measured in microns (thousandths of a millimetre) rather than millimetres. A number of techniques were trialled, most involving some method of condensing a film of the desired composition onto a substrate from a controlled atmosphere containing the chemical components needed to form the final film. The techniques the Westinghouse engineers trialled shared a large similarity to work going in other emerging materials domains such as the development of microfabrication techniques for the nascent electronics industry or investigation into superconductivity, much of which was also taking place in the well-resourced environments of corporate R&D laboratories.[61]

[59] Ibid. p. 214.
[60] Ibid.
[61] For example, see Mody, *The Long Arm of Moore's Law: Microelectronics and American Science*, p. 55.

The overall design of the thin-film cells, at least in terms of the flow of electrical and ionic currents through the device, was in some way analogous to the design philosophy of the bell and spigot. In the thin-film design, discrete bands of active cell materials were deposited along the length of a supporting tube. The positioning of the different bands of material was such that there was a slight offset across the array of layers. This created a protrusion of cathode from one end of the cells while a similar protrusion of anode emerged from the other end. Bands of interconnect material (an electrical conductor) were deposited in such a way as to

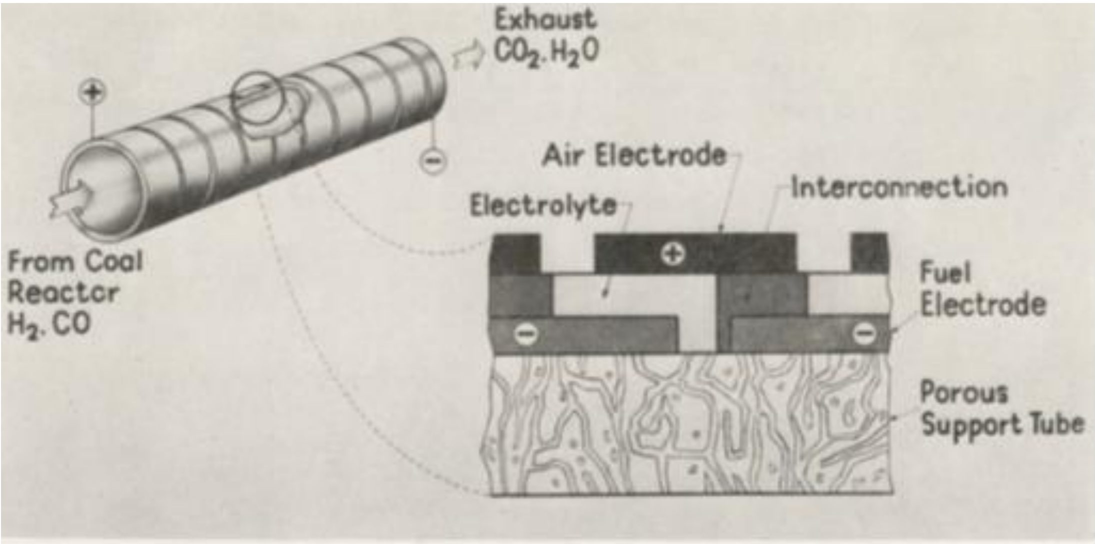

Figure 3Schematic of Westinghouse thin-film segmented in series cell arrangement. Source DOE Report: 'Annual Report Thin Film Battery/Fuel Cell Power Generating System Contract No EY-76-C-03-1197', (Pittsburgh, Pennsylvania: Westinghouse Electric Corporation, 1979) p.B-7.

connect these protrusions which completed the circuit and created a set of series connected cells.[62]

The current flow in this thin-film stack followed a very similar pattern to the bell and spigot, with current flowing from the cathode (air electrode) on the inner portion of the tube through the electrolyte layer to the anode (fuel electrode) on the outer tube surface, then passing laterally across this outer anode and returning to the inner cathode through the interconnect layer. This produced a zig-zag current path up the length of the tube with current moving sequentially between the inside and the outside of the tube. This was very similar in manner to the current path in the bell and spigot and suggests that in devising their thin-film cell the materials scientists were attempting to retain the essential features of the bell and spigot, these being the

[62] Sverdrup, "Project Fuel Cell Final Report", p. 216.

more robust mechanical properties of a tube and the nose to tail interconnection of the cells.

However, the development of the techniques to deposit the layers for the thin-film cell was no straightforward matter. Care had to be taken to avoid unwanted interactions between layers and the processing requirements of each successive layer had to be carefully considered such that the deposition of that layer did not detrimentally impact any previously applied layer. Therefore, the Westinghouse team did not have carte-blanche as to how to build their new thin-film cells and their options were restricted, not only by the various materials they needed to use to form a working cell, but also by how these materials interacted both during fabrication and subsequent operation. These limited the material decisions open to the researchers, suggesting certain paths as being more likely to succeed than others, in effect creating a set of "logics" which framed and directed innovation.[63] Where such pathways became too limited, contradictory or closed off, researchers needed to invent new materials with different or at least modified behaviours. Here, the new materials knowledges of the postwar decades allowed researchers to relate composition and structure to potential performance and to begin to consider tailored materials "by design".[64] This began to put materials science and engineering at the heart of SOFC development and nurtured the notion that the solution to a developmental problem would be attained through the invention or development of a new material.

Such new developments take time, and this is illustrated by the fact that the "first prototype thin-film battery" was not tested until early 1969, the final year of the project.[65] This was three-to-four years after the 100-Watt battery test, further, the thin-film cells had the fuel running on the inside of the tube. This was opposite from the earlier bell and spigot cells and importantly opposite from the conceptual design for the 100kW demonstrator. This three-to-four-year gap and the change in fuel gas orientation, suggests that developing a thin-film cell with the original configuration of air electrodes on the inside may have been more difficult than anticipated. Such a

[63] Lécuyer and Ueyama, "The Logics of Materials Innovation: The Case of Gallium Nitride and Blue Light Emitting Diodes".
[64] Bensaude-Vincent, "Das Konzept Von Werkstoffen in Historischer Perspektive".
[65] Sverdrup, "Project Fuel Cell Final Report", p. 217.

decision implies that materials constraints and processing challenges had forced this reversal of the arrangement of fuel and air in order to get a working thin-film cell and prove the concept of this arrangement within the timescale of the project, irrespective of the impact on the larger system design.

An Emerging Tension: Cells versus Systems

That such a decision was taken also reveals the tensions between the cell design and the system design, tensions which would persist across the history of the SOFC. In this case, the Westinghouse team felt that the performance of the bell and spigot design was untenable and could not produce a viable system, as without a tenable cell there is no system. However, in creating a tenable cell they also turned many of the design assumptions made around the system design on their head and in doing so created a significant disconnect, such that the output of the cell part of the project would not work with the conceptual system design.

In trying to bridge this cognitive gap, Edward Sverdrup took the rhetorical approach of just ignoring it. The individual goals of the project as listed in the introduction had been achieved; i.e., a detailed design of a 100kW demonstrator, a proof of concept demonstrator with the 100 Watt battery and promising cell performance being delivered at cell level with the move to the thin-film cell. However, these had been achieved in a rather disjointed and discrete manner and translating these individual achievements into something resembling a coherent system would require substantial development effort and further fundamental materials research. Therefore, Sverdrup determined that additional funding would be required to bridge the disconnects between the parts of the projects and concluded the report with a request for further support. In order to create as optimistic an outlook as possible on the outcomes of the project the individual achievements across the project are presented at several points within the report as having greater continuity than is perhaps merited from the results themselves.[66] These optimistic assessments of the programme outcomes were used as the basis of an outline proposal for continued support. Ambitiously titled "Program for Commercialisation",

[66] For examples of this presented continuity and equivalency of results see ibid. pages 4, 219 and 369.

this four-year project would again look to prove the commercial feasibility through construction of a demonstration system. However, much of the effort outlined in the proposal remained focused on improving fundamental materials and processes for the manufacture of the thin-film cell.[67]

While fundamental research into the materials may have been justified, I suggest that it also laid the foundations of a tendency for materials science to be given primacy as the route to solving technical problems within the SOFC research community. Materials had been at the centre of many of the technological advances, which had become prevalent in the US during the 1960s creating an optimism around what could be achieved in the future and the power of the yet undiscovered breakthrough material.[68] To some extent such optimism may have been engendered and reinforced by materials cultures and practices of an emerging community based around research and consisting primarily of materials scientists. Some of which may be evident in the foreword to the report where the primacy of materials science in the process is suggested by Sverdrup:

> The understanding of materials science gained in the 1960's and 1970's has reached the point that there is a good probability that the job of engineering - - "making science useful to mankind" - - can be done - - now. [69]

This puts the fundamental scientific endeavours of materials ahead of the engineering making the latter seem like just a "job of work" to be got on with. It replicated and reinforced the view of engineering being "applied science" with some notion of a linear development pathway. The place of linear models has long been contested in the practices of development and innovation, with some even going so far as to suggest that they were purely a construct for historians to argue over.[70] However, statements such as the one from Sverdrup suggest that even if they did not

[67] Ibid. pp. 369-374.
[68] Baker, "The National Role of Materials Research and Development, Address Delivered at the Materials Science Luncheon, Astm Materials Science Division Symposia [1961]". Baker, *Advances in Materials Research and Development*. Leslie, *The Cold War and American Science : The Military-Industrial-Academic Complex at Mit and Stanford*, pp. 188-232.
[69] Sverdrup, "Project Fuel Cell Final Report", p. iv. dashes appear in the original.
[70] Godin, "The Linear Model of Innovation: The Historical Construction of an Analytical Framework"; Balconi, Brusoni, and Orsenigo, "In Defence of the Linear Model: An Essay"; Scranton, "Technology-Led Innovation: The Non-Linearity of Us Jet Propulsion Development"; Edgerton, "'The Linear Model' Did Not Exist: Reflections on the History and Historiography of Science and Research in Industry in the Twentieth Century".

reflect the complex reality of practices in the laboratory or workshop they were certainly a feature in the heuristics of the policy planner and the technical manager promoting visions of pathways to progress.

Where such visions were constructed by more fundamental research orientated actors, they often underplayed the difficulties of the engineering tasks, creating an optimistic view that the fundamental science was the key and, once that had been completed, what remained was “only the engineering”. It also underplayed the interdisciplinary nature of developing a commercial SOFC system, where the differing needs between materials science and systems engineering had already shown that significant disconnects between the two could easily be created when tasks were considered in isolation. In his book *What Engineers Know and How They Know It*, engineer and historian Walter Vincenti suggested two spheres of design and engineering, “normal” and “radical”. “Normal design” occurs when engineers are working within established technologies and machines where inputs and outcomes can be considered familiar, and though they may be complex, rules of design and build are well established and understood. When in working in the “radical design” sphere, the engineer or designer must work outside of the normal limits of what would be “taken for granted” in terms of engineering need and function. This would lead to far greater uncertainties around design and build, and “no presumption of success.”[71] . It could be argued that in underplaying the difficulties of engineering the scientists were potentially conflating of “normal” versus “radical” spheres of design and engineering, and assuming that SOFC system design resided in the “normal” sphere, whereas much of it was actually “radical” in character.

The “normal” and “radical” spheres of engineering should not be taken as separate and discrete rather they lie on a continuum, when engineers are working toward the radical end of the spectrum, as it could be claimed is the case in SOFC system development, it may be suggested that they are working more like scientists, developing new knowledge, not unlike Edwin Layton’s “mirror image twins”.[72] However, the initial results of Westinghouse suggested that the flow of information

[71] Vincenti, *What Engineers Know and How They Know It : Analytical Studies from Aeronautical History*, pp. 7-9.
[72] Layton, "Mirror-Image Twins: The Communities of Science and Technology in 19th-Century America".

and knowledge between these twins could be a complex and convoluted “zig-zag” of information and knowledge flow, where materials science suggested directions for engineering and design, while engineering constraints suggested directions for new or improved materials. Such zig-zag models have been proposed where technology and innovation move into new areas, where little can be taken for granted and boundaries between fundamental and applied are ill-defined and contested.[73] This in many ways may lie at the root of this enduring tension which recurs throughout the history of SOFC development, defining the point at which either fundamental science or engineering development become the primary route to a commercial device. Such points will be determined by a minimum threshold of cell performance which must be reached.[74] However, defining that threshold proved to be elusive.

In Sverdrup’s opinion, the new thin-film cell provided that performance and with further development would provide the opportunity to take the SOFC forward. While no official appraisal of the project from the Office of Coal research has been uncovered, there appeared to be no continuation of the project after 1970. This seems to suggest that the Office of Coal Research did not share Sverdrup’s optimistic assessment of the project outcomes and future directions and refused follow on funding. Subhash Singhal project manager for the Westinghouse SOFC programme from 1985 to 2000, and staff member of the Westinghouse R&D centre in the early 1970s also recalled no formal SOFC research at Westinghouse at that time.[75] Therefore it could be suggested that the Westinghouse SOFC programme was in the wilderness for about 5 years until events at home in the US and the wider world brought the fragility of energy supply lines into stark focus and provided another opportunity to promote the SOFC as part of a future energy vision.

Energy Crisis and Renewed Interest

The energy crisis of the early 1970s revealed and laid bare the precarious position of the US in relation to its dependence on imported oil for its energy needs, predicating national gasoline shortages and rationing, cautioned by Senator Robert Byrd and

[73] Mody, *The Long Arm of Moore's Law: Microelectronics and American Science*, pp. 54-55.
[74] Anonymous Interview Conducted by Author July 2018
[75] Singhal Interiew

others many years before.[76] It was not the only factor in play in creating the conditions for strained energy supplies across the country over the course of the decade. Other structural issues across the US energy markets and energy policies were also contributing to strains in the US energy system, many of which were apparent to government and policymakers in the late 1960s and early 1970s, but which did not figure largely on the agenda of many Americans until the Arab-Israeli conflict of 1973 and the ensuing oil embargo.[77] This required re-examination of supply and demand of energy, the structure of governance around energy and the search for new technologies which could sidestep the multiplicity of issues facing US energy systems. This created the need for "technical fixes" and the SOFC would be promoted as part of a range of promised solutions.

One area of concern was natural gas supply. Federal government intervention in this market had long been a source of contention. The government had greater fears of the potential for monopoly formation with gas than it did with oil: whereas oil had multiple distribution methods such as road, rail, ships, as well as by pipeline, natural gas was limited in transportation options, restricting it to distribution by the pipeline network. This by extension tied local distribution utilities to individual interstate pipeline distribution companies which in turn were tied to individual wellheads and hence individual production companies.[78] In 1954 the Hinshaw amendment to the 1938 Natural Gas Act introduced federal price controls on all interstate gas transaction but left intrastate transactions exempt. The general trend of increasing energy use across the United States was mirrored in natural gas usage. During the immediate postwar years natural gas was mainly considered as a fuel for space heating and industrial uses.[79] By 1965 consumption of natural gas stood at

[76] Byrd Centre, "Senator Robert C. Byrd's Response to the Energy Crisis ".
[77] For example Morton, Rogers C. B., 'The Nixon Administration Energy Policy', *Annals of the American Academy of Political and Social Science*, 410 (1973)., a paper by Nixon's Secretary of the Interior, that does not explicitly mention the Middle East with respect to energy policy but refers to a "serious energy situation" presenting itself to the Nixon administration in 1968. Also see Lifset, Robert D., 'A New Understanding of the American Energy Crisis of the 1970s', *Historical Social Research / Historische Sozialforschung : Special Issue: The Energy Crises of the 1970s: Anticipations and Reactions in the Industrialized World* 39 (2014). and Mitchell, *Carbon Democracy*, pp. 173-.
[78] Lifset, "A New Understanding of the American Energy Crisis of the 1970s", p. 32.
[79] Office of Coal Research (US), 'Clean Energy from Coal Technology', (Washington DC: Department of the Interior (US), US Government Printing Office, 1973), (p. 9).

4,156 terrawatt-hours (TWh) rising over the decade reaching a peak in consumption in 1973 of 5,938 TWh.[80]

As natural gas was more difficult to transport internationally than oil at that time, the United States was largely tied to domestic gas production. Therefore, as use increased over the 1950s and 1960s demand began to outstrip production, pushing prices up. As prices increased, interstate price rises eventually became capped by the federal controls. This meant that better profits could be made selling gas to customers located within gas producing states and so producers were reluctant to distribute gas across state lines where prices would be limited. This led to gas shortages in states with no local gas reserves located within their boundaries, in particular the large conurbations and industrial complexes of the US Northeast, where gas had become an essential source of fuel for industrial processes and space heating in the cold winters.

Even although oil was easier to transport and had more distribution options, this did not mean that it avoided issues around supply, demand and pricing. Many of these issues stemmed around attempts to control the oil price to maintain a viable internal US oil exploration and production industry. Internal market controls included production quotas and rationing to guard against production outstripping demand, so depressing prices and forcing smaller independent operators out of the market. This effectively created a minimum price for oil in the US and created an opportunity for larger operators to import cheaper foreign oil and sell into the US market for a greater profit. This favoured the few large international oil companies over the many smaller independent US operators, again leading to fears of monopoly development by a few major companies.[81] To guard against this, President Eisenhower introduced import quotas on foreign oil which placed a limit of no more than 12% of domestic needs being met from overseas supply.[82] As demand for oil increased US oil consumption outstripped the ability of the domestic market to supply. Initially any shortfalls in supply could be met by increasing foreign imports: however as consumption continued to increase over the course of the later 1960s

[80] Ritchie, H. and M. Roser, 'Energy', *ourworldindata.org [online resource],* (2020) <https://www.ourworldindata.org/energy>.
[81] Lifset, "A New Understanding of the American Energy Crisis of the 1970s", pp. 24-25.
[82] Ibid. p. 26.

limitations on the amount of oil that could be imported, as defined by the Eisenhower era quotas, began to put pressure on ability to supply what the country demanded.

The third leg of the energy crisis was generation of electricity. As in all energy sectors over the postwar years, the demand for electricity had seen rapid growth. In 1965 the average person in the US used 5,235 kilowatt-hours (kWh) of electricity in that year while by 1975 this annual usage had risen to 8,522 kWh.[83] This rise is attributed to an increase in the standards of living and the emergence of a consumer society with increases in refrigerators, televisions, air conditioning, etc.[84] While coal had remained an important part of the electricity generation mix, during the later 1950s and into the 1960s issues around the cleanliness of coal combustion had become recognised, especially issues around emissions of sulphur and nitrous oxides leading to poor local air quality and acid rain.[85] This had led to many electrical utilities to begin to look at alternate fuels such as oil and gas, which would reduce such problem emissions. Further, new environmental legislation coming into force in the first half of the 1970s, such as the 1970 Clean Air Act, placed limits around sulphur emissions. This potentially removed around 33% of the United States coal reserves from the electricity fuel mix as the higher sulphur content of these coals would render them unsuitable for burning to produce electricity.[86]

This move towards oil and gas therefore placed electricity generation capacity within the supply restrictions beginning to be experienced by the oil and gas sectors, in turn leading to curtailments on the ability to generate the electricity supply needed with resulting “brownouts” being experienced by some customers.[87] In addition to the issues around fuels and supply there were also issues around hardware development. As design of generating equipment improved, engineers began to approach the thermodynamic limitations on the efficiencies of a heat-driven generating process. They tried to counter this by increasing the size of generating

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[83] Ritchie and Roser, "Energy".
[84] Cowan, *More Work for Mother : The Ironies of Household Technology from the Open Hearth to the Microwave*.
[85] Nakai, Nobuyuki and Mead Leroy Jensen, 'Sources of Atmospheric Sulfur Compounds', *GEOCHEMICAL JOURNAL,* 1 (1967). Stone, Richard, 'Air Pollution. Counting the Cost of London's Killer Smog', *Science (New York, N.Y.),* 298 (2002).
[86] Morton, "The Nixon Administration Energy Policy", p. 70.
[87] Boffey, P. M., 'Energy Crisis: Environmental Issue Exacerbates Power Supply Problem', *Science,* 168 (1970), p. 1555.

plant. However, larger plant proved to be not as reliable as smaller more established designs. Issues around the increased demand for electricity were further compounded by the slow uptake of nuclear generation. This was seen by many utilities as complex, costly and, with the potential for government interventions, a dubious investment strategy.[88]

This creeping crisis quickly became apparent to the incoming Nixon Administration in 1968. By the early 1970s signs were also becoming apparent across the US with "brownouts", fuel shortages and rising prices.[89] This prompted President Nixon to deliver a special message to Congress on energy resources in June 4th 1971.[90] This message announced a number of proposed initiatives intended to overcome the mismatches of supply and demand. An important part of this effort was a new agency to co-ordinate research and development activities on energy technologies. President Nixon's proposed programme identified that part of the problem had been the lack of an integrated energy policy, and that existing policies were largely based around fuel type and as such, ended up distributed across different government agencies.[91]

Of the proposed technology initiatives, the one which was most relevant to shaping future solid oxide fuel cell development directions was a renewed focus on coal utilisation, especially though gasification and desulphurisation in an attempt to minimise harmful emissions and the deleterious effects they had on air quality and the environment. Further initiatives were also proposed around increasing the conservation of energy by reducing waste and increasing efficiencies. The concern around energy can be seen through conferences focusing on energy conservation, such as those held around the US in 1972 by the Producers Council Inc., a nationwide lobby group of the construction industry, which included significant keynotes from prominent politicians such as, Secretary of the Interior Rogers Morton

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88 There are numerous papers referring to the difficulties of the emergent civilian nuclear industry in the 1950s and 1960s. For example see; Lowen, "Entering the Atomic Power Race: Science, Industry, and Government"; Winkler, Allan M., 'The "Atom" and American Life', *The History Teacher*, 26 (1993); Podobnik, *Global Energy Shifts, Fostering Sustainability in a Turbulent Time*, pp. 103-108.

89 Nixon, R., 'Special Message to the Congress on Energy Resouces, 4th June 1971', (1971) <https://www.presidency.ucsb.edu/node/240214>; Shabecoff, Philip, 'Nixon Offers Broad Plan for More 'Clean Energy' ', *New York Times*, (1971).

90 Boffey, "Energy Crisis: Environmental Issue Exacerbates Power Supply Problem". Nixon, "1971 Congressional Energy Message"; Shabecoff "Nixon Offers Broad Plan for More 'Clean Energy' ".

91 See also Lifset, "A New Understanding of the American Energy Crisis of the 1970s", p. 30.

and Congressman Gerald Ford, then minority leader in the House of Representatives.[92]

While events such as the Producers Council Inc meetings and Nixon's message to Congress outlined the depth of the problem regarding energy consumption and supply as well as demonstrating the administration's desire to tackle it, progress was slow. In his April 1973 energy message to Congress the President made several references to the lack of Congressional action on his proposals and made several uses of executive orders to remove direct control of oil quotas, instead replacing this by a tariff based system, and to reorganise federal energy activities including the enhanced co-ordination of energy research and development.[93] However, the Arab-Israeli conflict of October 1973 and subsequent oil embargoes from the Middle East brought the simmering background difficulties around energy supply into stark foreground relief. This allowed the president to return to Congress and also to address the nation in November 1973, not this time with descriptions of crisis in government organisation around energy unfolding over a long time, but with a full blown "energy emergency."[94]

This emergency allowed the President to push for extension and acceleration of the proposals outlined in both the 1971 and April 1973 statements. Many of the immediate measures revolved around increased energy conservation measures such as reducing highway speed limits, reducing heating and air conditioning in federal building and asking states, private businesses and citizens to follow suit. Of the most important strategic measures that would impact the development prospects for the solid oxide fuel cell was the increased emphasis on coal utilisation. Although this had also been outlined in the earlier statements, the 1973 emergency message placed increasing emphasis on this in several ways. It was the first action outlined in the statement, preventing further conversion of generation plant from coal to oil.

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[92] Gerald R. Ford Presidential Library, 'Ford Congressional Papers: Press Secretary and Speech File: Box D33, Folder "Energy Crisis Seminar of the Producers' Council, Grand Rapids, Mi, October 18, 1972" ', (1972).
[93] Nixon, R., 'Special Message to the Congress on Energy Policy, 18th April 1973', (1973) <https://www.presidency.ucsb.edu/node/255364>.
[94] Nixon, R., 'Special Message to the Congress Proposing Emergency Energy Legislation, Nov 8th 1973', (1973) <https://www.presidency.ucsb.edu/node/255505>; Nixon, R., '7th November 1973 Address to the Nation About Policies to Deal with the Energy Shortages', (1973) <https://www.presidency.ucsb.edu/node/255503>.

However, from the perspective of the group who had been working on the Westinghouse SOFC development activities, it was the proposed creation of the Energy Research and Development Agency (ERDA) and the initiation of “Project Independence” which were to be the most significant outcomes of the energy crisis.[95] Together these initiatives would allow the Westinghouse team to reframe and revalidate the aims and aspirations of their vision for a high temperature SOFC electrical generation system running on gasified coal.

“Project Independence” was a grand plan aiming to meet all of Americas energy requirements from internal resources by 1980, thereby negating the reliance on foreign oil and removing the perceived threats to national security by the use of oil as a weapon. In announcing this project in his November 1973 national address, Nixon invoked the spirit of the Manhattan Project and the later Apollo Project. He also mirrored the language of President Kennedy’s famous “Moon Speech”, using the phrase “by the end of this decade” not dissimilar to Kennedy’s own “before this decade is out” in exhorting the USA to put a man on the moon.[96] To enact this project, Nixon again proposed the formation of the ERDA to co-ordinate research and development activities across the energy portfolio. This new organisation would see the breakup of the Atomic Energy Commission (AEC) in its current form, with research activities moving to the Department of the Interior, joining other agencies such as the Office of Coal Research under the new banner of the ERDA. However, the new organisation did not appear overnight. It was not until the “Energy Reorganisation Act” was finally passed on October 11th 1974 and signed by the next President, Gerald Ford that the new ERDA finally came into existence on January 19th 1975.

Rekindling the Vision of the Solid Oxide Fuel Cell

Part of the ERDA’s early work was reviewing possible energy technology options for the US. In collaboration with NASA it under took a year-long survey of these

[95] Nixon, "1973 Energy Emergency Address".
[96] Kennedy, John F., 'Address at Rice University on the Nations Space Effort', (1962) <https://www.jfklibrary.org/learn/about-jfk/historic-speeches/address-at-rice-university-on-the-nations-space-effort>.

options, entitled the “Energy Conversion Alternatives Study” (NASA/ERDA, NAS3-19407; E(49-18)-1751).[97] The overall Energy Conversion Alternatives Study was a massive project, a dragnet, looking to pull in any potential technical solution. It encompassed many different alternatives to standard energy conversion technologies and one of those options was fuel cells. The full set of reports covers 12 volumes, of which just one concerns fuel cells running to 184 pages.[98] The fuel cell portion of the study was managed by the Westinghouse Research and Development Centre, with principal authors Rukka, Isenberg and Warde all from chemistry or materials backgrounds, who were also key architects and advocates for the SOFC development activities within the Westinghouse Research and Development Center.

In keeping with the central tenet of Project Independence in looking at increased utilisation of coal in the electricity generation system, this study looked to compare the sensitivity of different types of fuel cell when operated on various classes of coal gas. Designed to assess the influence of coal gas variability of the operational performance on different fuel cells, the report would look to recommend the most promising avenues for further development into a large-scale megawatt level fuel cell developments running on gasified coal. Building on the previous experiences and knowledge gained from the Office of Coal Research project, this gave Westinghouse an opportunity to reframe the attributes of the SOFC in relation to the new set of priorities defined by Project Independence. However, the remit of the project was wider than the SOFC and other types of fuel cell were also investigated, these being the Phosphoric Acid Fuel Cell (PAFC) which operated at lower temperatures of around 200°C, the Alkaline Fuel Cell (AFC) operating at 70°C, the type which had been used in the NASA Apollo missions to the moon, and the molten carbonate fuel cell (MCFC) the other type of higher temperature fuel cell. As the name suggests the MCFC utilised molten carbonate salts as the electrolyte, and while the operating temperature of around 650-700°C was several hundred degrees Celsius lower than the SOFC, it was still high enough to potentially utilise hydrocarbon-based fuels such as natural gas with minimal preprocessing.

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[97] Warde, C. J., R.J. Ruka, and A. O. Isenberg, 'Energy Conversion Alternatives Study, Westinghouse Phase I Final Report, Volume 12 - Fuel Cells', (Washington DC: 1976).
[98] Ibid.

In their introduction, the authors referred to a NASA stipulation that the systems modelled were to have an output of no less than 25 megawatts electrical (MWe) and went on to expand on that stipulation to point out that no fuel cell plants had yet been constructed that come anywhere close to that figure and that a lot of the data used arose from “the self-serving advocacy of their own systems by corporations engaged in fuel cell research”.[99] This study analysed 16-20 cases for each type of fuel cell varying parameters such as system efficiencies, cell specifications (such as catalyst loadings, electrolyte thickness etc), system size, cell sub-system lifetime, fuel types and projected costs, from which an estimated “cost of electricity” could be determined for each case along with deriving the four critical factors influencing this cost of electricity. These factors were stated as fuel cell useful life, power density, waste heat recovery systems and fuel type.[100] Better system efficiencies were estimated for the molten carbonate and solid electrolyte types of fuel cell due to the higher operational temperatures of these types of cell allowing for better thermal integration throughout the system. This in turn allowed these two fuel cell types to present the lowest potential costs for electricity.[101] However, these findings were caveated as “highly tentative” as being the product of a “multitude of assumptions”. With this in mind it is also impossible to ignore the irony of the quotation at the start of this paragraph when considering the Westinghouse authorship of this report and the close association of the key authors to the solid oxide fuel cell.

Another comparative fuel cell study was also published in 1976, this time by the Electric Power Research Institute (EPRI). The EPRI was a nonprofit organisation founded in 1973 after congressional hearings into the electricity supply problems of the late 1960s, to provide independent research output to support activities to improve capabilities and technologies around electricity generation.[102] This particular project was carried out by the Power Systems Division of United Technologies

[99] Ibid. p. 1.
[100] Ibid. p. 78.
[101] Ibid. p. 88.
[102] Barker, Brent, 'Born in a Blackout', *EPRI Journal,* (2012).

Corporation, a leading actor in the development of Phosphoric Acid Fuel Cells.[103] The report detailed work carried out between April 1973 and March 1976 building on an earlier program, RP114, which had looked to identify the potential for fuel cell generators distributed across the electricity distribution and transmission networks. In the continuation of RP114, the EPRI project aimed to further develop improved technology for advanced fuel cell generators which would find wider scope for application across the electrical utility networks, with greater operational flexibility such as wider ranges of suitable fuel types and opportunities for siting. Further objectives also included “determining the potential characteristics of centralised fuel cell power-plants operating on coal”.[104] This last action is almost identical to the objectives of the Westinghouse Office of Coal Research project from the 1960s.

The EPRI report again compared PAFC, MCFC and SOFC, as in the Westinghouse Energy Alternatives study. However, in the EPRI project the focus was on developing operational hardware for testing and using these results as a basis for the technological forecasting. Using this focus as a benchmark, the PAFC and MCFC were presented as being the worthiest of further study by virtue of their more advanced stage of hardware development, with these two types of fuel cell already having pilot level plant already in development. By contrast, the SOFC was presented as being only at a bench scale, still focused on fundamental materials development. The report did refer to the Westinghouse OCR project, but presented the high (1000°C) temperature of operation required for the zirconia-based systems as being troublesome in terms of interfacing with other stack components, leading to issues around sealing and corrosion. To overcome this, the report suggested investigations should be carried out to identify solid electrolyte materials with suitable conductivities which would permit operation at temperatures similar to MCFC (650-700°C). To this end, the report authors presented some fundamental work on doped cerium oxides as electrolytes but also identified the significant proportion of electronic conductivity in these materials as leading to their unsuitability for fuel cell operation at these temperatures.

[103] King, Joseph M., 'Advanced Technology Fuel Cell Program -Final Report Prepared by United Technologies Corp for Electric Power Research Institute, E.P.R.I Report Number Em-335', (Palo Alto, CA: 1976).
[104] Ibid. p. 1.

Overall, the EPRI report authors tried to build a perception that while PAFC and MCFC were moving towards testing of equipment that were ready for scale up and resembling what could be imagined as a realistic system, the solid oxide cells were still at the laboratory bench top level and required further fundamental materials research before further scale up could be considered. Together the ERDA and EPRI reports demonstrate how various actors could select multiple and differing terms of reference through which to interpret fuel cells, each arriving at diverse assessments of the viability of the different types.

The assessment of the SOFC made by Westinghouse in the Energy Alternatives report appeared to have convinced the ERDA that the technology had promise as a route to effective and efficient utilisation of coal, as in 1976 support for the SOFC was reinstated under Contract No. EY-76-C-03-1197.[105] However, this funding did not represent unqualified support and the focus of the work reflected some of the concerns highlighted by the EPRI report, that the SOFC was still a laboratory-based technology with a focus on the development of fundamental materials and processes. In an overview of solid oxide fuel cell technology presented to the 1977 Workshop on High Temperature Solid Oxide Fuel Cells, held at Brookhaven National Laboratory on Long Island, Ian Harry, a programme manager in the Power Systems Division of the newly established Department of Energy, described the solid oxide fuel cell programme as an “integral component of the Applied Research Project Area”.[106] This project area was specifically focussed on the development of emerging systems and developing a “technology base”, thus acknowledging the less mature state of development of this technology in relation other fuel cell systems. Harry did not appear to share Sverdrup’s more optimistic appraisal of the outcome of the initial Westinghouse “Project Fuel Cell”. Harry described the outcomes in terms of “short-lived demonstration and accompanying failure”.[107] However he also acknowledged the potential for such a technology,

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[105] Feduska, W., et al., 'Sixth Quarterly Report Thin Film Battery/Fuel Cell Power Generating System Contract No Ey-76-C-03-1197', ed. by US Energy Research and Development Administration (Pittsburgh Pennsylvania: Westinghouse Electic Corporation, 1977); Appleby and Foulkes, *Fuel Cell Handbook*, p. 587.

[106] Harry, I. L., 'A Doe Overview of Solid Oxide Electrolyte Fuel Cell Technology', in *Proceedings of the Workshop on High Temperature Solid Oxide Fuel Cells,* ed. by H.S. Isaacs, S. Srinivasan, and I.L. Harry (Brookhaven National Laboratory: US Dept of Energy, 1977), pp. 88-89 (p. 88).

[107] Ibid.

especially the promise to utilise coal, as being particularly beneficial to the nation. Harry therefore felt that the initial systems designs, and base technology were worth pursuing, even though he felt that the thin-film cell “required a rethinking from a technology development prospective [sic]”.[108]

Contract No. EY-76-C-03-1197 (formally C-1197-11) ran across two years, 1977 and 1978.[109] From the nature of the work carried out in this project, it could be argued that the research team at Westinghouse also appeared to share Harry’s concern that the thin-film SOFC technology needed revisiting from the fundamentals of materials composition and process development. It further suggests that the initial trials of the thin-film concept in “Project Fuel Cell” had been rapidly conceived as an alternative to the performance limitations observed when testing the original “Bell and Spigot” concept.[110]

This new project therefore gave the team time and opportunity to consider the thin-film concept as the primary development pathway and to revisit the issues identified in “Project Fuel Cell” from first principles. Peeling, cracking and porosity in the materials used to seal and electrically connect the adjacent cells of the tubular stack had been identified as one of the significant reasons for the poor performance and high degradation of the series-connected arrays of thin-film tubes and as such improvement of the materials used in this component, and their methods of deposition became one of the main areas of activity across this study. [111]

The award of the new Westinghouse project continued to underline the importance to which some in the US energy establishment viewed increasing coal utilisation as part of the US electricity generation mix, along with unease over the ongoing vulnerability of the US’s continued and increasing reliance on foreign oil within its total primary energy supply. Even after the 1973 crisis and the goals of “Project Independence” across both the Nixon and Ford administrations, US crude oil imports more than doubled from just over 1.1 billion barrels in 1973 to just over

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[108] Ibid. pp. 88-89.
[109] Feduska, W., et al., 'Annual Report Thin Film Battery/Fuel Cell Power Generating System Contract No Ey-76-C-03-1197', (Pittsburgh, Pennsylvania: Westinghouse Electic Corporation, 1979).
[110] Sverdrup, "Project Fuel Cell Final Report", p. 214.
[111] Issues around cell leakage from the interconnect overlap area are inferred from the contents of Feduska, et al., "Sixth Quarterly Report Thin Film Battery/Fuel Cell Power Generating System Contract No Ey-76-C-03-1197".

2.4 billion barrels in 1977.[112] Across the late 1970s and early 1980s stationary fuel cells were beginning to be mentioned as part of an emerging suite of technology development initiatives which would facilitate increased utilisation of the US coal reserves across a number of energy sectors. Within this context, stationary fuel cell research effort including phosphoric acid fuel cells, and molten carbonate fuel cells in addition to the Westinghouse SOFC would remain an important part of the new Department of Energy (DOE) electricity generation technology development portfolio for the next 20 years receiving $1.167 billion between 1978 and 2000, equating to 46% of the DOE budget for research into technologies for electricity generation.[113]

Department of Energy – New Organisation of Energy R&D

In referencing both the ERDA and DOE in the same text, Harry's short paper also reflects changes that were taking place in the federal organisation of energy research, especially the creation of the new Department of Energy (DOE) with election of President Carter and the incorporation of the roles of the short-lived ERDA into this new organisation. While President Ford had managed to create the ERDA, so bringing together research and development functions from several agencies under one organisation, wider integration of energy policy was still some way off. Ford would have liked further deregulation of price controls of domestic oil supplies and further tariffs on imports to shift the balance away from ever increasing levels of imports. However, in 1975, Congress passed the Energy Policy and Conservation Act which, while it introduced economy standards for vehicles and the creation of the national petroleum reserve, still maintained domestic price controls on oil and gas.[114] Although the price of oil remained higher than before the 1973 embargo, a return to unrestricted supplies of oil and the relatively low profile of energy in the 1976 presidential campaign, which saw the election of Jimmy Carter as the 39th

[112] US Energy Information Administration, 'Us Crude Oil Imports', 2024 <https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=mcrimus1&f=a >.
[113] National Research Council (US), *Energy Research at Doe, Was It Worth It? : Energy Efficiency and Fossil Energy Research 1978 to 2000 / [Internet Resource]*, pp. 52-54.
[114] Fehner, T.R. and J.M. Holl, *Department of Energy 1977 - 1994: A Summary History*, (Oak Ridge, TN: Dept. of Energy (US), 1994), p. 19.

President of the United States, suggested that many Americans felt the crisis was over.[115] However, the harsh winter of 1976-77 revealed that underlying structural issues in energy planning and pricing still existed, which resulted in poor continuity of gas supplies to the North-Eastern states and demonstrated that planning and policy around energy supply was still a significant issue in the US.[116]

Therefore, when Carter entered office in January of 1977 energy was at the forefront of his mind. He quickly enacted a campaign promise to create a new cabinet level position with the formation of the Department of Energy and appointed James Schlesinger as the new Secretary of Energy.[117] This new department looked to bring together all the Federal energy roles under one roof. In addition, it would also look to restructure how these activities were organised. The new department would attempt to move away from organisation by fuel type and restructure around function such as energy research, energy technologies, conservation and resources. Technologies would be positioned according to their level of development and readiness for commercialisation rather than by fuel type and there was an attempt to move away from the disaggregated fuel policy approach of the past towards a more integrated energy policy.[118] This new structure is what was described by Harry where he placed the SOFC in the applied research area, the level furthest from commercialisation and deployment.[119]

As well as the creation of the Department of Energy, President Carter also proposed a National Energy Plan (NEP). This would focus on conservation, price control and new technologies.[120] It moved away from the goals of the Nixon/Ford "Project Independence" insofar as it acknowledged that full energy independence would be unlikely in the 1980s. However, increased use of domestic resources such as coal remained an important part of Carter's plan, although there was also

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115 Ibid.
116 Ibid. pp. 20-21.
117 Hunter, Marjorie, 'Energy Department Is Voted by Congress', *New York Times*, (1977).
118 Fehner and Holl, *Department of Energy 1977 - 1994: A Summary History*, p. 22. Creed, Donald, 'Three Phase Public Affairs Plan Annoucing D.O.E - Memorandum to Ray Walters ', (US National Archives, 1977), (p. 78). this refers to page 7 of the "DOE Organisation and Functions Fact Book" appended as part of this memo.
119 Harry, "1977 Doe Sofc Overview", p. 88.
120 Carter, James E., 'Address to the Nation on Energy', (1977) <https://www.presidency.ucsb.edu/documents/address-the-nation-energy>; Ryan, Robert G., 'President Carter and the National Energy Policy', *Environment international*, 2 (1979).

increased emphasis on conservation. Whereas Nixon and Ford focused mainly on increasing domestic supply, Carter moved towards a stance of trying to use less. This was a significant change of rhetoric. Where Nixon could frame conservation measures contained in his policies as trying to minimise the impact of foreign events, such as the oil embargoes, on US supplies, Carter was beginning to address the lifestyles, cultures and practices of American citizens and businesses.

These changes of emphasis also created implications for the direction and priorities of energy research and development in the US. Although the Department of Energy had been created, many of the old agencies remained in a state of transition into the new department. This created some tensions around how and where budgets would be allocated. In 1978, the ERDA was still being allocated a budget as an agency. However, the Office Management and Budgets (OMB) suggested that the move away from the goals of “Project Independence” and other provisions in the NEP such as tax incentives, finance, etc, to create “market pull” for closer to market such as demonstrations, retrofits and scale ups should also be reflected in the way budgets were focussed. In the vision of the OMB energy R&D funding should focus on basic research “in search of dramatic breakthroughs in finding new, cheaper and cleaner, energy sources” and in concert with this focus the R&D effort should be less focused on nearer term technologies which only offer “marginal improvements”. [121] The move to longer term grand objectives as suggested by the OMB was further justified by the view that oil prices had stabilised and that this, along with the prospect of new discoveries, would remove the supply pressure that had been seen earlier in the decade. In the view of the OMB, this therefore gave more time to pursue more ambitious goals over the longer term. With respect to the prospects for fuel cell research it appeared that the OMB viewed this technology as one of the generic technologies with the prospects of delivering significant technological breakthroughs.[122] It could be argued that the OMB were echoing a Vannevar Bush-type worldview, where basic science will supply the solutions and full application will follow. While Bush was not specific on whether government or private projects

[121] Hall, George R., 'E.R.D.A. Energy R&D Budget - Memo to James R. Schlesinger (Seceretary of Energy, United States) ', (US National Archive, 1978). the quotations are from of the OMB 1979 Presidential Spring ERDA Budget Review appended to the Hall memo.
[122] Ibid. See page 13 of the appended OMB review for direct reference to fuel cells.

would utilise the fundamental knowledge, the OMB saw the efforts of private enterprises as clear routes to application, with market pull being provided by financial and tax incentives.[123]

However, it appears the view of the OMB was not universally shared. In response to the OMB budget review, George R. Hall, a senior staff member of Energy Policy and Planning, sent a memo to Secretary of Energy James Schlesinger concerning the 1978 budget allocations to the ERDA. From the tone of the language used, it appears that George Hall was not in agreement with the OMB's assessment of the need for a change of emphasis in research and revealed potential tensions within the setting of the research agenda for the new department. In describing the OMB's proposal, Hall used language such as "philosophy to which we don't ascribe" and "concerned about signals that a low R&D target for FY 1979 would send to ERDA, congress and the general public".[124] Hall also worried that the OMB was conflating "generic problems" with "technological problems" while excluding issues around commercialisation. Hall suggested such issues could still present significant technical problems which required demonstration systems to work out and overcome. In suggesting this, it could be argued that Hall had some understanding of the difficulties in taking new technologies from the laboratory to commercialisation and that many of the development issues would possibly lie beyond the laboratory walls.

This tension over the role and boundaries of federally-funded research and development would continue to influence and shape research and development programs across the DOE into the 1980s and beyond, especially as subsequent presidential administrations would look towards market-orientated approaches to drive and deliver new technologies.[125] The construction of funding-orientated demarcations between research, development and demonstration would become salient for technologies such as the solid oxide fuel cell where the practical distinctions between these phases was particularly blurred and technical activities often drew simultaneously from a broad base of knowledge inputs from fundamental science through to systems design and engineering.

[123] Bush, *Science - the Endless Frontier*.
[124] Hall, "E.R.D.A. Energy R&D Budget - Memo to James R. Schlesinger (Seceretary of Energy, United States) ", p. 3.
[125] Mirowski and Sent, "Commercialisation of Science".

While these debates were taking place in Washington, events in the Middle East would once again create another energy crisis in the US which would not only lead to reorganisation of the DOE but would be become a threat to the agency's existence. The Islamic Revolution in Iran in early 1979 resulted in another curtailment of global supply lines of oil. While the US was only marginally exposed to these shortages, with just 5% of its imported oil coming from Iran, the shock increase in global prices did impact the American consumer. Price controls on US domestic production were leading to producers turning to foreign production where profit margins were increasing in line with global price increases. This led to a constriction of domestic supply along with the threat of shortages and rising prices. One of President Carter's immediate actions was to start to remove price controls on domestic production which would allow US oil prices to rise towards parity with global prices, with the goal of stimulating domestic production. However, in the short term the removal of the production price controls did not immediately alleviate shortages and prices at the gasoline stations continued to rise. This led to a summer of high prices, long lines, and frustrated Americans.

With the shortages continuing into the summer and OPEC looking to increase the global price of oil again President Carter looked to the nation to help in dealing with the crisis. On the 15th of July 1979 he addressed the American people in an attempt to portray the energy situation as much as a "crisis of confidence" as a crisis of energy. A significant aspect of the speech was a call to the nation to rally round as a community and that the government would not be able to solve the energy crisis on its own without the help of its citizens. In particular, President Carter focussed on the over-consumption of the nation and appealed for people to examine their own consumption habits and to cut their own fuel use.[126] While he effectively chastised the American public for overconsumption, the speech itself was actually well

[126] Carter, James E., 'Energy and National Goals: Address to the Nation', (1979) <https://www.jimmycarterlibrary.gov/the-carters/selected-speeches/jimmy-carter-energy-and-national-goals-address-to-the-nation>.

received, with the president seeing rises in snap polls conducted immediately afterwards.[127]

It was in the days following the speech that Carter lost the confidence of the American people with a series of firings and resignations which included James Schlesinger the Energy Secretary. Reflecting on these events in 2017, respected journalist and political commentator John Dickerson suggested that such a high number of rapid changes in the cabinet suggested an air of chaos in the leadership which undermined the people's confidence in Carter's ability to deliver a solution to the crisis.[128] In many respects Schlesinger's departure from the Department of Energy could be seen as a direct consequence of the policies enacted by the department during the crisis. Many people, including a number of members of Congress blamed the DOE and its complex burdensome bureaucracy for exacerbating the effects of the shortages and high prices seen during the summer of 1979.[129]

A lot of the attention around this speech has focussed on Carter's remarks regarding American habits around consumption and promoting conservation, as well as the political fallout regarding the actions following it, resulting in Carter's unsuccessful bid for a second presidential term. However, the speech also contained details which were of direct consequence to those developing fuel cells. As well as looking to shift emphasis to domestic oil and gas production, Carter further committed to increased use of US coal reserves, not just in terms of burning more coal, but also using it to create alternative synthetic fuels.[130] Therefore, the previous decades of high temperature fuel cell development at Westinghouse continued to fit with this agenda and thereby retained the validity of further research in this field. Further confidence that continuity of current research directions would be maintained was reinforced by the announcement that the new Secretary of Energy, Charles W. Duncan, who on taking office in September 1979, stated he would continue with the

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[127] Mattson, Kevin, '"Crisis of Confidence" Jimmy Carter Was the Last President to Call for Americans to Stop Consuming So Much. Will Anyone Ever Do That Again?', in *Slate,* (2021); Yaqub, Salim, *Winds of Hope, Storms of Discord: The United States since 1945,* (Cambridge UK: Cambridge University Press, 2023), p. 283.
[128] Dickerson, John, 'What Happened When President Carter Fired Five Cabinet Officials', in *Slate,* (2017).
[129] Fehner and Holl, *Department of Energy 1977 - 1994: A Summary History*, p. 28.
[130] Carter, "Energy and National Goals: Address to the Nation".

existing technology research programmes that were ongoing under Schlesinger's tenure to implement the President's National Energy Plan and would "utilize the genius of American technology".[131]

However, Duncan also reorganised energy research at the Department of Energy and moved away from the system of organising research activities with respect to a technologies proximity to market deployment that had been implemented under Schlesinger and returning to the more traditional arrangement with organisational logic defined by fuel types.[132]

The result of this reorganisation would be that different families of fuel cell found themselves split across two different administrative programmes. The lower-temperature PEM development would fall within the Office for Energy Efficiency's portfolio which included not only industrial and buildings efficiency, but also transportation, which is where the fuel cell research would be situated. Stationary fuel cells, which included the high temperature variants such as the SOFC, were situated within the Office of Fossil Energy, which was subdivided into two further offices: the Office of Natural Gas and Petroleum Technologies, and the Office of Coal and Power Systems, with stationary fuel cell research falling within the latter office.[133] This reinforced the SOFCs position within the coal utilisation sector. Further, with a number of degrees of separation between the high temperature fuel cell variants and lower temperature PEM fuel cells, this meant that the research activities onto each type would be subject to very different policy agendas.

Duncan was a chemical engineer by his first degree, with graduate qualifications in business, and had spent most of his career before government in private industry. He had built considerable experience in business management, including spending time on the board of Coca Cola.[134] Duncan was seen as a sound manager rather than the technocrat, a label often applied to Schlesinger, while some

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[131] Carter, James E., 'Remarks at the Swearing in of Charles W. Duncan, Jr., as Secretary', (1979) <https://www.presidency.ucsb.edu/documents/department-energy-remarks-the-swearing-charles-w-duncan-jr-secretary>.
[132] Fehner and Holl, *Department of Energy 1977 - 1994: A Summary History*, p. 30.
[133] National Research Council (US), *Energy Research at Doe, Was It Worth It? : Energy Efficiency and Fossil Energy Research 1978 to 2000 / [Internet Resource]*.
[134] Hoagl, Jim, 'Charles Duncan: Amiable Loyalist, Longtime Manager', *Washington Post*, (1979); McFadden, Robert D., 'Charles W. Duncan Jr., Energy Secretary in Oil Crisis, Is Dead at 96', *New York Times*, (2022).

saw this as a positive, his approach during his tenure at the DOE was criticised by others.[135] Perhaps due to his management background, he highlighted the role of the market in the supply and distribution of energy and the responsibilities of the private sector in developing new energy technologies.[136]

It could also be argued that this was the beginnings of political mindsets which looked to reduce the level of government intervention and control across the energy sector. With the election of Ronald Reagan in the USA and Margaret Thatcher in the UK, this approach to limited government and increased focus on the market to drive innovation and development, which would become labelled as "Neoliberalism", would be given far freer rein in the coming decade and its effects would be felt across society. It would have profound impacts on the development of energy technologies, changing relationships between government, industry and academia which would in turn influence and shape the development of the SOFC.

This chapter described how US political and corporate needs for energy over the 1960s and 1970s provided the opportunity for the idea of the SOFC to be positioned within wider imaginaries of an energy independent US, while the corporate environment of the Westinghouse research and development laboratories provided a sound environment to establish the initial logics of SOFC materials and design. The next chapter explores how the team at Westinghouse would continue to drive SOFC development, creating a close relationship with the DOE and consolidating their position as technology leaders, but despite their technical progress, they struggled to find a home for their technology across established corporate business units. These Westinghouse activities are described against a context of changing political and policy imperatives within the new Reagan Administration, which when allied with new SOFC materials processing techniques adopted from the electronics industry, would open the door to a wider set of developers who would begin to define a new set of logics for SOFC design, manufacture and operation.

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135 Berry, John M., 'Duncan Defends Doe Solar Work', *Washington Post,* (1980); Murphy, Brian, 'Charles W. Duncan Jr., Energy Secretary During Carter-Era Oil Crunch, Dies at 96', *Washington Post,* (2022).
136 Fehner and Holl, *Department of Energy 1977 - 1994: A Summary History*, p. 30.

Chapter 4: Laying the Foundations of a Technology

Westinghouse Quietly Continues Development

While many organisational changes were taking place within the Department of Energy that would impact the positioning of SOFC research within this organisation, work continued in the Westinghouse research and development centre developing their SOFC concept. The research team had managed to secure additional funding from the DOE which allowed continuation of the initial two-year contract (C-1197), which had been awarded as a result of the findings of the Energy Technology Alternatives Study. This "continuation contract" (AC02-76ET 11305) ran from April 1978 to the end of March 1980, so covered most of the period of the second oil shock and the subsequent reorganisation in the DOE. Following the continuation contract, a further contract for SOFC development was again awarded to Westinghouse, so it appears that any change in organisation had not detrimentally affected the DOEs opinion of the potential merits of the SOFC.[1] However, as President Carter had emphasised the need to better utilise the domestic coal reserve in the US, a technology whose history to date had been built around exactly this improvement in effectiveness of coal utilisation was unlikely to fall out of favour.

The positioning of fuel cells with relation to coal utilisation in the thinking of the DOE was also evident in the awarding of significant contracts for the development of other forms of stationary fuel cell. In August 1979, the DOE awarded 33-month contracts, valued at between $13 million and $17 million each, to both United Technologies and General Electric for the development of high temperature molten carbonate fuel cell (MCFC), which were intended to demonstrate systems running on synthetic gas derived from coal. These cells were described by the DOE as "second generation", promoted by the developers of these technologies as building on the knowledge gained from earlier fuel cell developments such as the alkaline fuel cell (AFC) and phosphoric acid fuel cell (PAFC) and overcoming their

[1] This further contract was awarded under contract number AC02-80ET17089.

perceived shortcomings. With respect to the MCFC this meant that such “second generation” systems were more attuned to the needs of mass deployment within a carbon-based energy framework.[2]

Although these were not the first attempt to position other fuel cell types within hydrocarbon fuel frameworks. A previous attempt had involved the collaboration of aerospace company Pratt and Whitney with gas utilities in the TARGET programme, which had run across the 1970s, and aimed to use PAFCs with natural gas. Pratt and Whitney had looked to this programme to provide a possible route to commercialisation for the knowledge gained during their fuel cell developments for the space programme. While for the gas utilities, the goal had been to use fuel cells to bring electricity generation closer to the point of use, so allowing the gas grid to compete directly with the electricity grid in the delivery of electricity. Mismatches in expectation across the partners around the state of development of the various technologies required such as the fuel cells themselves and associated fuel processing ultimately led to disappointing outcomes for the TARGET programme which failed to provide a platform for further commercialisation.[3]

With a high operating temperature of around 650°C, the MCFC was promoted as simplifying fuel processing and reducing the need for precious metal catalysts required for the AFC and PAFC. The DOE planned a series of demonstrations for the MCFC programmes, with initial technology demonstrations taking place in 1982-1983 and leading to megawatt scale system demonstrations in 1983.[4] Westinghouse also received a further $4.4 million for the development of large phosphoric acid fuel cells (PAFC), to provide both electrical power and space heating.[5] The fuel on which this PAFC was to be run was not specified in the report detailing the contract award: however it is likely that this project was the same as the 7MW Westinghouse PAFC described the 1989 *Fuel Cell Handbook*, where fuelling by either natural gas or gasified coal are alluded to.[6]

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[2] For a discussion of how developers associated the different generations of fuel cells for utility applications see Appleby and Foulkes, *Fuel Cell Handbook*, pp. 55-103.
[3] For a more complete description of the TARGET programme see Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*, pp. 86-97.
[4] Department of Energy, 'Doe Picks Two Firms to Design Fuel Cells Using Syngas from Coal', *Energy Insider*, 2 (1979)..
[5] Department of Energy, 'Doe Briefs: Fuel Cell Contract', *Energy Insider*, 2 (1979).
[6] Appleby and Foulkes, *Fuel Cell Handbook*, pp. 79-80.

The size of the MCFC and PAFC projects also reflects the relative size of SOFC research versus the other more established “earlier generations” such as PAFC and MCFC. The 1998 edition of the *Fuel Cell Handbook* state that the bulk of the DOE fiscal year (FY) 1983 fuel cell budget of $26.8 million was mainly appropriated to PAFC development with a smaller amount spend on MCFC. SOFC did not receive a specific mention implying that the technology received a far lower percentage of the funding than either PAFC or MCFC.[7] This reflects the view of many at that time, that the SOFC was a highly immature technology that was still mainly focussed on laboratory studies. However, as the decade progressed, and debates continued about the role and limits of government in funding research, where government support should cease and where responsibility should be taken up by the private sector, the perception of the SOFC as very much a precommercial development of long-term technology helped to maintain continuity in the funding stream, which in turn helped to develop and sustain a community around the technology.

It was indeed the case that the SOFC was a laboratory-based technology in the late 1970s and early 1980s. The main aims of the Westinghouse programmes at this time remained fundamental studies of materials properties and behaviour to enable selection of a core set of materials which would form their stack. This was accompanied by complementary work on determining appropriate fabrication processes for the cells and stacks. Further, all of this work was taking place on small scale cells and stacks of a few watts or tens of watts, as opposed to the tens or hundreds of kilowatts of the prospective PAFC and MCFC demonstrations. Photographs contained within the periodic reports to the Department of Energy also show work taking pace within a laboratory environment, with little that resembled anything that could even remotely be described as approaching a prototype system.[8]

The Westinghouse effort over the period of the late 1970s and early 1980s did result in several important developments which would shape, not only the internal work at Westinghouse, but would also set the benchmarks for the wider SOFC industry going forward for the next few decades, defining the core sets of materials

[7] Ibid. p. 61.
[8] Feduska, et al., "Sixth Quarterly Report Thin Film Battery/Fuel Cell Power Generating System Contract No Ey-76-C-03-1197"; Feduska, et al., "Thin Film Battery 1979 Annual Report"; Feduska, W., et al., 'Final Report Task E4- Thin Film Battery/Fuel Cell Power Generating System Contract No Ey-76-C-03-1197', (Pittsburgh, Pennsylvania: Westinghouse Electric Corporation, 1978).

for many of the key cell and stack components. Important for Westinghouse was the consolidation of the electrochemical vapour deposition process (EVD) for fabricating cell layers, most importantly the zirconia electrolyte. This process was based around the deposition of a film of solid oxide ceramic condensed from the reaction of zirconium chloride and water vapours. Once the initial film was complete, film growth could continue utilising the oxide ion conduction of the deposited zirconia to continue to bring oxygen into contact with the reactive chemical vapours.[9] First conceived as part of the Office of Coal Research "Project Fuel Cell" programme in the late 1960s, the driver to develop this process was the need for thin, flaw-free electrolyte layers which were beyond the capabilities of the then contemporary bulk ceramic process, such as powder pressing or slip casting. While this programme allowed the concept of the EVD process to be shown to be technically feasible, the results had only demonstrated this at very small laboratory levels not commensurate with the overall goals of the programme, leading to its cancellation in 1970.[10] While the EVD process still required significant development to fully optimise the process and determine which other layers could be produced by the process, Arnold Isenberg, the Westinghouse scientist who had devised this process, continued to work to optimise the process within an independent research programme.[11]

This suggestion that Isenberg had the freedom to continue to work on developing this technique beyond the end of formal external funding demonstrated one of the essential advantages which led to the corporate industrial research centre being one of the powerhouses of invention and innovation across many decades of the twentieth century: that of allowing individuals or small groups of researchers to pursue ideas and topics out of intellectual curiosity. Indeed, at that time, the Westinghouse R&D centre was described as one of the "three great R&D centres in the US, along with Bell Labs and GE": it was run on an almost "university like" footing with a "freewheeling culture" where individual researchers had a lot of freedom and could pursue "research for the sake of research".[12] In his classic account

[9] Isenberg, A. O., "Method of Vapour Deposition", United States Patent Office, US Patent 4,374,163, Westinghouse Electric Corp., 1983; Feduska, W. and A.O. Isenberg, 'High-Temperature Solid Oxide Fuel Cell — Technical Status', *Journal of Power Sources,* 10 (1983), p. 91.
[10] Feduska and Isenberg, "High-Temperature Solid Oxide Fuel Cell — Technical Status", p. 90.
[11] Ibid.; Isenberg, US Patent 4,374,163.
[12] Singhal Interiew

of Bell Labs, John Gertner defines this freedom as a central characteristic of such an institution - the ability of researchers to "roam free".[13] However it also demonstrated Isenberg's tenacity, determination and even a stubbornness in believing that the EVD process would result in high quality, pore-free electrolyte layers. Described by colleagues as both "sharp" and "practical", Isenberg's determination paid off and the EVD process did produce dense, pore-free electrolyte layers of high quality and an appropriate thickness of a few tens of microns.[14] Such electrolyte layers formed the heart of the Westinghouse SOFC and it could be argued that Isenberg's continued work put the Westinghouse team in a good position to pick up the SOFC research when funding was reinstated in 1976.

When the programme was reinstated in the late 1970s, the Westinghouse team were still trying to perfect other aspects of the segmented in-series approach other than the electrolyte. It was the definition of materials and processes for other cell components and the interfaces between them that were to take up much of the research effort of the programmes running between 1976 and 1980. Of particular concern were the interconnect and the air electrode (cathode). The material being developed for the interconnect at this time was a ceramic based on lanthanum chromite. This had a modified crystal structure giving and almost pure electrical conductivity along with chemical stability in both air and fuel environments, an essential attribute for this component. This was also deposited by the EVD method: however, there were many issues at the overlap areas between the interconnect and other layers, such as the electrolyte, leading to poor adhesion and leakage between the fuel and air sides of the tube.[15] The cathode material was also causing problems. The initial material used was based around indium oxide: while this showed good properties for its role in the fuel cell, it was also leading to issues of poor adhesion and peeling. Further, cost estimates carried out by the team at Westinghouse had also suggested that this was the most expensive of the cell materials, which would impact cell costs and consequently there was considerable need to find an alternative.[16]

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[13] Gertner, *The Idea Factory : Bell Labs and the Great Age of American Innovation*, p. 152.
[14] Anonymous Interview, Conducted by Author on 29th April 2021
[15] Singhal Interiew
[16] Feduska, W., et al., 'Annual Report High Temperature Solid Oxide Electrolyte Fuel Cell Power Generating System Contract No. Ac02-80et17089', ed. by Department of Energy (Pittsburgh, Pennsylvania: Westinghouse Electric Corporation, 1981).

The search for solutions to the problems posed by the cathode and the interconnect occupied much of the research effort in the development programmes running between 1976 and 1980. This work involved either the synthesis and assessment of potential materials for these roles, searching for improved methods of processing and deposition, or mixtures of both. With respect to new cathode materials, a promising family of materials based on lanthanum manganite were identified and several compositions were trialled before a strontium-doped version was seen to show promise.[17] In a manner similar to the yttria-stabilised zirconia electrolytes and nickel-zirconia cermet anodes before it, this new strontium-doped lanthanum manganite (LSM) would form part of the essential canon of SOFC materials which would dominate SOFC design for decades to come.[18] While some progress was made and reports talked positively about materials performances and stabilities, a careful reading of the reports to the Department of Energy still revealed references to peeling cracking and leakage.[19] Such issues were often seen at the interfaces between cells, and while reasonable performances could be exhibited in laboratory scale trials, the ongoing focus on materials-based development suggested that such problems had not been completely resolved.[20]

In an effort to allow work to continue into other aspects of cell behaviour, including long-term testing and utilisation of potential real fuels such as coal gas, Westinghouse researchers adopted a single-cell-tube geometry. This avoided many of the difficult interfaces and overlaps between multiple cells on a tube and they hoped that this would give a reliable test bed for laboratory work.[21] This also alluded to the ongoing difficulties in trying to fabricate the multiple cell arrays of the segmented in-series design with the many interfaces and overlaps between materials which this design contained. This problem only grew as the length of the support tube increased to accommodate more cells.[22] The new single cell arrangement was

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[17] Ibid.
[18] Minh, "Ceramic Fuel Cells"; Steele and Heinzel, "Materials for Fuel-Cell Technologies".
[19] Feduska, et al., "Thin Film Battery 1979 Annual Report".
[20] Feduska, et al., "Final Report Task E4- Thin Film Battery/Fuel Cell Power Generating System Contract No Ey-76-C-03-1197".
[21] Feduska, et al., "Thin Film Battery 1979 Annual Report".
[22] Ibid.

based on a closed end tube and reference to it first appears in detail in the 1981 annual report.[23]

This arrangement returned to the original fuel and air configuration of the 1960s bell and spigot concept, with air on the inside of the tube and fuel on the outside.[24]

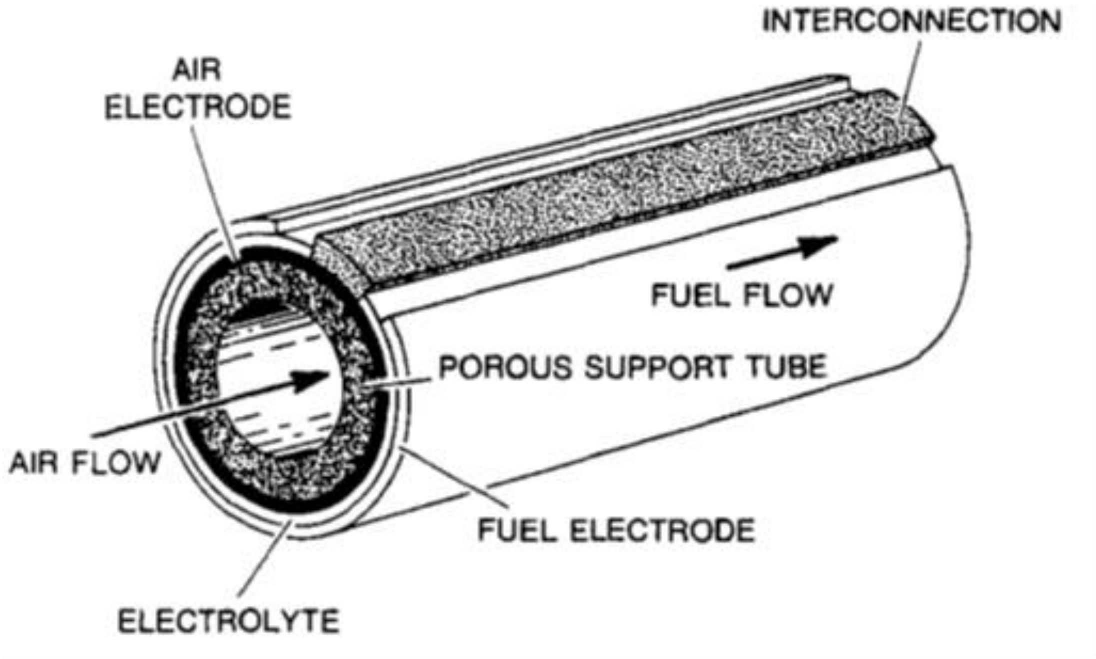

Figure 4; Westinghouse single cell tube arrangement. Source DOE Report: Isenberg, A. O., and W. Feduska, 'Solid Oxide Fuel Cell Power Generation System, the Status of Cell Technology : A Topical Report', (Washington DC: Department of Energy, 1984), p.3.

One possible reason for this change, suggested by wording in the report but never explicitly stated, was not only that the new LSM-based perovskite air electrodes demonstrated good electrochemical performance but that the also provided a better base for depositing the EVD electrolyte and interconnect layers, thereby making the cell easier to fabricate.[25] Further to this, being a single cell, there were vastly reduced numbers of materials interfaces and overlaps. With only a single strip of interconnect the majority of the surface was covered by the EVD-deposited yttria-stabilised zirconia electrolyte which Isenberg’s work had shown produced a high-

[23] Feduska, et al., "1981 Westinghouse Annual Doe Report".
[24] Ibid. p. 46.
[25] Ibid. pp. 56-60.

quality leak-free layer.[26] The immediate performance advantages of the single cell tube were expressed in the 1981 Annual Report to the Department of Energy when describing the open cell potentials observed when testing the first single cell tubes: “The cell showed one of the highest open cell potentials ever observed on a thin-film zirconia cell with an incorporated electrolyte.”[27]

The open cell potential, or open cell voltage as it is also known, is a very important number when describing SOFC performance. In a perfectly sealed system, this potential will attain a theoretical maximum, governed by the varying compositions of fuel on one side and oxidant on the other. The actual voltage is a measure of the electrochemical potential between the anode and the cathode of the cell, driven by the difference in the levels of oxygen contained in either the anode or cathode gases. It is this sensitivity to oxygen levels that has led to the widespread use of zirconia-based cells as oxygen sensors for various processes. Indeed, a number of senior figures in SOFC research started their work on oxygen sensors and it was also one of the initial applications for the technology that Westinghouse explored.[28]

This sensitivity to oxygen also means that the open circuit potential is a very sensitive measure of leakage in an SOFC system. In this sense, the open circuit potential became a principle measure of cell quality, through which the integrity and gas tightness of the ceramic layers would be described, with researchers aiming for as close to the theoretical maximum as they could. The wording of the quote above from the 1981 Annual Report relating to the single cell tube suggested that previous tests of multi-cell tubes had not approached the theoretical maximum and that there was potentially an ongoing issue with leakage across the interconnect regions and areas of the tube where cell layers overlapped. Further, the content of the future work section of this report discussed further development of the single cell tube and none of the future work tasks specifically mentioned segmented in series multi-cell tubes.[29] This again suggested that the promising results of the single cell tube began to take more prominent role in the minds and plans of the Westinghouse team. Indeed, over the early 1980s the single cell concept would become the central vehicle

[26] Two interview participants with good familiarity of this process talked of the high quality of electrolyte produced. Singhal Interiew and {Anonymous, 2021 #959
[27] Feduska, et al., "1981 Westinghouse Annual Doe Report", p. 56.
[28] Kilner Interview 30 Mar 22 Weissbart and Ruka, "Oxygen Gauge".
[29] Feduska, et al., "1981 Westinghouse Annual Doe Report", pp. 94-95.

for development with continued promising results allowing technical progress towards what would become the iconic tubular design synonymous with the Westinghouse SOFC programme.[30]

The move from the multi-cell to single cell tube, and indeed the move from the bell and spigot to the multi-cell thin-film a decade earlier, illustrate how materials properties and behaviours can have a causal effect in shaping the developmental history of a technoscientific artifact. Again, it is useful to draw on the work of Lécuyer and Brock, in particular their ideas around materialisation and the role of "contextual logics", in particular "materials logics", when considering historical accounts of technological development, discussed earlier in this thesis.[31] Applying the analytical framework of Lécuyer and Brock to this case, it could be considered that Westinghouse were beginning to consolidate around the local material logics of EVD and a single cell tube. These logics were in part formed from the constraints imposed by material compatibilities and the limitations of bulk ceramic processes of the 1950s and early 1960s and influenced decisions taken by the researchers on the Westinghouse team around both designs and fabrication methods. However, institutional environments also played a part, with the intellectual freedoms and resources afforded by the research centres of the large vertically integrated corporations allowing new techniques such as the EVD process to be pursued in ways that may not have been open to researchers in other institutional environments.

As the decade progressed, developments in processing elsewhere in the ceramics industry would gain the attention of SOFC researchers: these developments would bring new affordances to the researchers, allowing them to construct a new set of materials logics around SOFC fabrication. At the same time, changes in the organisation of R&D would bring a new set of "market logics" and, together with the changing SOFC "materials logics", would fundamentally change SOFC development and the way the technology was perceived within the wider energy landscape.

[30] Huang, K. and S. Singhal, 'Cathode-Supported Tubular Solid Oxide Fuel Cell Technology: A Critical Review', *Journal of Power Sources*, 237 (2013); Dollard, W. J. and J.T. Brown, 'Overview of the Westinghouse Solid Oxide Fuel Cell Program', in *Fuel Cell Seminar*, (Tucson, Arizona, 1986), pp. 28-31; Reichner, P. and J.M. Makiel, 'Development Status of Multi-Cell Solid Oxide Fuel Cell Generators', in *Fuel Cell Seminar*, (Tucson, Arizona, 1986), pp. 32-35..

[31] Brock and Lécuyer, "Digital Foundations: The Making of Silicon-Gate Manufacturing Technology"; Lécuyer and Brock, "The Materiality of Microelectronics".

Reagan Elected

In November 1980 Ronald Reagan was elected as the 40th President of the United States, consigning Carter to be a one-term president. Energy did not form a central part of the campaign, as Reagan refused to even acknowledge that there was an energy crisis: rather, Reagan's central campaign message was one of the reductions of government spending and bureaucracy.[32] This had significant implications for the Department of Energy, as it was singled out as an exemplar of extreme government spending and excessive bureaucracy, with Reagan standing on a platform of shutting down the department.[33] This was an idea which found some purchase with voters, as the DOE's actions during the 1979 oil crisis had not been well received in many parts of the country and it had been subjected to significant criticism from Republican quarters in Congress. In November 1980, Reagan appointed James B. Edwards, a former dentist and governor of South Carolina, as his new Secretary of Energy and when the administration took office in January 1981 he set about reorganising the Department of Energy.[34]

This latest reorganisation reflected the overall philosophy of the new administration to the role of the Department of Energy with respect to the development of energy technologies. Central to this philosophy was the belief that the role of government should be minimised with private industry and the "market" setting both the agenda and direction of technological development.[35] In keeping with President Reagan's campaign promise to reduce government spending various sections of the Department of Energy would see significant budget cuts. The Office of Fossil Fuel, which encompassed development of stationary fuel cells including the SOFC, saw its budget reduced from just under \$2 billion at the height of President Carter's programmes to produce synthetic fuels from US coal and oil shale at the turn of the decade, to just under \$500 million by 1983 when the new philosophies and policies of the Reagan Administration started to filter through.[36] From this

[32] Fehner and Holl, *Department of Energy 1977 - 1994: A Summary History*, p. 31.
[33] Ibid. p. 35; Gray, Peter, 'Will the Department of Energy Finally Stop Nuking America: Prospects for National Energy Reform', *Washington Monthly*, (1990), p. 23.
[34] Fehner and Holl, *Department of Energy 1977 - 1994: A Summary History*, pp. 31-35.
[35] Ibid. p. 33.
[36] National Research Council (US), *Energy Research at Doe, Was It Worth It? : Energy Efficiency and Fossil Energy Research 1978 to 2000 / [Internet Resource]*, p. 45.

budget, the fuel cells programme received annual funding of between $40-50 million which remained reasonably steady over the course of the 1980s.[37]

While spending was drastically reduced, the new administration still believed there was some place for government in the research and development of new energy technologies. It believed this place was to be focussed on new, high risk or long-term technologies where the market would show no interest in investing. However, the identification and definition of where the boundary lay between the longer term precommercial research, where the government would fund activity, and more commercially-oriented demonstrations, where industry should take the lead, would become a significant area of differing perceptions between the administration and Congress across the 1980s. This difference can be observed by looking at some of the Department of Energy requests for funding versus the larger sums that Congress felt should be appropriated. In the budget requests for the fiscal year 1985 (FY86) the Office of Fossil Fuel requested a total of $9.342 million across PAFC, MCFC and Advanced Concepts (which included SOFC) (the specific amount requested for PAFC itself was zero dollars), whereas the enacted budget from the House was $40,811 million, with almost $30 million eventually appropriated to PAFC.[38] Similar patterns existed for budget requests for FY86, with the House Appropriations Committee awarding $30.8 million more than requested, and in the following year for FY87 where the Office of Fossil Fuel requested a total fuel cell budget of just $5 million but the house committee intervened again and awarded $28.2 million.[39]

This disparity of funding was not just confined to fuel cells but was repeated across a wide cross-section of the energy R&D managed by the Department of Energy.[40] This mismatch between funding requested by the Department of Energy and that awarded by the House reveals a disconnect between the views of the Reagan administration and those of Congress of where the limits of federal funding for energy research should lie. While both the administration and Congress agreed to a large extent that longer-term, high-risk research, such as the fuel cell advanced

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[37] Ibid. p. 46.

[38] 'House Appropriations Committee Final Figures on Fossil Energy in Fy-86', *Inside Energy/with Federal Lands,* (1985).

[39] 'A Comparisonof Fy-87 Spending Levels for Doe Nuclear, Fossil Programs - Correction Appended', *Inside Energy/with Federal Lands,* (1986).

[40] "House Appropriations Committee Final Figures on Fossil Energy in Fy-86".

concepts, were appropriate for federal support, the administration was not in support of funding larger system demonstrations such as were currently underway with PAFC and MCFC.[41] From a 1985 report form the Congress Research Service, it appeared that despite the optimistic evaluations of some industry advocates, Congress agreed with a view that fuel cells were not yet ready for commercialisation and required further federal support.[42] This was at odds with the Administration who felt that private industry should be taking the lead in demonstration type projects and not looking to federal sources to take on the financial burden, which reflected the ideological foundations of the administration in looking towards market forces to deliver on what were essentially policy objectives, a central tenet of the Reagan administration.[43] The administrations views on these limits were highlighted in the response of Charles Cox, then manager of the Department of Energy's fuel cell programme, to the EPRI lobbying for federal funding of PAFC demonstrations at the 1987 American Power Producers Association (APPA) forum, where he replied that the "…government's role ends when the demonstrations start."[44]

While the sentiments expressed by Cox may have sounded good to a Reagan administration looking to reduce spend on energy technology development and some voices who were advocating a reduction of role of the state and increased roles for market forces in shaping this development, the rhetoric belied a misunderstanding of development practice. George Hall had understood just such a misunderstanding in his 1978 memo to Schlesinger criticising the Office of Management and Budgets (OMB) report on the ERDA budget requests of that year and the shaping the role of the then new Department of Energy. Responding to the OMB suggestion along precisely the lines of reducing government support to technology demonstrations, Hall was worried that reduction of this support failed to recognise the institutional and economic risks and uncertainties involved in such demonstrations and that

[41] Diamond, Stuart, 'A Rebound for Fuel Cells', *The New York Times,* (1984); 'Electric Utility and Gas Industry's Fuel Cell Models in Research Race', *Electric Utility Week,* (1985); Marshall, E., 'The Procrastinator's Power Source: The Fuel Cell Beckons in the 1990's Not Just with Cleanness and Efficiency but as a Way to Put Off Coal and Nuclear Investments', *Science,* 224 (1984).
[42] 'Crs Study Outlines Federal Action to Promote Use, Export of Fuel Cells', *Inside Energy/with Federal Lands,* (1985).
[43] Yaqub, *Winds of Hope*, pp. 304-306.
[44] 'Epri Seeks Financial Support to Build Fuel Cell Demonstration Plants', *Electric Utility Week,* (1987).

addressing these were also valid points for federal support.[45] It could be argued that Hall's fears are quite clearly borne out in the history of fuel cells where many system level demonstrations of numerous sizes have delivered various degrees of learning, but none have directly delivered a commercial product.[46]

However, despite the Reagan administration's push for the market to take the lead on these demonstrations, the market, or at least those actors which represented, market orientated companies and utilities, seemed less than willing to accept the responsibilities and the risks. This reluctance of the utilities to become involved in the development and demonstration of the PAFC was said by both the APPA and the EPRI to reflect the economic uncertainties of the technology, often focussed around the high costs, with previous demonstration programmes failing to show a clear pathway forward, leading to poor overall confidence in the fuel cell.[47] This waning enthusiasm of the utilities towards the fuel cell also need to be seen in the context of the wider energy context of the mid-1980s. Much of the interest in fuel cells around the late 1970s and early 1980s was as a direct consequence of the oil crises of the 1970s. Shortages of oil and spiralling prices of what was available had compelled various institutions to begin to investigate technological options which increased efficiencies of energy conversion or permitted uses of alternative fuel sources. The fuel cell was positioned as a prime candidate for such a technical fix to the crises. However, by the mid-1980s the crises were perceived as having passed, oil prices had dropped, and supplies were plentiful.[48] Therefore, the necessity to invest large sums of money into developing and demonstrating uncertain technologies had waned as existing energy technologies seemed to be meeting current needs.[49] This highlights the inherent short termism in systems governed by market forces. The prevalence of this short-term thinking is highlighted throughout this thesis, and it will

[45] Hall, "E.R.D.A. Energy R&D Budget - Memo to James R. Schlesinger (Seceretary of Energy, United States) ", p. 4.
[46] Fickett, "Fuel-Cell Power Plants"; Marshall, "The Procrastinator's Power Source: The Fuel Cell Beckons in the 1990's Not Just with Cleanness and Efficiency but as a Way to Put Off Coal and Nuclear Investments".
[47] "Epri Seeks Financial Support to Build Fuel Cell Demonstration Plants".
[48] Ritchie, H., P. Rosado, and M. Roser, "“Data Page: Oil Price - Crude Prices since 1861”, Part of the Following Publication: “Energy”. Data Adapted from Energy Institute. ', *ourworldindata.org [online resource]*, (2023) < https://ourworldindata.org/grapher/crude-oil-prices>; Podobnik, *Global Energy Shifts, Fostering Sustainability in a Turbulent Time*, p. 132.
[49] "Epri Seeks Financial Support to Build Fuel Cell Demonstration Plants".

be contended that it is a considerable limitation of relying on market forces to drive longer term developments and transitions, which has in turn, had a significant impact on fuel cell development over the decades.

New Policy Drivers Sustain Interest

While the perceived end of the energy crises was impacting the scale-up of PAFC, SOFC development was continuing apace at Westinghouse. The placing of the SOFC in the advanced concepts bracket of the fuel cell programme had to a certain extent insulated the technology from the attempted cuts of the Department of Energy. Further, the rationale for the SOFC was motivated by a different set of drivers compared to the PAFC. While the SOFC shared many similar attributes to the PAFC with respect to the prospect of delivering highly efficient energy conversion, the SOFC had remained more closely aligned to coal utilisation (as opposed to natural gas which had become the favoured potential fuel for PAFC).[50] The coal lobby remained strong in the US, with many states relying on coal extraction and utilisation as major drivers for their local economies.[51] However, increasing concerns around local air quality and acid rain was resulting in political pressure to act around emissions due to combustion of coal in power plants.[52] Therefore, finding cleaner ways to utilise coal in the generation of electricity, still the US's most significant primary energy reserve, remained a significant goal of the Department of Energy throughout the 1980s.[53]

These policy imperatives around coal favoured the Westinghouse SOFC project which, with the transition to the single cell tube was now beginning to make some tangible progress, so led the company to expand the programme. In 1984, the team had demonstrated a 400W stack consisting of 24 single tube cells arranged in

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[50] Appleby and Foulkes, *Fuel Cell Handbook*, p. 61.

[51] Byrd, Robert C, 'Expanding Our Use of Coal', *Byrds Eye View Collection 1981-1990*, (1983) <https://www.byrdcenter.org/uploads/6/7/8/7/67873389/bev-1981-1990.pdf>; Sheils, Merrill, William J. Cook, and Howard Fineman, 'Coals Future Burns Bright', *Newsweek*, (1980).

[52] Reinhold, Robert, 'Acid Rain Issue Creates Stress between Administartion and Science Academy', *New York Times*, (1982); Hoffman, David, 'U.S.-Canada Effort Set to Examine Acid Rain: Reaga, Mulroney Meet This Weekend', *Washington Post*, (1985); Burns, John F., 'Canada Is Not Placated by Reagan on Acid Rain', *New York Times*, (1987); Leary, Warren E., 'Reagan, in Switch, Agrees to a Plan on Acid Rain', *New York Times*, (1988).

[53] Siegel, Jack S., 'Coal Research in the United States', *Energy*, 11 (1986).

two 12 cell bundles, and in that same year they had also built and run a 5kW stack with a total of 324 cells.[54] It was the success of this 5kW stack which proved to be pivotal in the future growth of the Westinghouse SOFC programme. While approaches were made to the larger energy generation business units to promote the SOFC as a future technology, there was little if any enthusiasm from them. At that point, the few kilowatts produced from the SOFC just did not match with the 100s of megawatts that was the scale of large, centralised power generation plant, where the familiarity of those within the energy generation business units lay. The passing of the Public Utilities and Regulatory Policies Act (PURPA) by the Carter administration in 1978 is now recognised as a significant factor which would later result in the rapid growth of smaller distributed power generation of the 1990s.[55] However in the early 1980s it appears its implications had yet to enter the thinking of those in the large corporate energy machinery businesses, as they rather disparagingly dismissed smaller kilowatt scale systems of the SOFC as “little toys”.[56]

Nevertheless, the management of the Westinghouse research centre could see the potential for SOFC and in 1984 its vice president created what was termed an “internal technology venture”, a directed team with the goal of ensuring continued development of the SOFC system towards commercialisation.[57] This was to be run along similar lines to that which would be found in one of the larger Westinghouse business units with all the necessary functions required to take the technology forward.[58] This drew in personnel from across the research centre, representing many disciplines such as materials science, manufacturing, mechanical engineering, electrical engineering, systems development. In total approximately 80 people ultimately ended up under the umbrella of this venture.[59]

This expanding team led to some changes in management and leadership. In 1985 Subhash Singhal was appointed technical manager for the SOFC programme,

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[54] Dollard and Brown, "Overview of the Westinghouse Solid Oxide Fuel Cell Program"; Reichner and Makiel, "Development Status of Multi-Cell Solid Oxide Fuel Cell Generators".1986
[55] Hirsh, Richard F. and Benjamin K. Sovacool, 'Technological Systems and Momentum Change: American Electric Utilities, Restructuring, and Distributed Generation Technologies', *The Journal of technology studies,* 32 (2006).
[56] Singhal Interiew.
[57] Dollard and Brown, "Overview of the Westinghouse Solid Oxide Fuel Cell Program".
[58] Singhal Interiew
[59] Ibid.

with a team of around 40 people: the role was focussed on developing the materials and fabrication processes required for scaling up cell manufacturing, and improving testing methodologies to gain better understanding of cell performance.[60] Arnold Isenberg, who had been the technical driving force behind the initial work on the development of the tube and the electrochemical vapour deposition processes since the 1960s, while very much viewed as a technically excellent scientist, was not considered as well suited to the wider co-ordination and management roles required for steering the growing programme. Isenberg did however remain on the team in the position of senior scientist, allowing him a lot of intellectual freedom to further develop the processing and continue to make valuable contributions to the development of the Westinghouse SOFC concept.[61]

Singhal had joined the R&D centre at Westinghouse in 1971 after completing a PhD at University of Pennsylvania, where he studied thermodynamics of refractory metals using electrochemical cells with zirconia electrolytes.[62] At Westinghouse, he had worked on high temperature coatings for turbine blades again utilising zirconia-based films. He was therefore very familiar with both the physical and electrochemical behaviour of zirconia and had on occasion given advice to the SOFC team as they developed the processing techniques for the zirconia-based SOFCs. Singhal had also worked on the NASA/ERDA energy alternatives report, in the advanced turbine investigation rather than fuel cell analysis. However, through his work on the energy alternatives report and barrier coating for turbine blades, he had become familiar to many of the Department of Energy personnel and developed working relationships with several of them. He knew how the DOE systems worked and likewise was viewed by DOE managers as somewhat of a “known quantity”.[63]

Roswell Ruka, who had carried out the initial Westinghouse work into zirconia-based fuel cells in the early 1960s, also remained on the team, eventually being regarded as an elder statesman, and an inspiration to new engineers coming into the field. [64] Ruka remained with the SOFC team until the eventual closure of the project, when he was the longest serving member of staff across the whole of

[60] Ibid..
[61] Ibid.; Anonymous Interview 29th Apr 21
[62] Singhal, Subhash C., 'Fuel Cells and Me - No.33', *Journal of Fuel Cell Technology,* 20 (2020).
[63] Singhal Interiew.
[64] Anonymous Interview 29th Apr 21

Westinghouse (then Siemens Westinghouse) retiring in 2011 aged 88, with 49 years of service.[65] Colleagues from Westinghouse recall him as an archetypal scientist with his laboratory crammed full of different specimens, results of different experiments, some dating back decades.[66] An incredibly well-respected scientist, Ruka continually worked away in the background, where his extensive knowledge and experience proved to be invaluable in helping the continued development of the Westinghouse SOFC programme.[67]

As Singhal took over managing the team, one of his main roles was developing the Westinghouse SOFC programme from a laboratory exercise and set it on a path towards a commercial footing. The team at Westinghouse continued to forge close links with the Department of Energy, dealing directly with energy technology laboratories based out of Pittsburgh and Morgantown.[68] While the programme was managed out of the Morgantown laboratory, the close co-location of the Pittsburgh laboratory helped forge strong links between this laboratory and the Westinghouse team, further aided by the Pittsburgh Energy Laboratories focus on the development of processes for coal gasification.[69] Not only was this viewed as the most likely fuel for the SOFC: it also dovetailed nicely with larger Westinghouse and DOE partnerships on developing the coal gasification plant. In the early to mid-1980s, the Westinghouse tubular project had become the most established industrial-based SOFC project at that time, and therefore was an important learning opportunity for the DOE, However, there remained a considerable predisposition to thinking about the technology in terms of aiming for installations in the 100's MW size and larger, as this fitted with the existing, pre-PRUPA, US energy paradigm of large, centralised electricity generation.[70]

The successes of the stack tests in 1984 and 1985, in particular the 5kW test, had convinced the DOE to continue to invest in the SOFC. However, rather than the renewable two-year funding cycles which had been the norm since the resumption of

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[65] Crompton, Janice, 'Obituary: Roswell Ruka — Research Chemist for Westinghouse, Siemens', *Pittsburgh Post-Gazette*, (2020).
[66] Anonymous Interview 29th Apr 21
[67] Singhal Interiew
[68] Dollard and Brown, "Overview of the Westinghouse Solid Oxide Fuel Cell Program".
[69] Singhal Interiew
[70] Ibid.

the programme in 1976, the team at Westinghouse managed to convince the DOE to commit to a longer 5-year block running until 1989.[71] Although funds still had to go through annual appropriation hearings in Congress, this extended commitment allowed Singhal the latitude to go and hire new talent for the team from outside of Westinghouse. He embarked on a tour of universities, giving talks on the Westinghouse programme followed the next day by rounds of interviews.

From his knowledge that universities and colleges were not teaching fuel cells in their programmes and his wider appreciation of the limited reach of the field at that time, Singhal knew he was unlikely to find fuel cell or SOFC experts in his search. Shortages of scientists and engineers in certain specialist technical areas had been identified as an issue in national research and development plans. Over the course of the twentieth century and particularly after the end of the Second World War, physics had become the discipline of choice for bright, ambitious graduates, often to the detriment of recruitment and training in other disciplines. Although the apparent lead by the Soviet Union in space technologies, suggested by the launch of Sputnik and the orbital flight of Yuri Gagarin in 1957 and 1961 respectively, had focussed the attention of the US Government on the need to develop programmes in other areas such as materials science.[72]

Singhal drew on the prevailing culture of the corporate research centres from the 1960s and 1970s of bringing together the best people from the different disciplines that he knew he needed - ceramic materials, electrochemistry, fabrication and mechanical - and electrical engineering, and focussing them on the problems associated with developing the SOFC.[73]

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[71] Dollard and Brown, "Overview of the Westinghouse Solid Oxide Fuel Cell Program", p. 29., also Singhal Interiew.

[72] Skills shortages for energy conversion technologies are highlighted here, ERDA, 'A National Plan for Energy Research, Development, and Demonstration - Creating Energy Choices for the Future - Volume 1: The Plan', (Washington DC: ERDA, 1976).. The role of physics in shaping the American scientific community is detailed in Kevles, Daniel J., *The Physicists: The History of a Scientific Community in Modern America*, (Knopf : distributed by Random House, 2013). while Leslie, *The Cold War and American Science : The Military-Industrial-Academic Complex at Mit and Stanford*. discusses the increasing importance given to materials science across the Cold War. Against these trends Eisler, "Fuel Cell Research and Development and the Pursuit of the Technological Panacea, 1940-2005", pp. 182-183. describes how electrochemistry had become a rather neglected discipline which had declined in the postwar US.

[73] Singhal Interiew

The new five-year programme from the DOE provided a further $15 million of support which would bring the total funding for the decade of the 1980s to $28 million, which included $6 million indirect cost share from Westinghouse.[74] While these may seem like significant sums of money when taken in the wider context of energy technology development they were in fact relatively modest sums and belied the laboratory scale of the SOFC technology. Within this programme Westinghouse was aiming to further consolidate the design and materials set used in its tubular concept, formulate cost goals for market entry and continue scale-up of test modules from the existing 5kW towards 20kW and future designs of 200kW. To support this scale-up, Westinghouse was going to invest a further $5 million of capital spend to construct a mini pilot plant for improved fabrication capability.[75]

While DOE remained the most significant funder of the Westinghouse development, the company also attracted interest from the Gas Research Institute (GRI), a government funded non-profit organisation to support the gas utilities, who had for many years maintained an interest in distributed fuel cell systems running from the natural gas grid.[76] The GRI funded a 21-month, $2.6 million programme in 1985 to investigate the use of natural gas as a direct feedstock for the SOFC.[77] This programme signalled an important new direction for the SOFC, moving away from large, centralised power generation based on coal utilisation, towards cogeneration of heat and power based around the gas grid and reflected shifting attitudes towards smaller more distributed generation.[78]

New Actors, New Approaches

By the mid-1980s the Westinghouse Research Centre SOFC tubular concept was the main focus of Department of Energy support in this type of fuel cell which suggested

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[74] Dollard and Brown, "Overview of the Westinghouse Solid Oxide Fuel Cell Program", p. 29.
[75] Ibid.
[76] For the historical interest of the gas utilities and GRI (formally Institute of Gas Research) in smaller distributed systems see descriptions of the origins of the earlier TARGET program, Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*, pp. 85-90.
[77] Dollard and Brown, "Overview of the Westinghouse Solid Oxide Fuel Cell Program", p. 30.
[78] Abelson, P. H., 'Applications of Fuel Cells', *Science,* 22 (1990); Marshall, "The Procrastinator's Power Source: The Fuel Cell Beckons in the 1990's Not Just with Cleanness and Efficiency but as a Way to Put Off Coal and Nuclear Investments"; Carey, John, et al., 'Can Fuel Cells Light the Way?', *Newsweek,* (1984).

to many observers in the field that this was the most advanced SOFC design, certainly in the US, arguably in the world. However, other groups of researchers were also beginning to turn their interest towards the SOFC, with a number of these from outside the US. Further, as the DOE was focussed on the Westinghouse project, other US groups had to find funding from differing sources, which situated the technology within new contexts and agendas of energy futures outside of the large, centralised 100s of MW scale plant which had been the main context of US energy planning up until that time. These new contexts and agendas allowed for different approaches to the design and fabrication the SOFC which would in turn form the basis of a new set of narratives around the SOFC, that paralleled emerging agendas of energy based around deregulation, decentralisation and distributed generation.[79]

In the mid to late 1980s one such SOFC concept emerged from Argonne National Laboratory in the US and was known as the Monolithic Solid Oxide Fuel Cell (MSOFC). Argonne National Laboratory had been working on fuel cells for some time, although this was mainly on molten carbonate fuel cells. Their involvement with SOFC had, up until the mid-1980s, been through some contract management activities of the Westinghouse programme for the DOE.[80] Although, by the early 1980s, some researchers were beginning to view the costs and complexities of vapour deposition-based processing of the Westinghouse design as potentially problematic and began to explore other potential manufacturing routes which avoided the vacuum chambers and controlled atmospheres required for vapour deposition. They looked instead to processing methods where ceramic films could be deposited in air at ambient room conditions. These methods were based on what was known as “thick-film processing” and were perceived by some to offer a simpler and therefore cheaper, route to manufacture and scale-up of the types of ceramic layer required for the SOFC.[81]

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[79] Flowers, A and K Krist, 'Overview of Gas Research Institute R&D Program', *International Journal of Hydrogen Energy*, 12 (1987), pp. 672-673; 'Vaughn: Doe's Interest in Coal Use at Maodular Power Plants Increasing', *Inside Energy/ with Federal Lands* (1985).

[80] Interview with Nguyen Minh, Conducted by Author on 18th May 2021.

[81] Morse, T.F. and W.C. Seymour, 'Fabrication of Planar Solid-Oxide Fuel Cells : Report Prepared for the United States Department of Energy under Contract De Ac02 82ch10124', (Butte, Montana: Montana Energy Research and Development Institute, 1983), pp. 1-35.

Production of thick-films involved depositing fluid ceramic slurries across flat surfaces before drying them and then subjecting them to a high temperature heat treatment, known as firing, to form the final ceramic piece, which could be a self-supporting plate, or a film supported on a substrate. While thick-film manufacturing approaches would become a significant enabling technology in SOFC development and facilitated the rapid growth of the SOFC development community observed in the 1990s, it is important to capture the early emergence of these techniques in the mid-1980s as this began to establish the technological promises and challenges which would shape the course of SOFC development over the next decade.

Many of the designs for molten carbonate fuel cells featured large, flat porous ceramic plates which were used to contain the carbonate electrolyte when in the molten state. These were often made by the thick-film method of tape casting and as a result of this, researchers at Argonne National Laboratory had a familiarity with these techniques. This not only gave them a potential lead into this alternate method in the general manufacturing of fuel cells, but also an appreciation of the utility of thick-film processing for the manufacture of SOFCs.[82] One of the advantages of an SOFC based on a stack of flat plates (known across the SOFC community as a planar arrangement) is the very low levels of unused space within the volume of the stack, which allows higher electrical power to be generated for any give volume, resulting in a very compact system.[83]

SOFC systems are not defined purely by the cells themselves. Other important design considerations are electrical connections, sealing, and gas channels to allow reactants in and products out, all of which can complicate the design of the stack and reduce its actual compactness. Indeed, one of the significant factors for Westinghouse researchers adopting the single cell tubular design was in order to simplify sealing, both at the cell interfaces and for the stack level gas management, they described this as a “seal-less concept” but resulted in a system with a relatively

[82] McPheeters, C. C., et al., 'Fabrication of a Solid Oxide Fuel Cell Monolithic Structure', in *Fuel Cell Seminar,* (Tucson, Arizona: Courtesy Associates Inc., 1986), pp. 44-47.

[83] Fee, D.C., et al., 'Monolithic Fuel Cell Development', in *Fuel Cell Seminar*, (Tucson, Arizona: Courtesy Associates Inc., 1986), pp. 40-43.This expression of power density is known as “volumetric power density” relating to the overall physical size of the fuel cell stack, not to be confused with the electrochemical power density which refers to the watts per unit area generated at the cell electrochemical interfaces.

low packing density of individual cells.[84] In 1983, researchers at Argonne National Laboratory suggested what they called the "Monolithic Solid Oxide Fuel Cell, the purpose of which was to result in as compact and lightweight a system as possible.[85] In the design of the monolithic SOFC the researchers at Argonne proposed to build the electrical connection, gas channels and sealing into a single block using cast tapes. This block would then be fired in a single operation, offering the promise of fewer processing steps and therefore lower costs.[86]

The space taken up by the SOFC stack was generally of lower concern for designers of utility scale systems, such as Westinghouse, as they were eventually aiming for very large systems which would resemble industrial installations and cover significant areas of land. Therefore, Westinghouse's adoption of the single cell tube over the previous multi-cell tube, which resulted in a less efficient packing of the fuel cells, would have been seen as a lesser priority than the electrochemical performance advantages conferred by the new design.

By contrast, an SOFC based on the planar design offered the prospect of a more compact SOFC system, which began to reignite the interest of the military. When this compactness was also combined with the potential for multifuel capabilities promised by the high operating temperatures, the SOFC looked more likely to deliver the "miracle battery" the military had long sought through fuel cells.[87] Therefore, in the mid-1980s, the Department of Defense under the auspices of their research arm the Defense Advanced Research Projects Agency (DARPA) began to sponsor investigative work into the monolithic SOFC first, at Argonne National Laboratory and later at Allied Signal.[88]

The best way to imagine the monolithic SOFC concept is to think about a corrugated cardboard box, with corrugated layers sandwiched between flat layers resulting in a strong, robust structural component. The monolithic SOFC had a similar appearance, in that after tape casting, the layers of unfired and flexible ceramic tape could be formed into corrugated structures and then layered together

[84] Dollard and Brown, "Overview of the Westinghouse Solid Oxide Fuel Cell Program", p. 28.
[85] Steindler, M.J., et al., 'Chemical Technilogy Division Annual Technical Reoprt', (Argonne National Laboratory, 1985), pp. 1-181.
[86] Fee, et al., "Monolithic Fuel Cell Development".
[87] Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*, pp. 34-65.
[88] Minh Interview 18 May 21

with flat tapes to form the overall stack assembly, analogous to the cardboard box. The corrugations also formed natural channels which facilitated transport of fuel and oxidant to the anode and cathode respectively. Over the mid to late 1980s, researchers at Argonne, and later Allied Signal, worked to perfect the optimum arrangement of corrugations and flat plates, resulting in two main arrangements of cell layers and orientation of the corrugations. In the first, corrugated fuel cells were separated by flat interconnect plates. In the second, alternating layers of flat fuel cells and interconnects were separated by alternating structures of corrugated anode and cathode. In the first design all the corrugations ran in the same direction, this became known as the "coflow" design as both fuel and oxidant flowed in parallel. In the second design the corrugations of the alternating anode and cathode structures were arranged at right angles to one another, which resulted in the oxidant and fuel flowing perpendicular and was known as the "crossflow" design.[89]

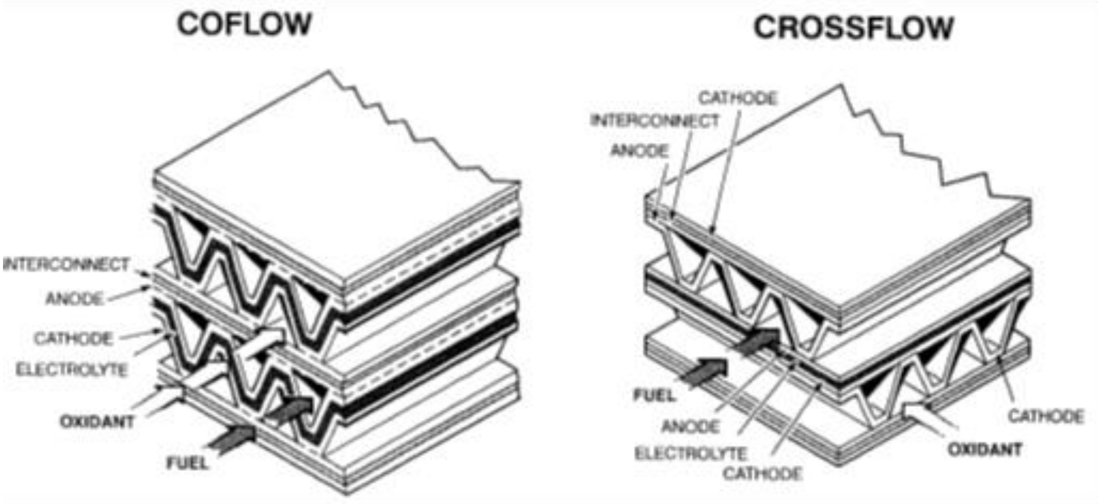

Figure 5; Allied Signal monolithic SOFC arrangements showing coflow on the left and crossflow on the right. Reproduced with Permission from Minh, Nguyen Q., 'Ceramic Fuel Cells', Journal of the American Ceramic Society, 76 (1993), 563-588, p578.

During this development the defence and aerospace company Allied Signal had reached an agreement with Argonne National Laboratory to continue the work on the monolithic SOFC concept towards potential commercialisation. Allied Signal had a significant development programme on high temperature ceramic heat

[89] Minh, Nguyen Q., et al., 'Forming and Processing of Monolithic Solid Oxide Fuel Cells', *ECS Proceedings Volumes*, 1989-11 (1989).

exchangers for aerospace applications and as such many characteristics, such as the need for multi-layer structures containing integrated gas channels, were shared between the two technologies.[90]

Allied Signal located their monolithic SOFC development within their Torrance facility in California, rather than at their main research centre in Los Angeles. This reflected where the company saw the positioning of the technology as the Torrance facility was focussed on military aerospace and space applications.[91] This facility was also home to the ceramic heat exchanger project and existing ceramics engineering group: however, as the ceramic heat exchanger was far closer to commercialisation than the MSOFC, the focus of this group was not fully in alignment with the needs of the MSOFC team, with the heat exchanger team being far more concerned with later stage product development rather than the more fundamental materials investigations which was still required for the MSOFC. Therefore, the majority of the skill sets which existed across the Torrance facility revolved around product, mechanical and systems engineering, and while these skills would be required to fully commercialise the MSOFC, they did not meet the immediate needs of the project.[92]

In a pattern that reflected the experience of the SOFC researchers in Westinghouse and would become familiar to other SOFC researchers in larger established energy engineering companies, the SOFC researchers at Allied Signal found themselves as a small group within a much larger organisation where the SOFC was not well understood. The wider company management were either trying to understand how this new technology fitted with existing products and developing markets, and whether it was a threat to be countered, an opportunity to be embraced, or a combination of these. This was frequently accompanied by a lack of appreciation of the development state of the technology. These factors often led to indecision over commitment and funding for the technology or the setting of unrealistic development and commercialisation targets and goals.

The drive to commercialisation reflected the changing landscapes of research management which, in the mid to late 1980s, saw company executives increasing the

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[90] Minh Interview 18 May 21.
[91] Minh, et al., "Forming and Processing of Monolithic Solid Oxide Fuel Cells".
[92] Ibid.

pressure on researchers to deliver commercial dividend on any R&D expenditure, superimposing shorter-term, profit focussed models onto research practice. The era of the large corporate Cold War research centre, with wide ranging intellectual freedom for employees to pursue longer-term, open-ended projects was coming to its end.[93] Fortunately for the team at Allied Signal, the manager of the ceramics group held a sympathy for their research position and allowed the team a great degree of latitude to pursue the research directions they felt most appropriate. Nevertheless, for those who had moved across to Allied Signal from Argonne to continue development of the monolithic SOFC, the move to a company setting, with the overall ethos and focus on commercial product development, was still quite a change from the more university-like environment at the National Laboratory in the mid-1980s.[94]

Despite considerable effort, the contradictions of the monolithic approach soon became apparent. The central tenet of the monolithic SOFC was to utilise a single high temperature heat treatment, processing all the stack layers in a single step. This created several problems for researchers. Some layers, such as the electrolyte and interconnect, were required to be free of any porosity, while others, such as the two electrodes, were required to remain porous. Further, the different materials which constituted the various layers reacted in different ways to the firing process, creating a difficult balancing act in engineering the different materials such that each layer possessed the desired properties related to its intended function.

Trickiest of all the layers was that of the interconnect, the layer which separated the oxidant and fuel between cells while connecting them electrically. This had to be constituted of a material that was stable in both the fuel and air environments, dense enough to prevent mixing of fuel and air, and also had to be electrically conducting to maintain the series electrical connection between the cells of the stack. The standard material for the interconnect in the 1980s was based around a lanthanum chromite ceramic, a semiconductor which exhibited adequate conductivity and was stable in both fuel and air environments. However, it was difficult to produce a high-density layer of this material in air, and the other option,

93 Mirowski and Sent, "Commercialisation of Science", p. 655.
94 Minh Interview 18 May 21

firing in an atmosphere containing low levels of oxygen, would be damaging to other cell layers.

This had not been an issue for Westinghouse as they deposited the layer using their EVD process in a separate process step.[95] For the researchers at Allied Signal and Argonne it was a potential showstopper. To attempt to overcome this problem, the research team at Argonne modified the chromite material to introduce additional chemical elements such as calcium that would react to enhance the firing behaviour in air, leading to better densification and a leak-free interconnect. This modification would change the existing materials logics which prevented the single firing step to be realised and allow all of the monolithic SOFC stack components to be fired together in the single step as originally envisaged.

While the addition of elements such as calcium did indeed improve the firing properties of the chromite, their presence led to other issues.[96] Due to their reactive nature, the additional elements proved to be highly mobile during the high temperature processing and would diffuse throughout the stack, accumulating at material interfaces where they resulted in deleterious effects, such as high resistances, leading to poor performance. Such contradictory effects highlighted the trade-offs between materials processing and cell performance, which have been at the heart of many of the trials and tribulations of SOFC development over the decades. Despite several years of effort over the second half of the 1980s and early 1990s, the teams at Allied Signal and Argonne could not find a solution to this problem. To sidestep these issues, researchers at Allied Signal would build on the learning of the tape casting process from the monolithic SOFC but begin to take their ideas of compact planar SOFC in another direction.[97]

As is often the case when attempting to develop advanced materials and processes for energy conversion technologies, the monolithic SOFC, while not in itself a success, laid important materials processing foundations for much of the

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[95] Singhal Interiew

[96] Myles, K. M. and C. C. McPheeters, 'Monolithic Solid Oxide Fuel Cell Development', *Journal of Power Sources,* 29 (1990), p. 318.

[97] Allied Signal Aerospace Corp., 'Monolithic Solid Oxide Fuel Cell Technology Advancement for Coal-Based Power Generation', (Torrance, CA: Allied Signal Aerospace Corp., 1992); Minh, Nguyen Q., 'Tape-Calendered Monolithic and Flat Plate Solid Oxide Fuel Cells', *ECS Proceedings Volumes,* 1993-4 (1993); Minh Interview 18 May 21

development of the 1990s.[98] The promise of the compact, high-power density SOFC stack remained an attractive technological goal and continued to pull in funding for Allied Signal both from the military and later from the Gas Research Institute (GRI). While working on the processing options for the MSOFC, Nguyen Minh, a researcher who had moved from the Argonne molten carbonate project to the Allied Signal SOFC development, led a team who established a tape rolling process, where laminated unfired tapes of anode and electrolyte layers were repeatedly rolled, each time getting thinner. This resulted in a thin layer of electrolyte supported on a thicker layer of anode forming what would become known as the “anode-supported cell”.[99]

Europe Takes an Interest

Curiosity in the SOFC was also beginning to blossom in Europe. Towards the end of 1986, Ulf Bossel, an engineer at the Swiss research centre of BBC, (Brown Boveri and Cie), the large Swiss energy conglomerate with an international portfolio of large energy systems, was given the task of finding out more about fuel cells, in particular the high temperature MCFC and SOFC.[100] In many ways, the BBC company shared many characteristics with Westinghouse. It was a large industrial corporation operating across many international markets, with a significant part of its business related to building and integrating equipment associated with large scale energy conversion and electricity generation, such as steam turbines. BBC operated across its various international markets as subsidiary companies under the Swiss parent.[101] In initiating his development of the SOFC, Bossel faced a similar problem to that of

[98] Similar stories can be seen in related electrochemical technologies such as the relationships between the processing and operation of beta-alumina and sodium sulphur batteries in the 1970s, where difficulties in processing led to poor performances; May, G.J. and S.R. Tan, 'Recent Progress in the Development of Beta-Alumina for the Sodium-Sulphur Battery', *Electochemica Acta,* 24 (1979). and Jones, I. W., 'The Sodium-Sulphur Battery', *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences,* 302 (1981). Like fuel cells these devices maintain a promise in applications in energy storage which sustains interest with recent researchers building on the foundation laid by the earlier work for example see Rudola, Ashish, et al., 'Commercialisation of High Energy Density Sodium-Ion Batteries: Faradion's Journey and Outlook', *Journal of Materials Chemistry A,* 9 (2021). and Fertig, Micha P., et al., 'From High- to Low-Temperature: The Revival of Sodium-Beta Alumina for Sodium Solid-State Batteries', *Batteries & Supercaps,* 5 (2022).
[99] Minh Interview 18 May 21
[100] Bossel Interview 28th June 22
[101] ABB, 'History of Abb', (2024) <https://global.abb/group/en/about/history>.

Singhal in the US; how to build a team to carry out the work? Again, like Singhal he found that he would need to hire people from differing disciplinary backgrounds, often not with direct fuel cell experience, to form a nucleus of talented scientists and engineers to produce the required knowledge from which to understand, fabricate and deliver an SOFC. Starting with a team of two people, initial small-scale results were promising, and the team grew to seven people by the end of 1987 and to 14 members by the end of following year. In addition to these researchers based in Switzerland, the group also collaborated with another BBC research team from the German subsidiary in Heidelberg.[102]

The team at Heidelberg was led by Franz Joseph Rohr, who had a considerable background in solid electrolyte electrochemical devices such as SOFC, electrolysis and sensors. In 1970, he had patented an early design of SOFC based around an ionically-conducting ceramic electrolyte disc, and contributed to the 1977 workshop on solid oxide fuel cells held at Brookhaven National Laboratory in the US, a meeting which drew together all of the significant US SOFC actors of the time.[103] In the Brookhaven paper, Rohr described a segmented tubular design of SOFC made up of separate fuel cell rings connect in electrical series, a design which shared many characteristics of the earlier Westinghouse “bell and spigot” concept.[104] However, this work did not appear to develop much beyond the 1970s with the focus turning to using the technology in the development of oxygen sensors.[105]

Although working together, there were tensions between the between the Swiss and German groups around the where direction setting lay, resulting in poor co-operation.[106] Rohr looked to consolidate on his previous experience and continuing to develop cell arrangements based around the segmented-in-series arrangement, similar to that trialled by Westinghouse in their original thin-film concept, but with some important differences. Whereas the Westinghouse concept

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[102] Bossel Interview 28th June 22
[103] Rohr, F. J., "Electric Battery Comprising a Plurality of Siries Connected Fuel Cells with Solid Electrolyte", US Patent Office, Brown Boveri & Cie, 1970; Harry, "1977 Doe Sofc Overview".
[104] Rohr, F. J., 'High Temperture Solid Oxide Fuel Cells: Present State and Problems of Development', in *Proceedings of the Workshop on High Temperature Solid Oxide Fuel Cells,* ed. by H.S. Isaacs, S. Srinivasan, and I.L. Harry (Brookhaven National Laboratory: US Dept of Energy, 1977), pp. 122-138.
[105] Rohr, F. J. and A. Reich, "Electrochemical Measuring Cell", US Patent Office, Brown Boveri & Cie, 1983., Bossel Interview 28th June 22
[106] Bossel Interview 28th June 22

was based around a cylindrical tube, the BBC concept was based around a rectangular tube. Also, rather than cells being deposited directly onto the tube, they were manufactured separately by the ceramic slurry-based "thick-film" techniques of tape casting and screen printing, before being attached to the tube in an arrangement that resembled roof shingles.[107] However, Bossel had been carrying out systematic analysis of both the ionic and electrical current paths in the different design arrangements of SOFC and had come to the conclusion that in the contemporary designs of segmented-in-series cells, and also the single tube of Westinghouse, the current paths were just too long, leading to electrical resistances which would limit the performance of the SOFC. In Bossel's opinion, these resistances were too high to be considered acceptable for a commercial system and a flat plate planar design with good electrical connection across the entire electrode faces was the only realistic option.[108] Despite offering suggestions on various options that he considered would improve the design, Bossel's proposals were not taken up and Rohr patented the design based upon the assembled "roof shingle" approach, underlining the tensions and difficult relations between the two groups.[109]

Bossel's work on the systematic analysis of the various resistive loss mechanisms of the cells was not wasted. In early 1990, the International Energy Agency set up a number of working group annexes to better understand the critical issues of advanced fuel cells. Covering various topics central to fuel cell development, Annex Two related to the modelling and evaluation of advanced solid oxide fuel cells. Now working as an independent consultant, Bossel continued to develop his systematic cell analysis as part of the SOFC micro-modelling activity. This would later be published as an output report from this project, known as *SOFC Facts and Figures,* a wide-ranging data book for SOFC phenomena and became a significant resource of knowledge and information for new SOFC researchers

[107] Rohr, F. J., "Fuel Cell System Including Porous Panel Type Support and Process for Producing the Same", US Patent Office, ABB Patent GmbH, 1992.
[108] Bossel Interview 28th June 22; Bossel, Ulf G., 'Comparative Evaluation of the Performance Potentials of Ten Prominent Sofc Configurations', *ECS Proceedings Volumes,* 1993-4 (1993).
[109] Rohr.

entering the field across the 1990s.[110] In recognition of the influence of Bossel's report, John Irvine, professor of Solid-State Chemistry at the University of St Andrews and Chair of the 9th European SOFC Forum held in 2010, brought together the keynote presentations from that meeting as a new *Facts and Figures,* in a tribute to Bossel's original report.[111]

BBC, now called ABB after a merger with ASEA (Allmänna Svenska Elektriska Aktiebolaget) in 1988, had withdrawn from SOFC development in 1989, but they were not the only large European energy machinery company with an interest in the technology. For a decade, German company Dornier had been investigating high temperature electrolysis, essentially a fuel cell running in reverse, to produce hydrogen. Their system was based on tubular systems with zirconia electrolytes as part of their "Hot Elly" concept and, being a segmented tubular array, appeared to draw heavily from earlier designs from Westinghouse and BBC.[112] In addition to the Dornier electrolyser project and the aborted work at BBC's Heidelberg facility, the late 1980s also saw development work getting underway at Siemens, another significant German power systems company. This time researchers were investigating SOFC systems based around a ceramic flat plate of zirconia as the structural element of the cell.[113] Consequently, by the late 1980s Germany had become a significant European actor in SOFC development. A catalyst for much of this work was the European Community's 1987 two-year project to carry out investigative work into the promise of SOFC. A significant focus of this effort was to investigate cost reductions via improved ceramic processing, with thick-film technologies being identified as a key route to accomplish this.[114]

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[110] Bossel, Ulf G. and Leo Dubal, 'Facts and Figures: Final Reoprt on Sofc Data', *Programme of Research Development and Demonstration on Advanced Fuel Cells Annex II, Modelling and Evaluation of Advanced Solid Oxide Fuel Cells*, ed. by International Energy Agency (Berne, CH: Swiss Federal Office of Energy, Operating Agent Task II, 1992).

[111] Irvine, John T. S. and Paul Connor, *Solid Oxide Fuels Cells: Facts and Figures: Past Present and Future Perspectives for Sofc Technologies*, (Springer Verlag London Limited, 2013).

[112] Doenitz, W and R Schmidberger, 'Concepts and Design for Scaling up High Temperature Water Vapour Electrolysis☆', *International Journal of Hydrogen Energy,* 7 (1982); Dönitz, W. and E. Erdle, 'High-Temperature Electrolysis of Water Vapor—Status of Development and Perspectives for Application', *International Journal of Hydrogen Energy,* 10 (1985).

[113] European Commission, 'Brite/Euram Programme : Synopses of Current Projects: 1990-1991,' (Publications Office. : Directorate-General for the Information Society and Media, 1992).

[114] Zegers, P., 'Status of Sofc Development in Europe', *ECS Proceedings Volumes,* 1993-4 (1993), p. 18.

This kernel of projects would form the catalyst for a significant growth in European SOFC development over the next 20 years, not only in terms of new research groups and companies but also in terms of the collaborative nature of European funding, which would be instrumental in fostering the development of a knowledge community around SOFC, a community which would grow rapidly across the US, Europe and Japan. While Westinghouse retained a position of technical leadership at the end of the 1980s, the coming decade would witness the wider adoption of new thick-film methods of processing based on ceramic slurries. This would drastically reduce the cost of entry into the world of SOFC research and development and open up the technology for a whole new range of actors.

The next chapter describes how SOFCs based on thick-film processing would emerge as the most significant cell architectures in the 1990s. The small, compact systems promised by such cells became instrumental in shifting the perception of the SOFC away from a singular vision of the technology as part of large industrial centralised generation systems and allowed it to be reframed within compact, distributed power systems. Such new imaginaries aligned with the emerging contexts of privatised energy, deregulated markets and entrepreneurial investors, where the large corporate R&D laboratory was no longer central to technoscientific knowledge production. Allied with the apparent successes of emerging digital technology investments, these interrelated contexts helped lay the foundations for the fuel cell hype seen in the second half of the 1990s.

Chapter 5: Thick-Film Processing: New Ways of Making - New Ways of Knowing

"It's just like making pizza dough"[1]

While the emergence of thick-film processing was introduced in the previous chapter, this chapter describes the considerable impact that these processing techniques had on reshaping the materials logics and development pathways of SOFC technology throughout the 1990s and into the early 2000s. I will further explore how these processing methods became established as the preferred way of making an SOFC and enabled the rapid growth of activity and formation of a technical community around the SOFC. I will also explore how new ideas of managing research and development, and an increasingly privatised and deregulated energy market, combined with wider shifts in energy contexts, repositioned the place and role of the SOFC and provided the conditions that helped to stoke the fuel cell hype at the turn of the century.

It was 1993 when I entered a laboratory at Edinburgh Napier University as a young PhD researcher to begin my own research journey. My supervisor was keen to engage in fuel cell research and I conducted an initial survey of the field, which suggested that the emerging the fabrication of solid oxide fuel cells utilising ceramic thick-films processing was a promising area. Due to the emergent nature and laboratory scale of this area of SOFC development, I felt it was an area where a young materials scientist with little support could still make a contribution. I was based in the Mechanical, Materials and Manufacturing Department, Napier which was also home to the "Scottish Electronics Manufacturing Centre" a consultancy-based research service for the then-buoyant electronics industry of the Scottish central belt. This industry had long utilised thick-film manufacturing and the Napier centre provided background knowledge into the many skills required for the transfer

[1] This phrase encapsulates how Wayne Surdoval of the US Dept of Energy SECA team attempted to portray the perception of simplicity attached to the tape casting and rolling processes which had been developed by Minh and his team over many years, David Talbot, 'A Practical Fuel-Cell Power Plant', in *MIT Technology Review*, (Cambridge, MA: Association of Alumni and Alumnae of the Massachusetts Institute of Technology, 2006).

of thick-film processing techniques to SOFC manufacture. As such, it provided a catalyst for my own research directions of trying to emulate the Allied Signal rolled anode-supported cell, but using the techniques of tape casting and screen printing rather than the rolling.

I obtained a screen printer from the Scottish Electronics Manufacturing Centre, an old machine which had been donated by the Hughes Electronics plant in Glenrothes. It signalled a cultural tie between researchers applying thick-film methods to the SOFC and the related processing methods of the electronics industry. Such connections to the electronic industry can also be seen in the other major thick-film technique, tape casting.[2] Both activities reflected advances in technoscientific capabilities and knowledges around processing of ceramics based around dispersion of fine powders.

Crucially, the thick-film processing techniques were a far cry from the large furnaces, vacuum chambers and reaction vessels of the Westinghouse labs. This meant cell manufacture was no longer the preserve of the large corporate research institute or capital-intensive laboratory and could now be accomplished by a single researcher in the corner of a lab with minimal funding. This change would have a significant impact on the growth of SOFC research as the shifting sands of science management, energy regulation, emerging markets and environmental awareness moved around it.

That I was able to engage with SOFC research in the early 1990s further highlighted the changing nature both of the SOFC field and the wider landscape of research and development management at that time. Neoliberal imperatives were becoming increasingly central in political thinking and policymaking, leading to increased levels of marketisation within the industrial research and university sectors.[3] The increased focus on market forces was resulting in a draw-down of the large corporate research centres epitomised by institutions such as Bell Labs which reached their zenith in the 1960s. The large monopolistic entities such as AT&T were split up and sold off as smaller entities focusing on specific market areas during the 1980s and 1990s, and a similar fate awaited the large associated research

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[2] Mistler, Richard E. and Eric R. Twiname, *Tape Casting Theory and Practice*, (Ohio, USA: The American Ceramic Society, 2000).
[3] Mirowski and Sent, "Commercialisation of Science".

institutions such as Bell Labs. The previous long-term research and development visions of these institutions were replaced by short-term thinking based on the direction of “the market”.[4] AT&T and Bell Labs were not alone in finding this transition difficult. Other large corporate players also found the move to an environment where the short-term returns of the market began to dominate commercial thinking to be troublesome, as the problems and eventual sale of the Westinghouse Power Division to Germany’s Siemens showed in 1996.[5]

Other landscape changes taking place that would also shape the positioning of the SOFC by various developers, specifically within energy, included the increasing realisation of the impact that ever-increasing amounts of carbon dioxide in the atmosphere was having on the climate of the planet. Increasing numbers of voices were suggesting that existing energy generation paradigms were unsustainable.[6] Fuel cells were seen by some as one potential technology that could become part of a lower emissions energy framework. High temperature variants, such as the molten carbonate fuel cell or the solid oxide fuel cell, were initially proposed as highly efficient energy conversion technologies within existing hydrocarbon frameworks, often as part of large, centralised installations.[7] The emergence of thick-film technologies to fabricate the SOFC along with changing energy markets allowed new sets of material and market logics to be constructed. These were based around reduced manufacturing and scale-up costs of smaller devices existing across imaginaries of distributed power generation and low carbon fuel frameworks. This allowed developers to begin to reframe the place of the SOFC within a changing energy landscape as a bridging technology which would help enable energy transitions.

[4] For an overview of the impact of this market-based thinking on Bell labs see Gertner, *The Idea Factory : Bell Labs and the Great Age of American Innovation*, pp. 330-338.
[5] Singhal Interiew
[6] 'Action Is Urged to Avert Globall Climate Shift', *New Your Times*, (1985); Lashof, Daniel A. and Dilip R. Ahuja, 'Relative Contributions of Greenhouse Gas Emissions to Global Warming', *Nature*, 344 (1990).
[7] Office of Coal Research (US), "Clean Energy from Coal Technology".

Thick Films: New ways of Making

The term “thick-film,” briefly introduced in the previous chapter requires some further explanation. It is something of a misnomer, as in absolute terms the films are still very thin. At their thickest, films may range towards half a millimetre while at the other end of their thickness spectrum thick-films may be of the order of a few hundredths, maybe a few thousandths, of a millimetre, far thinner than a human hair. By comparison, “thin-film” manufacture, as used in semiconductor-based electronics fabrication will often be thinner than one one-thousandth of a millimetre (one micron). While there may be some overlap in thicknesses between the thinnest of the thick-films and the thicker of the thin-films, what really defines a thin-film from a thick-film are the differences and details of the deposition processes and it was these differences which allowed the thick-film to take such a prominent and technology defining role in SOFC fabrication in the 1990s.[8]

In processing a thin-film, the ceramic layer is deposited onto a substrate material by condensation of elements from a mixture of gases containing the constituents of the desired ceramic as in the Westinghouse EVD process, or by an ion-induced evaporation of the required elements from a solid source, which then deposit onto the substrate in what is known as a sputtering process. In both cases, the final ceramic layer is grown directly from the condensing elements and to achieve this requires various combinations of controlled atmospheres, vacuum chambers and high temperatures, which all require complex and costly processing equipment and infrastructure. [9]

By way of contrast, thick-film processing revolves around suspending ceramic particles in a viscous liquid to form a slurry. Due to its fluid nature, a slurry may be deposited by a number of different techniques, such as casting, spreading, screen-printing or spraying, to form layers of differing thickness that can be either self-supporting or be supported by an underlying substrate. An important difference to the thin-film layer is that the slurry based thick-film layer requires additional high

[8] Carter, C. Barry and M. Grant Norton, *Ceramic Materials: Science and Engieering*, (New York: Springer, 2007), p. 494.
[9] Isenberg, A. O., 'Energy Conversion Via Solid Oxide Electrolyte Electrochemical Cells at High Temperatures', *Solid State Ionics*, 3 (1981), pp. 432-433; Carter and Norton, *Ceramic Materials: Science and Engieering*, pp. 494-505.

temperature processing, or “firing” to burn out the non-ceramic components of the slurry and coalesce the particles into a coherent ceramic structure.

The equipment required for thick-film processing and fabrication was on the surface reasonably straightforward: mills, blenders, mortar-and-pestles for mixing slurries: a smooth glass sheet and steel bar with an adjustable gap at the base for casting: and a furnace for firing the resulting layers. In all this was essentially only a slight step up from what one would find in a kitchen store, maybe a little more robust to deal with the abrasive ceramics and the furnace more than a little hotter than the average oven. Basically, the process was making smooth pastes spreading these evenly and “cooking” them. In fact, Wayne Surdoval of the US Department of Energy, when describing the tape casting and rolling process pioneered by Allied Signal, was reported as likening it to making pizza dough.[10]

That these deposition processes could be carried out at room temperature and ambient pressures with “cheap and simple” equipment kindled notions of rapid routes to scale up with would result in a mass manufactured cost-effective device. Such perceptions were reinforced when similarities were drawn with the widespread application of related thick-film techniques supporting the electronics industry.

After the earliest developments in the late 1940s and continued work in the 1960s, thick-film approaches to ceramic processing first began to find traction across the electronics industry in the 1970s and 1980s. This related to improved synthesis of fine ceramic powders, better understanding of the behaviour of fine particles, and new instruments, such as laser scattering, to quantify and monitor particles in suspension.[11]

Much of the historical focus around the emergence of the electronics industry has been on the semiconducting transistor, arguably the key piece of technology that enabled the solid-state microelectronics revolution.[12] Notwithstanding this attention on the transistor, it is still only one piece in a larger array of electronic components

[10] David Talbot, "A Practical Fuel-Cell Power Plant".
[11] Howatt, G. N., R. G. Breckenridge, and J. M. Brownlow, 'Fabrication of Thin Ceramic Sheets for Capacitors', *Journal of the American Ceramic Society*, 30 (1947); Mistler and Twiname, *Tape Casting Theory and Practice*, pp. 4-5; Kendall, "History", p. 38.
[12] For examples of histories focussing on semiconductor development see Berlin, *The Man Behind the Microchip: Robert Noyce and the Invention of Silicon Valley*; Lécuyer, *Making Silicon Valley : Innovation and the Growth of High Tech, 1930-1970*; Riordan and Hoddeson, *Crystal Fire*.

which make up the circuitry of microelectronics. Much less attention has been given to other ceramic-based electronic materials, such as resistors and capacitors, which were just as important within the circuit boards that were part of the complex electronic systems within emerging military, aerospace or computing hardware. These materials were incorporated into Multi-Layer Capacitors (MLC) and Multi-Layer Ceramic Packages (MLCP), which formed essential components in microelectronic circuitry. Often manufactured via thick-film processes, their fabrication had developed into multi-billion-dollar industries in their own right, and as, such were beginning to attract their own research interest.[13]

The increasing interest in thick-film processing was demonstrated in 1975 when the *Tenth Annual University Conference in Ceramic Science* focussed on the issues around thick-film processing, in particular “ceramic processing before firing”.[14] Around 200 delegates attended this conference representing academia, the US National Laboratories and industry, including several participants from the Western Electric Company, the manufacturing arm of AT&T, responsible for taking many of the laboratory breakthroughs of Bell Labs from the lab towards mass production and commercialisation.[15] The focus of the conference and the number and range of delegates attending suggested a growing importance placed on components manufactured by thick-film methods to the continued development of microelectronics.

The focus on processing before firing also revealed the emergence of the understanding in the importance of how the characteristics and flaws in the unfired ceramic are carried through to the final ceramic where they affect performance. It was improved understanding of the relationships between the fired and the unfired ceramics that allowed for steady improvements in the quality of thick-film processing across the 1970s and 1980s. While improved thick-film electronic

[13] Mistler and Twiname, *Tape Casting Theory and Practice*; Trotter, Donald M., 'Capacitors', *Scientific American,* 259 (1988); Hyatt, Edmond P., 'Making Thin, Flat Ceramics - a Review', *American Ceramic Society bulletin,* 65 (1986); Carter and Norton, *Ceramic Materials: Science and Engieering,* p. 488.

[14] Onoda, George Y. Jr. and Larry L. Hench, 'The Science of Ceramic Processing before Firing: Conference Report on Tenth Annual University Conference on Ceramic Science', (US Army Research Office, 1977).

[15] Leslie, Stuart W., 'Blue Collar Science: Bringing the Transistor to Life in the Lehigh Valley', *Historical Studies in the Physical and Biological Sciences,* 32 (2001); Riordan and Hoddeson, *Crystal Fire*.

components provided one driver towards improving the quality of ceramic powders, engineers in other disciplines, such as aerospace, automotive and medical applications, were also turning towards improving the properties of ceramics so they could be used as components which could counter the ever more aggressive and demanding environments and operational conditions seen across applications in these disciplines.[16]

Much of this improvement revolved around the elimination and control of agglomerated particles, clumps of powder, that led to flaws in the final ceramic. This is reflected in the many papers on grinding and milling, the use of improved slurry additives, and the interaction of very fine particulates with the fluids in which they were suspended. New methods of producing such fine particles from solution, or other chemical routes, also formed an important part of the ongoing research of this community.[17] These new, fine particles were critical in providing new affordances around processing which were not available with earlier bulk powders. These earlier powders were physically crushed from larger ceramic grains and did not have the reproducibility or consistency of the newer solution and chemical powder production routes. It was these limitations in quality of bulk powders that had constrained the practicality of the initial bell and spigot designs of Westinghouse, creating a set of material logics which in turn moved the Westinghouse team towards vapor deposition processes. The new solution and chemical routes to powder manufacture opened up a new set of logics, in which suspensions of fine powders could be used to manufacture high quality ceramic films which approached the quality of those deposited by vapour deposition.

It was not just the quality of the films that were important but also the thickness ranges that could be deposited. The slurry methods provided fabrication routes to a range of layers thicknesses that would not be practical to produce by vapour deposition routes, in turn this had led to a new range of electrical products such as multilayer capacitors, resistors and flat plate ceramic substrates which

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[16] Westwood, Albert R.C. and Stephen R. Winzer, 'Advanced Ceramics', in *Advancing Materials Research*, ed Peter A. Psaras and H. Dale Langford (Washington, D.C.: National Academy Press, 1987), pp. 225-244; Marsh, Peter, 'Minerals Come into Their Element', *Financial Times*, (1986); Broad, William J., 'New Ceramic Compounds Set for Major Technology Role', *The New York Times*, (1984).
[17] Onoda and Hench, "Ceramics Processing before Firing".

became important commercial products in their own right.[18] A further indication of the importance of both this conference and the research discussed at it was that after the conference the papers were collected into an edited volume published by Wiley and Sons in 1977.[19] This book became an important reference to many researchers looking to incorporate thick-film processing as a means to manufacture SOFCs.[20]

The need for the conference, the range of topics discussed, and consequent book also suggest a level of complexity in the processing that would arguably not be apparent from the way thick-film techniques were often portrayed, described and promoted. Often described with terms such as “simple”, “inexpensive” and “scalable,” thick-film technologies were commonly described in direct opposition to the complex and expensive perception of thin-film processing with its need for controlled atmosphere chambers and other high-end infrastructure.[21] Scrutiny of the conference topics shows that much of the complexity of the process was not linked to any of the deposition processes. In the main, the tape casting or screen processes were in themselves, as straightforward as advertised. It was the relationships between the powders and fluids that constituted the ceramic slurries and how these interacted during the processing was where the complexity lay. Indeed, it could be argued that the quality or success of any given ceramic layer was determined long before the slurry got anywhere near the deposition equipment.

Understanding the relationship between the particles and the fluids they were suspended in was at the heart of controlling the quality of the final ceramic layer. Key factors in this relationship were the size and size distribution of ceramic particles to be used, and the related measure of surface area, as these influenced how the particles would move and interact in the fluid which would in turn determine how the slurry would flow when being printed, cast or sprayed. As particle size and distribution varied between batches of ceramic powder, so the flow behaviour of the

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[18] Trotter, "Capacitors"; Westwood and Winzer, "Advanced Ceramics", pp. 240-241; Carter and Norton, *Ceramic Materials: Science and Engieering*, p. 488.
[19] Onoda, George Y. Jr. and Larry L. Hench, *Ceramic Processing before Firing*, (New York: Wiley, 1978).
[20] McPheeters, et al., "Fabrication of a Solid Oxide Fuel Cell Monolithic Structure", p. 46; Cassidy, Mark, 'The Production of Solid Oxide Fuel Cells with Anode Supported Screen Printed Electrolytes', (Edinburgh Napier University, 1997), pp. 136-142.
[21] Carter and Norton, *Ceramic Materials: Science and Engieering*, p. 481; Mistler and Twiname, *Tape Casting Theory and Practice*, p. 3; Minh, "Ceramic Fuel Cells", p. 579.

slurry would vary. These slurries also exhibited complex flow behaviours (rheology) not only increasing or decreasing viscosity with changing addition levels of ceramic particles, but also changing viscosity as forces were applied to the slurry, such as when being forced through the apertures in a printing screen. Further to this, was the potential for the presence of agglomerated particles in the slurry. If agglomerates were present, they again changed the flow characteristics, and caused flaws in the final film, leading to a pinhole or crack which could seriously degrade the quality and performance of the final ceramic. Therefore, a significant proportion of the papers at the *Tenth Annual University Conference in Ceramic Science* were focussed on understanding the nature of the forces causing particles to agglomerate together, developing strategies to prevent any clumping during the processing and investigating effects on the rheological behaviour of a slurry.[22]

The effect of all of these interrelated variables resulted in slurries with highly complex sets of behaviours which were not only difficult to predict from first principles, but were also unique to the specific set of powders and fluids being used. It required researchers to become skilled in an appreciation of how these variables interacted and changed slurry behaviour, not only when, for example, using a powder from a different manufacturer, but even when moving to a new batch of powder from the same manufacturer.[23] The impacts on slurry behaviour induced by the changing variables were not something that could be easily quantified. Over the decades there have been many attempts to create mathematical models to predict effects of changing the size distribution or amount of powder in a slurry, but such were the number and nature of the assumptions made within the construction of a model system that it often struggled to match the observed behaviour.[24] Trying to improve

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[22] Onoda and Hench, "Ceramics Processing before Firing".
[23] Again, I draw on my own experiences here. When working in industrial level SOFC development and moving to create larger batches of slurry with repeatable and reliable behaviour, moving to a new batch of powder could result in very subtle changes in a property such as particle size distribution or surface area which were enough to have deleterious impacts on not only the ink flow behaviour but also the final integrity and performance of the layer in question.
[24] For example see Brady, John F. and Georges Bossis, 'The Rheology of Concentrated Suspensions of Spheres in Simple Shear Flow by Numerical Simulation', *Journal of Fluid Mechanics,* 155 (1985); Russel, W. B., 'Theoretical Approaches to the Rheology of Concentrated Dispersions', *Powder technology,* 51 (1987).

understanding of these complex interactions remains an active research topic within groups working across various types of concentrated suspensions and soft solids.[25]

To overcome these difficulties, the researchers who developed thick-film processes for the SOFC relied heavily on empirical observation, developing practical experience of the materials and systems that they worked with. It could be argued that this tacit, undocumented knowledge was analogous to that of the craft artisan, where knowledge and knowhow was not something that could be learned from a book, rather it required many hours of practice and application to come to know and understand the materials and anticipate their behaviour. It could be proposed that the practitioners of thick-film processing worked between Ingold's two differing worlds: the material world, defined by a materials properties, objective, predictable, generalisable, and the world of materials, more subjective, more open to interpretation, with closer links to place and person.[26] In the latter, the researcher must gain a tacit knowledge of the materials system with which they are working, as Ingold suggests: " a knowledge born of sensory perception and practical engagement", resulting in a "skilled practitioner participating in a world of materials".[27]

This tacit way of knowing of this world of materials meant skills were often learnt by practice, by trial and error. It also placed emphasis on community. Informal communication between peers and mentoring of newer researchers by more experienced colleagues all became important conduits of knowledge transfer. It therefore helped create the culture of information exchange across the emerging SOFC technological community. While researchers did not give away specific "trade secrets", more general conversations around wider issues did take place, whether within formal conference presentations or discussions over coffee. This was not something that was unique to SOFC or even fuel cells. As Ann Johnson noted in her study of the development of ABS braking in cars *Hitting The Brakes*, such tacit transfer and exchange of knowledge, knowhow and ideas can be observed in many

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[25] Clegg, Paul S., 'Characterising Soft Matter Using Machine Learning', *Soft Matter,* 17 (2021); Chen, Daniel T.N., et al., 'Rheology of Soft Materials', *Annual Review of Condensed Matter Physics,* 1 (2010); Morris, Jeffrey F., 'A Review of Microstructure in Concentrated Suspensions and Its Implications for Rheology and Bulk Flow', *Rheologica Acta,* 48 (2009).
[26] Ingold, "Materials against Materiality", pp. 13-14.
[27] Ibid.

knowledge communities, often challenging notions around the protection of proprietary or privileged information.[28] Johnson highlights, an important part of this movement of knowledge was the exchange of information: there had to be a two-way flow of either ideas or knowledge. In the case of proprietary or sensitive information, Johnson likened this to a game of poker with participants gaming the value of information released against the value of information likely to be received.[29]

In the SOFC community the specificity of ceramic powder properties allied with their highly variable effects on slurry behaviour helped engender conditions for just such exchanges. It was quite possible for SOFC researchers to discuss the influences of changing, say, particle size distribution on the behaviour of a slurry without revealing their organisation's specific particle size distribution or the exact chemical composition of their electrode. It was well understood across many SOFC thick-film researchers that the devil was in the detail: it was one thing to have knowledge of the components of a slurry, but it was a different thing entirely to be able to make and utilise that slurry purely from knowledge of the components. The order of addition of the components, the exact mixing times, the exact mixing speeds, resting times between process stages, were all critical to result in producing a slurry that could be deposited as a high-quality film. Even transferring a process between the laboratories of closely collaborating groups where there was complete and open information exchange was found to be a difficult task, as slight variations in equipment or environments between the two locations could all impact the success of the process transfer.[30] Awareness of these difficulties therefore allowed researchers to discuss effects and observations of thick-film processes in relatively fine detail, but at the same time remaining confident that a potential competitor could not simply run off and replicate the process.

This relationship of the thick-film processing with both the person and place through the acquired skills of the individual, was an important aspect in shaping the culture of the knowledge community around the SOFC and therefore it could be argued that by placing thick-film processes within Ingold's ideas of his "world of

[28] Johnson, *Hitting the Brakes: Engineering Design and the Production of Knowledge*, pp. 137-155.
[29] Ibid. p. 144.
[30] Price, Robert, et al., 'Upscaling of Co-Impregnated La0.20sr0.25ca0.45tio3 Anodes for Solid Oxide Fuel Cells: A Progress Report on a Decade of Academic-Industrial Collaboration', *Advanced Energy Materials,* 11 (2021), pp. 18-19.

materials" imbued it with a high degree of materiality.[31] This new way of making also changed wider perspectives of the way the SOFC was viewed as a device, through the processes by which it was made and the places in which it was made. In this respect, this new way of making was an instrumental part in the reimagining of the SOFC that took place across the 1990s. It took the SOFC from the large corporate R&D centre to the workshop of the small entrepreneur or start-up company, and from established concepts of the central generation facility to ideas and promises of distributed generation, even individualised generation in the basement of a house. In both the large Westinghouse tube and the planar thick-film cell, the materials were broadly very similar. What set them apart was the way of making the device, which in turn led to a new way of knowing the device.[32]

A Community Establishes

From his involvement in managing the materials and technology programme of the Westinghouse SOFC development effort, Subhash Singhal had significant engagement with many of the collaborative SOFC system demonstration projects that Westinghouse was undertaking, both across the US and further afield in countries such as Japan. This collaborative work convinced Singhal of the need for a forum for discussion, where scientists and engineers with an interest in SOFC technology and systems could come together and discuss the specific issues facing them. Although there were other fuel cell conferences, such as the *Fuel Cell Seminar*, which had been running since the mid-1970s, or *The Grove Symposium*, running from the late 1980s, these meetings covered all types of fuel cell. Singhal felt that that these did not provide a suitable platform for the in-depth technical discussion he felt was required to allow scientists, engineers and developers of the SOFC to make progress.[33] There were SOFC-specific meetings, such as the regular Department of Energy SOFC contractors' meetings, but as these were often related to national development efforts they were not always open to external participants and

[31] Ingold, "Materials against Materiality"; Ingold, "Writing Texts, Reading Materials. A Response to My Critics".
[32] Pickstone, *Ways of Knowing : A New History of Science, Technology and Medicine*.
[33] https://www.fuelcellseminar.com/past

lacked a truly international dimension. What he felt was required was some form of regular international gathering, where SOFC researchers could come together in a collegiate spirit to discuss the current issues surrounding SOFC and present progress made in addressing these.[34]

Singhal approached the Electrochemical Society (ECS), the US based umbrella organisation in the representing the professional interests of scientists and engineers engaged across the wide-ranging discipline of electrochemistry, about setting up an international SOFC symposium. To ensure internationality, he also invited the SOFC Society of Japan to co-sponsor and suggested the meeting rotate between locations in the US, Japan and Europe.[35] Singhal also looked at getting some co-sponsorship from a European organisation, but he could not identify a central learned type institution with a focus on electrochemistry, such as the ECS, for Europe.[36]

It may seem counterintuitive that when looking for a home for a conference series for a device which so heavily steeped in materials science and technology that Singhal approached the ECS rather than say The Materials Society (TMS) however it makes sense when the functionality of the device is considered, that of an electrochemical energy converter. While the chemistry and processing of materials is central to a properly performing SOFC, the assessment of the merits of this performance is discussed in the language of the electrochemistry. Discourse around performance would often revolve around terms such as “open circuit voltage”, “area specific resistance”, “current density”, “voltage degradation”, and while materials related properties such as porosity, adhesion and coefficient of thermal expansion were vital to a functioning SOFC these were discussed with respect to optimising electrochemical parameters.

Terms such as the open circuit voltage described in Chapter 3, often described complex interrelated relationships as a single number. This embodied what Latour described as an inscription device, a shorthand way for actors in the field to describe and compare the different objects which they have fabricated, and the first

[34] Singhal Interiew
[35] The SOFC Society of Japan, was originally founded in 1988 as a sub-group of the Electrochemical Society of Japan. It served as a forum for the growing numbers of scientists and engineers who were engaging in SOFCs as the field grew across the late 1980s.
[36] Singhal Interiew

step in defining the performance of a cell.[37] Several graphical inscription devices also existed in SOFC discourse, from current voltage curves to AC impedance arcs all embedded complex information about the performance of the cell and the relationships between the materials within it. Similar to the open circuit voltage, these were often couched in the language and discourse of electrochemistry. This positioned the SOFC within an electrochemical community, a positioning further reinforced by some of the early significant communications around high temperature solid-state electrochemical devices being published in the *Journal of the Electrochemical Society*.[38]

This was not to say that other materials focused societies ignored the SOFC. For example, the American Ceramic Society has had a long association with communicating SOFC developments having a well established symposium session withing their annual conference on advanced ceramics and composites, and Minh's classic 1993 review paper which appeared in the *Journal of the American Ceramic Society*.[39] However in many of these cases a significant mode of discourse around performance remained the language of the electrochemist, which suggested the ECS as being a good home for any SOFC focussed conference series.

Singhal's suggestion for a conference was well received by both the ECS and the SOFC Society of Japan and in October 1989 the *First International Symposium on Solid Oxide Fuel Cells* convened as part of the *179th Meeting of the ECS* in Hollywood, Florida.[40] This meeting consisted of around 50 delegates with 39 papers presented. As it turned out, the Electrochemical Society, although based in the US, was an international organisation with many European members. As such, European authors were well represented at this event and the ECS became the institution through which meeting announcements conference organisation and publication of proceedings were co-ordinated. Since then, the co-sponsorship with the SOFC

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[37] Latour, *Laboratory Life : The Social Construction of Scientific Facts*.
[38] Kiukkola and Wagner, "Measurements on Galvanic Cells Involving Solid Electrolytes"; Weissbart and Ruka, "A Solid Electrolyte Fuel Cell"; Tedmon, C. S., H. S. Spacil, and S. P. Mitoff, 'Cathode Materials and Performance in High-Temperature Zirconia Electrolyte Fuel Cells', *Journal of The Electrochemical Society*, 116 (1969); Bacon, Francis T., 'The Fuel Cell: Some Thoughts and Recollections', *Journal of The Electrochemical Society*, 126 (1979).
[39] Minh, "Ceramic Fuel Cells".
[40] Singhal, Subhash C., 'Preface', in *Proceedings of the First International Symposium on Solid Oxide Fuel Cells*, ed. by Subhash C. Singhal (Hollywood, Florida: Electrochemical Society, 1989), p. iii.

Society of Japan has remained and all of the meetings have been co-chaired by Singhal and at least one representative from Japan.[41]

The *First International Symposium on SOFC* marked the start of what would become one of the most significant gatherings of SOFC scientists, engineers, developers and policymakers. Meeting every second year, the conference rotated across various venues in the US, Europe and Japan as first envisaged by Singhal. Over the course of the 1990s and into the 2000s the conference would continue to grow. By 1999, the number of papers had more than tripled to almost 150 and in 2015, at the 14th Symposium, over 500 participants attended, with over 400 papers presented across three parallel oral sessions and a further three accompanying poster sessions.[42]

In the mid-1990s, the Singhal's ECS symposia was joined by the *European SOFC Forum*. This was the creation of Ulf Bossel, who was working as an independent consultant after leaving ABB when their SOFC programme was cancelled in the late 1980s. Like Singhal, Bossel was frustrated at the lack of opportunities for in-depth technical discussion among those working in SOFC technology that he felt was essential if knowledge in the field was to be constructed and advanced.[43] At the *Third Grove Symposium*, held at Imperial College London at the end of September 1993, Bossel distributed a short questionnaire around the delegates to gauge support for his idea of a European meeting focussed on the science and technology of the SOFC. Again, like Singhal, he found his suggestion was well received, representing both the general increase in interest in the technology and a growing European contingent of researchers and developers moving into this space.[44]

[41] Minh, Mizusaki, and Singhal, "Advances in Solid Oxide Fuel Cells: Review of Progress through Three Decades of the International Symposia on Solid Oxide Fuel Cells", p. 73.
[42] Ibid. p. 65.
[43] Bossel Interview 28th June 22
[44] As well as the interview I conducted with Bossel, I also draw on my own memories here. I attended the 3rd Grove Symposium where Bossel distributed his questionnaire, as one of a number of new researchers in the field of the SOFC I filled it in with a positive response and later would present a paper on my doctoral research to the first forum a year later, see Cassidy, Mark, Gordon Lindsay, and Kevin Kendall, 'Production of Ysz Based Planar Solid Oxide Fuel Cells with Operating Temperatures of 750-800c by Thick-Film Methods', in *First European SOFC Forum*, ed. by Ulf G. Bossel (Lucerne, Switzerland: European Fuel Cell Forum, 1994), pp. 577-586..

In October 1994, participants gathered in Lucerne Switzerland for the 1st European SOFC Forum. This took place in a medium-sized hotel ballroom with around 100 attendees. Again, like the ECS meeting, the European Forum quickly became established on the calendar of SOFC actors, attracting representatives not just from Europe, but also from the US, Japan and further afield. Initially, Bossel also moved the meeting around various locations, although in this case always European. However, this created some frustration for Bossel. He wanted the event to have a strong sense of identity and felt the shifting venues diluted this. Therefore, the fourth forum returned to Lucerne, now housed in the large and impressive KKL conference centre on the lakeshore, where it remains to this day, featuring hundreds of participants and papers over parallel sessions.[45]

While having two such conferences, both focussed on the science and technology of the SOFC may have created issues around competition and split potential attendees between them, Singhal and Bossel ensured that each meeting ran every two years and that they alternated. This provided a meeting every year where SOFC actors could gather to discuss the latest issues arising in SOFC development and could debate potential solutions to these issues.[46] Bossel also suggested that he felt the two meetings had developed slightly different identities, with the European Forum focused more towards systems development, and the interfaces of science, technology and engineering towards the creation of a commercial product, whereas the ECS symposium focused more around the materials development.[47] While there may be some merit in Bossel’s description of this differentiation, reviewing the papers published and through my own experiences at these events, it was clear there was a significant overlap in both content and participants at both meetings.[48]

In practice, this overlap did not create significant issues as the field of SOFC research and development was growing rapidly across the 1990s. A significant part of this growth in SOFC developers was related to the adoption of thick-film ceramic

[45] Bossel Interview 28th June 22
[46] Ibid.; Singhal Interiew
[47] Bossel Interview 28th June 22
[48] Survey of the content pages of both events over the years reveal many individuals and organisations being represented through multiple papers published at both events. I also draw on my own experiences engaging with both conference series over the years, publishing at both and meeting familiar faces at both events.

processing, this lowered cost of entry to bench-scale cell fabrication, facilitating the growth in activity by allowing many new actors to enter the field. This in turn generated many new research questions around how best to use these methods to make a high performance, durable fuel cell. The meetings allowed regular gatherings of researchers, where such questions could be discussed and debated. This permitted SOFC researchers to construct new sets of material logics around the thick-film SOFC, and identify critical problems which when common across the field could be considered a “reverse salient”, a term which historian of technology Thomas Hughes described as specific, identifiable technical problems, which slow advancement and eventually hold back progress across an entire field.[49]

One such critical issue which emerged in the late 1980s and early 1990s around the thick-film, flat plate SOFC was that of operating temperature, as many of the deleterious effects on the performance of planar SOFCs were linked to the operating temperature of 950-1000°C. Through these two SOFC conferences, researchers could compare results and discuss evidence which allowed not only the operating temperature to be identified as a reverse salient, but also built consensus that the reduction of operating temperature would become a significant focus of planar SOFC research over the course of the 1990s. Historian of technology, Michael Mahoney referred to this second action, coming to a consensus on how to tackle the reverse salient, as “setting the agenda” and defined this action as an indication of the coherence and standing of a research community.[50]

Gatherings of SOFC researchers were not just taking place at international meetings: local gatherings were also beginning to take place. While meetings such as the Department of Energy contractors’ meetings had been ongoing since the mid-1970s, changes to research and development management practices starting in the 1980s, resulted in the closure or reduction in size of the large corporate research centres. This led to a movement of people across the early 1990s, which created new opportunities for local communities to develop and engage. One such example occurred in the United Kingdom, where Kevin Kendall, who had recently taken a

[49] Hughes, *American Genesis : A Century of Invention and Technological Enthusiasm, 1870-1970*, pp. 71-74.
[50] Mahoney, Michael S., 'Finding a History for Software Engineering', *IEEE Annals of the History of Computing*, 26 (2004), p. 9.

chair in materials chemistry at Keele University in central England, looked to bring together UK SOFC actors in an informal workshop setting to discuss work in progress and recent findings.[51] These workshops attracted academics, industrial researchers and representatives of funding agencies, with Kendall keen that they were an opportunity for doctoral students to discuss their work.[52] These meetings became invaluable for new or young researchers just entering the field, as it gave exposure of their work, not only to more established actors in the field who could give valuable feedback, but also to emerging industrial research groups who, in a similar manner to the growing SOFC groups of the 1980s, needed to identify and recruit new researchers to expand their own research activities. Such industrial groups could follow the progress of new researchers and both guide and support their efforts.[53]

Kendall was not the first to attempt to bring together interested parties in small, informal gatherings as a conduit for knowledge exchange. In the 1980s Brian Steele of Imperial College London had formed an industry “club” around the subject of electrochemical reactors. He invited interested industrial companies to contribute a small amount of money to help fund a meeting venue and catering around which presentations and discussions of relevant and recent work could be held. Industrial members of this early club were a number of UK firms with interests in solid state electrochemistry including Johnson Matthey, British Nuclear Fuels Limited (BNFL), and ICI Advanced Materials where Kendall was then working.[54] John Kilner, professor of materials science at Imperial College London, described Steele’s club as

[51] While many such meeting were taking place across Europe, the US and Japan, here I describe a UK meeting series which I had direct involvement and had significant impact on my own research work in SOFC.
[52] Kendall Interview 9 Mar 22
[53] The Keele meetings had a direct impact on my own experience. I was encouraged to both attend and present my work at these meetings by Kendall, who was acting as an external supervisor to my doctoral research. Through these meetings I met Bob Lewin and Steve Barnett of British Nuclear Fuels Ltd. (BNFL), and Jim Gardener, Michael Day and Nigel Brandon of Rolls Royce. BNFL supported my doctoral research through the donation of a single cell test rig which proved invaluable in assessing the performance of the cells I produced. Similarly, the team at Rolls Royce encouraged my exploration of screen-printed electrolytes which was similar to the ceramic processing approaches being pursued by Michael Day in the development of their Integrated Planar SOFC (IP-SOFC). The Rolls Royce team continued to follow and support my work (interview with Nigel Brandon, Conducted by Author on 8th November 2022), and eventually recruited me onto their team towards the end of my doctoral research, see Gardner, F. J., et al., 'Sofc Technology Development at Rolls-Royce', *Journal of Power Sources,* 86 (2000).
[54] Kilner Interview 30 Mar 22

somewhat "ahead of its time" and it could be argued that the small scale and informal nature of such "clubs" led to researchers getting to know one another on a human level, forming the basis of later close collaborative relationships. Kilner discussed the importance of such relationships, especially when collaborations were required to span multiple projects or funding cycles, as would become common across Europe in the 1990s and beyond. As such, it could be argued these clubs formed a nucleus for the close European collaborative community.[55]

The collaborative requirement to gain European Commission funding was another important factor in developing the SOFC research community, as the collaborative partners in any project had to span several European countries. The European Commission's aim in this requirement was explicitly to build collaborative networks across various technologies bringing together academia, national laboratories and companies to create a strong knowledge base around a specific technology such the SOFC. There were reflections of the thinking of Vannevar Bush in this approach, as many of the earlier European Commission programmes focussed on funding more fundamental aspects of research "from which [as a 1996 EU assessment report suggested,] all new technologies ultimately spring".[56]

In the case of developing the SOFC, such collaborative programmes did help in creating a strong community of researchers across Europe. It was noted by some that they felt that there was a collegiate environment, where actors were generally supportive of one another, and the community was focussed on trying to advance the technology as a whole. There may have been some "secret sauces" around specific materials and methods, but overall, the level of debate and discussion at meetings and conferences was fairly open with different groups trying to solve the same problems, but in different ways.[57]

Between both the international conferences, local meetings, and collaborative programmes, the knowledge community around the SOFC began to take shape. The need to understand the materials and their high temperature interaction created a community whose composition reflected these needs, primarily scientists and

[55] Ibid..
[56] European Commission, 'Brite-Euram : A Measurable Impact : A Synthesis of the 1993 Evaluation Studies of the Industrial and Materials Technologies Programme, Publications Office, ' (Publications Office: Directorate-General for Research and Innovation, 1995).
[57] Interview with Heather Haydock, Conducted by Author 24th October 2022

engineers with a background or interest in materials. While a number identified directly as materials scientists, others would identify as chemists, chemical engineers, physicists and mechanical engineers, but all were focussed on using their background training with respect to the behaviour of materials and their role in the functioning of the SOFC.[58] This materials-centric worldview of the SOFC community has persisted. Any review of the table of contents in an SOFC conference proceedings over the last few decades will reveal the predominance of papers focussed on materials research, or development where materials play a significant part of the discussion. Even though there has been an increased level of systems development in more recent years this focus on materials remains: of the 111 papers presented at the 2018 European SOFC Forum, it could be argued that around 60% still had a significant materials focus. This indicates that the power of promissory materials remains a strong driving force in SOFC development with the solutions to critical problems or reverse salients predicated around the discovery, development and deployment of a new material which will solve the problem and change the existing material logics constraining progress.

More Funding, More Actors, More Designs

Apart from the activities of ABB, little significant SOFC development had taken place across Europe for much of the 1970s and early to mid-1980s. Any work that was ongoing was mainly taking place in university laboratories where figures such as Brian Steele were trying to understand the basic ionic and electronic transport mechanisms of SOFC materials.[59] However, in the later 1980s and into the 1990s, changes to the management of research and development, both in industry and academia, and the deregulation of energy markets combined with the rise of natural gas from the North Sea as a growing source of fuel for electricity generation, created a new European energy and research policy context. These changing contexts,

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[58] Such a review of backgrounds comes from the interviews conducted for this work where a common initial question was for the participant to describe what they felt their professional background was, and how this had led them to a career in SOFC research. I also draw on my personal experiences talking to many research peers over the course of my own SOFC research career.
[59] Steele, B, 'Mass Transport in Materials Incorporated in Electrochemical Energy Conversion Systems', *Solid State Ionics,* 12 (1984). Kilner Interview 30 Mar 22

combined with the advent of thick-film SOFC fabrication technologies, allowed emerging SOFC developers and advocates to construct a new set of material and market logics which would attempt to situate the SOFC at the centre of potential energy markets based on distributed cogeneration (combined generation of heat and electricity), that was becoming seen as a prominent potential application for fuel cells.[60]

Much of the discussion around the emergence of neoliberal market-oriented thinking, leading to the breakup of the large vertically integrated corporation and the challenges this created for the associated in-house research centres, has centred on events in the US.[61] While the US corporate environment may have been the epicentre of such changes, they were not confined solely to the US. When President Reagan had come to office in the US, Prime Minister Margaret Thatcher was already in power in the UK, also initiating policies that reduced government intervention and embraced privatisation. At the centre of this ideology was a belief in “the market” to deliver solutions, not just for technical innovation but also for social issues. This ideological approach shared many similarities with the thinking of Reagan and these shared beliefs led to the close association between the two leaders over the course of the 1980s.[62] This market-based thinking also began to pervade large corporate institutions of the UK in a similar manner to those of the US. The view that such large institutions were cumbersome and slow to respond resulted in a pressure to split them into smaller, separate business units which would operate on a more market-oriented footing and therefore be more responsive to any changes in market conditions.[63]

[60] Abelson, P. H., 'Applications of Fuel Cells', *Science,* 248 (1990); Stann, Ian, 'Conference Report. Fuel Cells Are Coming to Town', *Power Engineering Journal,* 6 (1992); Newman, A., 'Fuel Cells Come of Age', *Environmental Science and Technology,* 26 (1992).
[61] Mirowski, *Science-Mart*; Mirowski and Sent, "Commercialisation of Science"; Lave, Rebecca, Philip Mirowski, and Samuel Randalls, 'Introduction: Sts and Neoliberal Science', *Social Studies of Science,* 40 (2010).
[62] Amott, Teresa and Joel Krieger, 'Thatcher and Reagan: State Theory and the “Hyper-Capitalist” Regime∗', *New Political Science,* 2 (1982); Hoover, Kenneth R., 'The Rise of Conservative Capitalism: Ideological Tensions within the Reagan and Thatcher Governments', *Comparative Studies in Society and History,* 29 (1987).
[63] Hatfield, Donald E. and Julia Porter Leibeskind, 'The Effects of Corporate Restructuring on Aggregate Industry Specialisation', *Strategic Management Journal,* 17 (1996); Mirowski and Sent, "Commercialisation of Science", p. 655.

One such UK company was ICI (Imperial Chemical Industries), a venerable institution of British industry, which had a significant research laboratory, ICI Research Materials, based in Runcorn in the northwest of England. As ICI were major suppliers of ceramic powders as raw materials to many industries, a major focus of the work at Runcorn was ceramics processing, in particular understanding the particle-particle and particle-fluid interactions which were central to the quality of ceramic components and had become an important factor in the growth of thick-film technologies. Over the course of the 1980s, changes in chemical markets had seen ICI move away from many of its traditional chemical activities towards pharmaceuticals and life sciences.[64] These changes were accelerated during the later 1980s and early 1990s as a number of corporate takeovers, mergers and restructurings broke up the iconic institution that was ICI and created a new set of companies, each with a with particular market focus.[65]

The research centre activities also reflected the changing company emphases, moving to support more lucrative pharmaceutical research. This shift in activities eventually resulted in the company ending its ceramic research activities and closing that part of the Runcorn research centre. As Kevin Kendall reflected, “with the end of the Cold War there was less money in ceramic nose cones for supersonic missiles”.[66] The cessation of ceramic research at Runcorn led to a significant movement of people from the commercial sector into academia. For example, Kendall left for a chair in the chemistry department at Keele University while others would find themselves spread across the UK academic sphere, taking up positions at several institutions such as Imperial College London, University of Cambridge, and University of Birmingham, where they would continue to research into many aspects of ceramic materials and processing.[67]

Kendall’s interest in SOFC development had started at ICI Advanced Materials, as a supporting partner on an early European Commission BRITE/EURAM project entitled *New Manufacturing Technologies for Advanced*

[64] Kendall Interview 9 Mar 22
[65] Owen, Geoffrey and Trevor Harrison, 'Why Ici Chose to Demerge', in *Harvard Business Review,* (Cambridge, Mass., 1995); Wachman, Richard, 'How Competition Ate Away Britain's Chemicals Giant', *The Guardian,* (2007).
[66] Kendall Interview 9 Mar 22
[67] Ibid.

Solid Oxide Fuel Cells.[68] This project was one of two European projects initiated by the European Commission across 1990 and 1991 under the BRITE/EURAM banner and marked the start of an increased interest in SOFC research by the Commission. The BRITE/EURAM programme was the European Union's industrial and material research and technology development programme initiating in1985-1986 with the BRITE and EURAM aspects each having specific focus. The BRITE aspect focussed on applications of new technologies and materials to existing industry sectors while the EURAM aspect dealt more specifically with discovery of new materials. In 1989 these programmes were merged to form BRITE/EURAM and continued into the 1990s.[69]

The project ICI were involved in was led by the ABB research centre in Heidelberg, demonstrating continued interest in the SOFC by researchers at this location into the early 1990s. The project description outlined extruded supports and planar cells manufactured from tape casting and screen printing, suggesting that ABB were still following their roof-tile approach to construction of a series connected array of cells. Another important partner on this project was Risø, the National Laboratory of Denmark. Risø would begin to develop their own cell concepts across the 1990s, becoming a significant and respected centre for the research and development into the understanding solid state electrochemistry and SOFC component design and manufacture.[70] In the second project, also focussed on the manufacturing of components for flat plate SOFC, the lead partner was ECN, the Dutch National Energy Research Laboratory who were a significant actor in molten carbonate fuel cell research.[71]

The other significant partner in the second project was Siemens, the large German multinational industrial power equipment manufacturer.[72] While ABB eventually withdrew from SOFC work in the 1990s, Siemens would become highly influential. In this initial BRITE/EURAM project, research activities included increasing production quantities of the ceramic powders required for SOFC

[68] European Commission, "1990/1992 Brite/Euram Synposes", p. 75.
[69] European Commission, "Brite/Euram Impact Report", p. 6.
[70] European Commission, "1990/1992 Brite/Euram Synposes", p. 75.
[71] Pietersz, S., 'An Overview of the Dutch Mcfc Program', in *Fuel Seminar*, ed. by E.A. Gillis (Tucson, Arizona: Courtesy Associates, 1986), pp. 151-154.
[72] European Commission, "1990/1992 Brite/Euram Synposes", p. 76.

fabrication, investigating tape casting for electrolyte production and other techniques for coating electrodes onto electrolytes.[73] The Siemens design would revolve around an electrolyte-supported flat plate based on yttria-stabilised zirconia. This zirconia plate was considered by many researchers to be the standard SOFC thick-film electrolyte against which any new electrolyte material or arrangement would be compared. In the electrolyte-supported configuration the SOFC still demanded operational temperatures of 950-1000°C. Rather than adopting the lanthanum chromite ceramic interconnect then used by many other developers, Siemens chose to work with a new metallic chromium-based alloy being developed by a company called Plansee in Austria, which they hoped would avoid some of the issues of the ceramic component.

Further, rather than just alternating cells and interconnects to form a series connected stack which many other developers were attempting, Siemens developed a more convoluted layout where several cells would be electrically connected in parallel, arranged within a flat "window frame" type arrangement.[74] This allowed the development team at Siemens to sidestep one potential issue that was facing planar developers: maintaining flatness and structural integrity on cells with larger areas. In the Siemens approach, the increased power per stack layer could be attained by increasing the number of cells in the window frame. Earlier designs illustrated four cells in a two-by-two arrangement, sixteen cells in a 4x4 arrangement, or for larger stacks, nine larger cells in a three-by-three arrangement. These design options allowed Siemens to attain significant gains in the electrochemically active layer of a stack layer with only modest increases in the actual surface area of individual fuel cells.[75]

[73] Ibid.
[74] Blum, L., 'Multi-Kw-Sofc Development at Siemens', *ECS Proceedings Volumes,* 1995-1 (1995).
[75] Ibid.; Beie, H.J., 'Sofc Development at Siemens', *ECS Proceedings Volumes,* 1997-40 (1997).

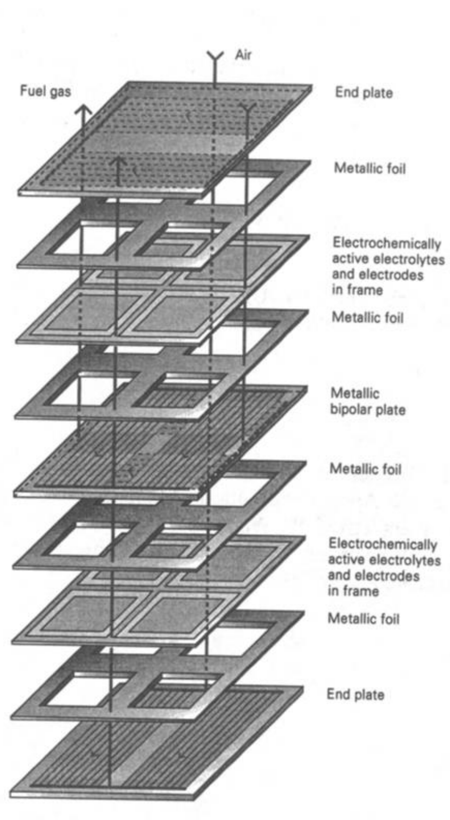

Figure 6; Siemens window frame planar stack arrangement. Reproduced with permission from Blum, L., 'Multi-Kw-Sofc Development at Siemens', ECS Proceedings Volumes, 1995-1 (1995), 163-172, p168.

Such variations in design again illustrated the trade-offs which were common in trying to reconcile the behaviour and performance of the materials against a practical stack design, and while the Siemens arrangement may have offered potential solutions to one set of problems, it introduced others. Matching of the expansion rates of the different materials became more critical than other designs as the placement of the cells within the window frame resulted in a more constrained component, with a lower degree for lateral movement than would possibly be available in a simpler vertically stacked arrangement of alternating cells and interconnects. The window frame arrangement also demanded more complex sealing arrangements than a straightforward vertically stacked array. This is not to say that sealing was not a significant issue in the single vertical arrays. It was. However, the extra interfaces in the Siemens design did not make finding a solution to this task any easier and the development of sealing materials and their behaviour at the high operational temperatures would become a major impediment to progress.[76]

The presence of ABB in Heidelberg and Siemens in Erlangen as significant European actors in SOFC development reinforced the cluster of activity in Germany which had first emerged in the 1980s and would act as a catalyst for further activity. Significant amongst these were the activities within the Forschungscentrum Jülich, one of the largest of the Helmholtz Association Centres, which formed a network of national research centres across Germany. Starting in the late 1980s and picking up momentum across the 1990s, the main activities were very generic materials development, gaining knowledge and understanding of the materials, their interactions and the electrochemical mechanisms, which at this time were still not well understood. Researchers at Jülich had some freedom to explore as they were not too closely tied to the industrial developers, so were able to position thick-film slurry-based cells with an eye towards the emerging distributed power markets and would be an early mover towards the thinner, anode-supported electrolytes, developing several processing approaches to achieving these goals.[77]

Jülich, along with Risø and ECN, the National Laboratories of Denmark and the Netherlands respectively, would become three of the significant centres for SOFC development in Europe during the 1990s. Between them they would be involved in many of the European Commission projects and have an influential voice in setting the research agenda, with both Jülich and Risø maintaining strong leadership positions well into the 2000s.

During the late 1980s and early 1990s, the move towards a flat plate or planar SOFC based around a tape cast electrolyte as the structural element had begun to emerge as a common design. This would become the preferred embodiment of the cell in the early 1990s, at least from a European perspective, from which the important reverse salient around the high operating temperature would emerge, resulting in several different material logics that would shape approaches to potential solutions. There can be little doubt that the emergence of thick-film technologies as a means to fabricate the SOFC opened many new design options for developers of the

[76] Interview with Tony Wood, Conducted by Author on 28th November 2022 Singhal Interiew.
[77] Interview with Frank Tietz, Conducted by Author on 17th October 2022.

device. In contrast to the more established route of SOFC development via the well-funded and equipped larger corporate research centres, the lower costs afforded by the thick-film techniques had allowed many more actors to enter the field with a host of new research groups emerging from university laboratories, national laboratories and a number of brand-new companies being formed.

The Drive to Reduce Temperature

Even with the adoption of tape cast electrolytes, the high temperature required for operation was still creating issues for developers. One of the key concerns facing developers of planar SOFCs was how to connect cells together when operating at 1000°C. While lanthanum chromite had long been recognised as a material which possessed the correct mix of properties with respect to stability and conductivity, it was expensive and difficult to process. Westinghouse had circumvented both difficulties by utilisation of their vapour deposition process, which by depositing a thin-film, used very little material and also resulted in a ready formed ceramic phase avoiding the difficulties with firing a dense layer in air which faced the planar developers. This is not to say that the vapour deposition processes were problem free: by the early 1990s the high costs of scaling the vapour deposition processes were beginning to become apparent and were setting up a set of competitive logics which would continue to cause issues for Westinghouse across the 1990s and beyond.

By contrast to the thin-films of the Westinghouse tube, the interconnect in a planar system was far more of a bulk component which had to match the surface area of the cell and was maybe a millimetre or so in thickness, as it often contained arrays of channels to facilitate gas distribution.[78] This required firing at high temperatures in atmospheres with very low oxygen contents, or the addition of extra elements to

[78] Milliken, Christopher and Ashok Khandkar, 'Fabrication of Integral Flow-Field/Interconnects for Planar Sofc Stacks', in *First International Symposium on Solid Oxide Fuel Cells,* ed. by Subhash C. Singhal (Hollywood, Florida: The Electochemical Society, 1989), pp. 316-376. Knudsen, Per, Carsten Bagger, and Mogens Mogensen, 'Combining Science and Practice in the Danish ‘Dk-Sofc’ Program', *Journal of Power Sources,* 49 (1994); Itoh, Hibiki, et al., 'Production Cost Estimation of Solid Oxide Fuel Cells', *Journal of Power Sources,* 49 (1994), p. 316.

result in dense, leak-free interconnects.[79] This latter approach also carried issues, as the teams at Argonne and Allied Signal had discovered when they observed that these additional elements diffused throughout the stack and resulted in performance degradation when they redeposited on electrochemical interfaces, an effect which would be exacerbated at an operating temperature of 1000°C.[80]

The degradation issue was not solely caused the diffusion and interactions of chemical additions that helped the interconnect densify. Many developers had observed the initial performance of cells rapidly deteriorate with time. Issues around the chemical interactions of cell materials, changes to the structures within the cell materials, separation and sealing of the fuel and air gases, and the connection of the cell stack to its wider system had all been identified as possible sources of this performance degradation.[81] All of these issues combined appeared technically difficult and costly to overcome and to many developers an overarching solution appeared to be to find a way that would allow the temperature of operation to be reduced. This, they assumed, would result in reducing the severity of the many other technical issues which had to be broached in order to realise a viable commercial system.

By the early 1990s, researchers were beginning to gravitate around two potential approaches to achieve this aim. These were the reduction of the zirconia electrolyte thickness or the development of a new ionically conducting material with a higher conductivity than zirconia. Both approaches utilised the relationship between material conductivity, thickness and resulting cell resistance established by Brian Steele.[82] Steele was already established as a central figure in solid oxide fuel cell research, starting in the late 1950s with a PhD in the Nuffield Research Group for Extraction Metallurgy at Imperial College which focussed on thermodynamic

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[79] Allied Signal Aerospace Corp., "Monolithic Solid Oxide Fuel Cell Technology Advancement for Coal-Based Power Generation", pp. 4-1.

[80] Myles, K.M. and C.C. Mcpheeters, 'Monolithic Solid Oxide Fuel Cell Development', *Journal of Power Sources*, 29 (1990), p. 318.

[81] Khandkar, Ashok and S. Elangovan, 'Development of Planar Sofc Technology : Progress and Problems', *Denki Kagaku oyobi Kogyo Butsuri Kagaku,* 58 (1990); Khandkar, Ashok, S. Elangovan, and M Liu, 'Materials Considerations for Application to Solid-State Electrochemical Devices', *Solid State Ionics,* 52 (1992); Ivers-Tiffée, E., 'The Materials and Technology Development of Ceramic Components for a Reduced Temperature Sofc', *ECS Proceedings Volumes*, 1995-1 (1995).

[82] Steele, "Mass Transport in Materials Incorporated in Electrochemical Energy Conversion Systems"; Steele, B. C. H., 'Oxygen Transport and Exchange in Oxide Ceramics', *Journal of Power Sources,* 49 (1994).

measurements in solid electrolytes for high temperature sensors. Such sensors were becoming an important part of process control, monitoring the atmospheres within furnaces for metallurgical processing. In 1964 a visit to the US brought him into contact with researchers from the SOFC development projects of both Westinghouse and General Electric which kindled a lifelong interest in the technology. Due to a lack of interest in SOFC in the UK during the 1970s, it would not be until he formed the Wolfson Unit for Solid State Ionics at Imperial College in 1979 that he was able to focus his research activities on the fundamentals of ionic transport in solids, especially oxygen transport in fluorite structured ceramics such as the zirconia commonly used in SOFC.[83]

In addition to zirconia electrolytes, Steele had also become very interested in another ceramic system based on cerium oxide (ceria), which showed a higher conductivity than zirconia. Over the course of these studies in the 1980s, Steele became convinced about the utility of reducing the operation temperatures in SOFC systems as a way of circumventing some of the problems that developers were beginning to encounter such as sealing, interconnection and degradation. He constructed a graph which became very well-known across the SOFC community illustrating the relationship of the specific ionic conductivities of various ceramic electrolytes to changes in temperature. Steele then calculated what the acceptable resistance to conduction across an electrolyte layer would be, and from this he could superimpose how the thickness of any particular electrolyte material would determine the temperature required for cell operation.[84]

It could be argued that one of Steele's aims with this diagram was to demonstrate the material logics around self-supporting electrolyte systems. He showed that zirconia electrolytes did not have sufficient conductivity to be operated much below 900°C and that new systems, such as those based on ceria, were required for future generations of SOFC systems. Not everyone agreed with Steele's assessment that ceria-based electrolytes represented the best development option. Several research groups had commented on the observation that the ceria was not completely stable and when exposed to the low oxygen environments of the anode:

[83] Kilner, J. A., 'Brian Steele's Contributions to Solid State Ionics', *ECS Proceedings Volumes,* 2005-07 (2005), pp. 13-14.
[84] Steele, "Oxygen Transport and Exchange in Oxide Ceramics", p. 10.

ceria would exhibit significant electrical conductivity alongside the required ionic conductivity, with the former reducing the electrochemical potentials which could be attained, effectively short circuiting the cell. [85]

The electrical conductivity issues in ceria-based electrolytes were not in themselves new, with issues being highlighted in the EPRI fuel cell report in the 1970s.[86] However, despite these challenges, Steele remained committed to his exploration of ceria as an electrolyte material. He had shown that the detrimental electrical conductivity was thermally activated and decreased with temperature. Therefore, he proposed that in a ceria-based system operating at between 500°C and 600°C the electrical conductivity would have reduced to such a small level that a cell could be operated effectively. Steele termed this lower operating temperature regime as “intermediate temperature”.[87] Notwithstanding his eminence amongst the SOFC community, not everybody agreed with him that ceria would be suitable an electrolyte for SOFC, even at the proposed intermediate temperatures, and zirconia-based systems remained the most popular electrolyte for SOFC development.[88]

The data presented in Steele’s diagram also revealed another potential approach to reducing the operating temperature of the SOFC, one which allowed advocates of zirconia-based electrolytes to construct a new set of logics based around the thick-film processing techniques that were beginning to be adopted towards the end of the 1980s. As the researchers at Argonne National Laboratory and Allied Signal were struggling with the process contradictions of their Monolithic SOFC concept, members of the Allied Signal team led by Nguyen Minh had noticed that repeated passes of the laminated tape-cast cell layers through an ever-smaller gap between the rolls of their tape rolling equipment would result in a thinning of the layers in proportion to their original cast thicknesses. From this, Minh postulated that if they continued to sequentially roll laminated layers of thicker anode and thinner

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[85] Steele, B. C. H., 'Appraisal of Ce1-Y Gdy O2-Y/2 Electrolytes for It-Sofc Operation at 500c', *Solid State Ionics,* 129 (2000).
[86] King, "Advanced Fuel Cells Program", pp. 34-36.
[87] Steele, B. C. H., 'Materials for It-Sofc Stacks: 35 Years R&D: The Inevitability of Gradualness?', *Solid state ionics,* 134 (2000), pp. 14-16.
[88] Wood Interview 28 Nov 22, also Kilner, "Brian Steele’s Contributions to Solid State Ionics", p. 16.

electrolyte together this would result in an electrolyte layer of less than 15 microns supported on a thicker anode.[89]

Steele's diagram had shown that the resistance of a zirconia-based electrolyte of this thickness would be low enough to permit operation at between 800 and 700°C. Allied Signal researchers shared the view of Steele that reducing the operating temperature was an essential requirement in the realisation of a viable SOFC system. As more SOFC researchers came to this view, the 1000°C operating temperature became a reverse salient, and research to reduce this operating temperature became an agenda around which many researchers would congregate in the 1990s. However, as the different approaches of Minh at Allied Signal and Steele at Imperial illustrated, no single set of material logics would be constructed around how best to achieve this, and a number of different approaches to reducing the operating temperature would emerge over the course of the 1990s.

Not Everybody Needs Reduced Temperatures

The need for reduced operating temperature was not universally accepted by all SOFC developers as a reverse salient holding back the field. The Westinghouse tubular design had circumvented some of the sealing issues through the arrangement of the tubes and their vapour deposition techniques sidestepped the issues around interconnect densification that were plaguing the planar developers. Further, the higher operational temperature also minimised the losses due the electrical resistance in the inherently long current pathways around the tube, which Bossel had calculated would limit performance in a tubular system.[90]

While these led to some important performance factors which were specific to the Westinghouse design, these were not the only considerations in the minds of developers looking at applications around larger centralised industrial power generation. Calculations were beginning to reveal that pressurising an SOFC system could further boost the efficiency of the unit and that when this pressurisation was combined with the passing of these high temperature and high pressure SOFC

[89] Minh Interview 18 May 21
[90] Bossel Interview 28th June 22, Bossel, "Comparative Evaluation of the Performance Potentials of Ten Prominent Sofc Configurations".

exhaust gasses through a gas turbine, then the overall system efficiencies could be further increased.[91]

It was this synergy between the gas turbine and the SOFC which began to further interest some in Rolls-Royce Plc in the UK. In the early 1990s, Rolls-Royce began a small research programme to investigate the SOFC. This was not the first fuel cell research carried out by researchers at Rolls-Royce. Earlier studies had been carried out within Rolls-Royce and Associates, a division of the company focussed on energy and propulsion systems for submarines, where a group within this division had investigated polymer fuel cell systems as a method for providing electrical power for submarines. [92] This work had created a small group of scientists and engineers within the company with an awareness of fuel cell technology and it was one of these, Jim Gardner, who would later become the team leader of an SOFC research project within the Rolls Royce Applied Science Laboratory (RRASL), the company’s strategic research department, where I would take up my first post-doctoral position in 1996.[93] Unlike the classic image of a corporate research centre forged by the large US companies such as Bell Labs, GE or Westinghouse, the Rolls-Royce centre was a far more modest affair. While researchers in RRASL were engaged in forward-looking technology development there was far less intellectual freedom than was common in the large US centres and the development undertaken at Rolls-Royce was far more aligned with the immediate needs and concerns of the company business.[94]

Rolls -Royce was often most associated with manufacture of aero-engines and had been at the centre of turbojet development for both military and civilian applications. In the late 1980s and early 1990s however, the increase in production of North Sea gas as a fuel both in the UK and across Europe had seen a large growth in its use to generate electricity. This generation often utilised industrial gas turbines, a stationary derivative of the aerospace gas turbine. Such industrial turbines proved to be a flexible and cost-effective means of rapidly setting up electrical generation capacity. These factors were in tune with what was rapidly becoming a more

[91] Gardner, et al., "Sofc Technology Development at Rolls-Royce".
[92] Anonymous Interview July 2018; Shoesmith, J.P., et al., 'Status of Solid Polymer Fuel Cell System Development', *Journal of Power Sources,* 49 (1994).
[93] RRASL would be renamed the Strategic Research Centre (SRC) by the late 1990s
[94] Brandon Interview 8 Nov 22.

deregulated and market-orientated energy system in the UK and industrial gas turbines proved to be a central factor in what became known as “the dash for gas” in the UK energy system.[95] As a result, Rolls-Royce had become a significant supplier of industrial gas turbines and by the early 1990s a significant portion of Roll-Royce’s business was closely linked to industrial power generation. [96]

Therefore, the emergence of the high temperature SOFC and the interest of competitors Westinghouse, ABB and Siemens also raised interest at Rolls-Royce, especially in the need to understand what this technology meant for their industrial gas turbine business.[97] To better understand SOFC technology, Gardner was tasked with setting up a small project to investigate the SOFC. His small team’s role was not to develop an SOFC system in itself but rather to learn about the advantages and disadvantages of the SOFC by carrying out practical empirical research on appropriate materials and systems. Like others developing SOFC systems for larger industrial applications, Gardner quickly recognised that the advantageous synergies of a pressurised SOFC working in combination with a gas turbine, which would result in high system efficiencies, which he estimated could be as high as 80%.[98] With his previous exposure to fuel cell technology at Rolls-Royce and Associates, Gardner already had a positive view of the technology. He became an advocate for the SOFC within Rolls-Royce and positioned the project such that as well as learning about the technology, the work of the group would also result in a technological concept that could be developed into a viable SOFC system. Through this advocacy, he further developed technoscientific imaginaries of SOFCs as part of a highly efficient distributed power network running of existing primary energy frameworks.

Elements of the Rolls Royce concept, which they termed the “integrated planar SOFC” (IP-SOFC) would be familiar to both researchers at both Westinghouse and ABB. Like its predecessors, Rolls Royce chose a tubular support and like ABB’s design this was rectangular in cross-section with an array of series-connected cells on the larger flat faces of the support, where the current would travel through a set of overlapping cells in a manner very similar to the early Westinghouse

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[95] Winskel, Mark, 'When Systems Are Overthrown: The 'Dash for Gas' in the British Electricity Supply Industry', *SOC STUD SCI,* 32 (2002).
[96] Gardner, et al., "Sofc Technology Development at Rolls-Royce".
[97] Brandon Interview 8 Nov 22.
[98] Gardner, et al., "Sofc Technology Development at Rolls-Royce".

multi-cell thin-film cells. Unlike the ABB design, where the cells were added as separate components, or the original Westinghouse multi-cell thin-film design, where cells were deposited by electrochemical vapour deposition, in the Rolls-Royce design the various cell layers were deposited by screen printing, the thick-film technique that had become widely used in planar systems. As Gardner often said, the aim was to try to combine the advantages of both the tubular and planar systems while avoiding the disadvantages.[99] Underlying cell design similarities and differences aside, ultimately both Westinghouse and Rolls-Royce saw the system advantages of coupling the SOFC with a gas turbine. Here, the higher operating temperatures of around 950°C were seen by these teams as an advantage rather than a reverse salient.

Climate Change as an Emerging Driver of Development

By the mid to late 1990s, many SOFC developers, including Westinghouse (in common with developers of other types of fuel cell) were beginning to reframe their devices as technologies which could be part of the future energy systems that were emerging around the need to reduce carbon dioxide emissions. While the developers of fuel cells had always been aware that the electrochemical conversion processes in the SOFC would lead to less carbon dioxide being emitted per kilowatt of electricity generated when compared to combustion processes, this quality, in itself, had not been a significant driver for development of the technology up until this time.[100] During the preceding decades, policymakers where more concerned with conversion efficiencies in the face of the fuel supply issues of various energy crises of the 1970s, and local air quality issues relating to localised pollution and acid rain from combustion of coal.[101] This would begin to change after 1985 when Carl Sagan's well publicized address to Congress and the Villach climate change conference in Austria both highlighted the role of carbon dioxide in global warming.[102] While global warming had been discussed in scientific circles for many years, these two events are often seen as the beginning of increased public awareness of the link

[99] Ibid.
[100] Kilner Interview 30 Mar 22
[101] Anonymous Interview July 2018
[102] "Action Is Urged to Avert Globall Climate Shift"; Pearce, Fred, 'Histories: The Week the Climate Changed', in *New Scientist*, (London, 2005).

between the climate change and the level of carbon dioxide in the atmosphere moving it from scientific debate and into the political sphere.[103]

While Sagan's address became well known as a landmark event in the US, the Villach meeting would become the catalyst for further meetings in Montreal and Toronto which would lead to the formation of the Intergovernmental Panel on Climate Change (IPCC). Further meetings would follow with significant agreements being reached in Rio de Janeiro in 1992 and Kyoto in 1997, both of which would lay the framework for future limits and controls of the emissions of greenhouse gasses.[104] Through these various events the need to drastically reduce the amount of carbon dioxide being pumped into the atmosphere by the various carbon-based combustion processes employed around the globe became more prominent in the thinking of policymakers. The emerging policy emphases on reducing carbon dioxide emissions to mitigate against climate change in turn allowed SOFC developers to subtly reposition their technology as having the potential to meet the demands imposed by these new policy imperatives.

However, the implementation of new environmental regulations which would have allowed fuel cell developers to take full advantage of the environmentally friendly characteristics of fuel cell technology were a moving and uncertain target, with manufacturers of incumbent combustion-based technologies also looking to manage the impacts of any new regulations on their own products. The increasing awareness of the impacts of carbon dioxide and greenhouse gas emissions on climate change and acknowledgement of the need to limit such emissions through international agreements such as the Kyoto Protocol, were now leading to discussion and debate around how to introduce new and more stringent regulations around the emission of carbon dioxide.

The promise of future but relatively near -term environmentally friendly technologies, such as fuel cells, allowed manufacturers of combustion-based technologies to lobby government to delay or lessen proposed regulations on

[103] Franz, Wendy E., 'The Development of an International Agenda for Climate Change: Connecting Science to Policy', *ENRP Discussion Paper E-97-07* (Kennedy School of Government: Harvard University, 1997), pp. 1-35.

[104] Bodansky, Daniel, 'The History of the Global Climate Change Regime', in *International Relations and Global Climate Change,* ed Urs Luterbacher and Detlef F. Sprinz (Cambridge, Massachusetts: MIT Press, 2001), pp. 23-40.

emissions which would impact currently available combustion-based equipment. Their argument was that the far lower emissions from these “revolutionary products” would make the proposed regulation of incumbent technology a moot point. Forcing them to “upgrade” existing technologies to meet the new more stringent regulations would ultimately delay the introduction of the “revolutionary” products by diverting resources away from the development of the new technology. This approach was most apparent in the US automotive sector of the late 1990s, where a series of new rigorous emissions regulations for automobiles in California were eventually watered down against the promise of the imminent rollout and adoption of polymer fuel cells as a “zero-emission engine”.[105]

The use of such political moves by the developers of incumbent combustion technologies constructed and promoted a technological optimism around the promise of the new technologies in solving issues around carbon dioxide emissions and climate change. This optimism validated the idea of the latent potential of the fuel cell in the minds of policymakers, justifying continued investment and funding for the technology. This created an environment for the continued research and development of the SOFC and other similar technologies with continued funding predicated on this future promise. However, it also skewed the short-term regulatory and market conditions in favour of the status quo. This allowed incumbent combustion technologies to retain a cost advantage over more environmentally friendly technologies, as the combustion technologies did not have to bear the cost burden of meeting new more stringent emissions regulations. This in turn created a contradictory situation where, on one hand, the future was couched in terms of optimism around the paradigmatic changing promise of new technology, while, at the same time, this very same new technology could be dismissed as being too expensive for the market to bear without significant advances in cost reduction.

Like other advanced power sources being researched in this period including the PEM fuel cell and advanced storage batteries, the SOFC was caught in a “chicken and egg” conundrum of needing to reduce costs, typically achieved by increasing

[105] For more detailed history of this story see Eisler, "Getting Power to the People: Technological Dramaturgy and the Quest for the Electrochemical Engine". Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*.`Chapter 6and Eisler, *Age of Auto Electric : Environment, Energy, and the Quest for the Sustainable Car* pp. 101-110.

production volume, while having a very little actual opportunity to increase volume as the technology was seen as too expensive for prospective customers, limiting sales.

The powerful imaginary of zero-emission vehicles captured the public imagination, with the PEM and hydrogen fuelling entering more widespread popular discourse and the investment of major vehicle manufactures in companies such as Canadian PEM developer Ballard rapidly and significantly raising stock values.[106] While this had some advantages for SOFC developers, it also created tensions. The wider public discourse often failed to identify or differentiate the different types of fuel cell and their varying operating parameters. This led to the conflation of all fuel cell devices under the catch all term of "hydrogen fuel cell". This meant that the hydrocarbon capabilities of the SOFC were often lost with some projecting the PEM's need for very pure hydrogen onto the SOFC and linking the device with hydrogen economies. This tension would remain with the SOFC across the years, being most dramatically illustrated with the SOFC being caught in funding cuts due to changes in US energy policy to hydrogen in the 2000s described in Chapter 7.

Cracks Appear in the Westinghouse Approach

This conundrum was acutely felt by Westinghouse, not just because of the inherent costliness of the vapour deposition process, but also because the changing dynamics of the energy landscape was forcing them to revisit their long-established market logics based on large multi-megawatt central generation facilities. Throughout the early and mid-1990s, Westinghouse had continued to develop their tubular approach with considerable patronage from the US Department of Energy with significant technical success. The SOFC development team under the leadership of Singhal had moved the technology from the small tens-of-kilowatt demonstrators of the late 1980s towards larger demonstration units of around 100-200kW by the later 1990s. Some of the older 25kW units had now been running for almost 8000 hours and

[106] Koppel, *Powering the Future : The Ballard Fuel Cell and the Race to Change the World*, p. 221; Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*, p. 143.

some long-term single cell tests were now approaching 70,000 hour durations.[107] Plans were also outlined to increase the size of the closed end tube by a factor of three, from 50cm to 150cm with a resulting increase of power from 65 watts to 210 watts per tube and, to accommodate this size increase, a new pilot manufacturing facility was also planned with an estimated output of cells equating to four megawatts of electrical power per year.[108]

Figure 7; Illustration of the increased length of the Westinghouse single cell tube. Source DOE Report: George, R., 'Westinghouse Program Overview', in DOE Review Meeting (Morgantown, West Virginia US: Department of Energy, 1996), p.8.

Therefore, while by the mid-1990s it could be argued that Westinghouse was the leader in SOFC development, with the largest production facility at that time, this position was in some ways a product of the longevity of the Westinghouse

[107] George, R., 'Westinghouse Program Overview', in *DOE Review Meeting,* (Morgantown, West Virginia US: Department of Energy, 1996).
[108] Ibid.

programme allied with the generous DOE funding. Together, these factors had allowed the team at Westinghouse to drive the technology forward at a greater scale than was available to other developers at that time.

Although Westinghouse appeared to have a strong technical lead, when looking at the position of SOFC technology against the shifting wider energy contexts of the mid to late 1990s, the strength of the Westinghouse approach was far less certain. The 1980s projections that the company had made for initial commercialisation in the 1990s had not materialised and commercial products were now being discussed for the early 2000s, a decade later than anticipated.[109] Further, over the 1980s and 1990s the landscape of electricity generation had changed, and the large, centralised generation facility of tens or hundreds of megawatts was no longer the certain future model of the industry. The deregulation of energy markets that had taken place over this time led to an increasing prominence of ideas focussed around smaller decentralised and distributed generation facilities potentially owned and run at local or regional levels.

Much of this thinking had been spurred by increasing utilisation of newly opened natural gas reserves in conjunction with highly efficient and cost-effective industrial gas turbines. Although such ideas were gaining traction, the optimal form and size of such distributed generation systems would remain uncertain.[110] These uncertainties were heightened by the many often conflicting regulatory pressures that were emerging during the 1990s. On one hand, there was the neoliberal drive for relaxation of restrictive regulations and greater emphasis on the market to control the supply and demand for energy. Pulling in the other direction was the increasing awareness of the impacts of greenhouse gasses on the climate and the need for regulation to control emissions of combustion products, such as carbon dioxide from generation processes.[111]

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[109] Casanova, Allan, 'A Consortium Approach to Commercialized Westinghouse Solid Oxide Fuel Cell Technology', *Journal of Power Sources*, 71 (1998).
[110] Barker, P.P. and R.W. De Mello, 'Determining the Impact of Distributed Generation on Power Systems. I. Radial Distribution Systems', in *2000 Power Engineering Society Summer Meeting (Cat. No.00CH37134)*, (IEEE, 2000); Puttgen, H.B., P.R. Macgregor, and F.C. Lambert, 'Distributed Generation: Semantic Hype or the Dawn of a New Era?', *IEEE Power and Energy Magazine*, 1 (2003).
[111] For reference to such conflicting regulatory pressures see Eisler, *Age of Auto Electric : Environment, Energy, and the Quest for the Sustainable Car* p. 8.

This dynamic regulatory environment led to difficulty in forecasting where the Westinghouse SOFC would fit and led to significant hedging of what size the Westinghouse SOFC would eventually be. In a 1998 paper, Allan Casanova of Westinghouse revealed that distributed energy systems were presenting the company with a new space in which it was just beginning to operate and the amount of hedging about where its products would sit within this market reflected both the uncertainties around the market and the company's view of its position within it. In this paper Casanova suggested that Westinghouse would target SOFC systems between 250 kilowatts and seven megawatts and that this would revolve around a standard 500kW module. However, the limits of both ends of these projected system sizes were caveated by the statement that the company would be led by the demands of the market and would look at systems down to 100 kilowatts as well as larger than 7 megawatts.[112] Casanova presented such large range in system sizes as consistent with the modularity and scalability often promoted as one of the advantages of the SOFC. It could also be argued that systems at either end of this scale would look significantly different. This suggested that important design decisions with long-term investment consequences were being driven by short term market dynamics, influenced by changing contexts of regulations, fuel price fluctuation and the commercial placement of competing, and in many cases, established combustion technologies.

Along with the uncertainties of its place in a changing energy landscape that was becoming dominated by distributed generation, the question of cost would remain an issue which could, and would, be used against the SOFC. While this was felt by all SOFC developers, it was something which was felt especially keenly by the Westinghouse team. While adoption of the vapour deposition routes had allowed the Westinghouse team to define a new set of material logics which overcame existing limitations in the ceramic processing of the 1960s and 1970s, the associated controlled atmosphere chambers and other related equipment led to some high embedded costs. As early as the beginning of the 1990s, some questions were already beginning to be raised within the team about the costs associated with EVD and the

[112] Casanova, "A Consortium Approach to Commercialized Westinghouse Solid Oxide Fuel Cell Technology".

implications of these for scale-up of the technology.[113] One part of this scaling up was the effort to increase the length and diameter of the tubes, resulting in more power per tube and therefore fewer tubes for a given system power rating.[114]

While it might have been the expectation that the fewer tubes that would be required with the increased length and diameter may have helped reduce the cost pressures from the EVD processes, with reflection and hindsight some have concluded that this might not have been such a good approach. The longer tubes demanded larger controlled atmosphere chambers and furnaces, which themselves incurred far higher costs, with the new EVD described as a “multi-million-dollar beast”.[115] The longer tubes also became far more difficult to handle. Where the 50cm tubes used in the early 25kW demonstrators were easier to manoeuvre through the various process steps, the larger tubes, approaching two metres in length, required large-scale bespoke and costly automated handling equipment. The design at this stage was also not yet fully fixed and new changes were regularly emerging from the research team to improve performance, whether this be increasing the length or diameter of the tube for greater power, or getting rid of the inert support and changing to using the air electrode for support to further reduce the electrical resistance within the stack, all of which put pressure on the team working on the scale up and process development.

All of these changes meant that the scale-up activities did not reduce costs as planned, as equipment was commissioned only to quickly become obsolete due to additional changes in design. This created tensions between the research and process development teams, with the latter always complaining “those R&D guys are always changing their minds.”[116]

Wider Westinghouse Wobbles

The difficulties facing the SOFC development team at Westinghouse were not just confined to the practical challenges in developing a new technology. By the mid-

113 Singhal Interiew.
114 George, "Westinghouse Program Overview".
115 Anonymous Interview 29th Apr 21.
116 Ibid..

1990s, changes at the wider corporate level across the whole Westinghouse organisation were also creating existential issues across Westinghouse's energy engineering businesses. As detailed by Steve Massey in his 1998 six-part series in the *Pittsburgh Post-Gazette* "Who Killed Westinghouse", these problems were a culmination of multiple short-term fixes made by an apparent rotating door of CEOs who had run Westinghouse across the 1980s and 1990s.[117] Issues in the 1970s related to uranium contracts and prices led to poor profits and earnings in the early 1980s, just as the Reagan-era market-oriented ideologies centred around growth as a critical measure of success were taking hold. To counter this market pressure, Westinghouse needed something that would quickly drive growth. This driver was found in its financial services division, which moved from financing appliance purchases to underwriting large loans relating to commercial real estate. Through a combination of bullish market attitudes to risk, the corporate need to maintain short term growth and high shareholder revenues, and the large fees that guaranteeing the higher risk and more dubious loans attracted, the corporate due diligence and governance around financing many of these loans was less than robust. These risks were exacerbated by CEO John Marous, who signed an agreement that the parent company would underwrite any losses or depts incurred by the financial services business.[118]

The exposure to this risk was realised when the market around corporate real estate collapsed in the late 1980s and early 1990s. It left Westinghouse needing to fund billions in bad loans which eventually came to a value at $3.8 billion for which, due to Marous's agreement, Westinghouse Electric Corp. was liable. On top of this the recession of the early1990s resulted in no spare cash in the company coffers and so to maintain liquidity the only option for Westinghouse management was to sell off some of the business units.[119] While the initial sell-offs had no direct impact on the SOFC team, any members of staff within the R&D centre who were directly associated with business units that were sold were also included in the assets of the sale. This had the effect of reducing the number of personnel within the centre and across the course of the 1990s the size of the R&D centre, in terms of staffing, would

[117] Massey, Steve, 'Who Killed Westinghouse - a Special Report in Six Parts', *Pittsburgh Post-Gazette*, (1998).
[118] Ibid.
[119] Ibid.

rapidly reduce as various business units were sold, with the R&D centre becoming a shadow of its former self.[120]

However, these sell-offs did not solve the company's financial issues. Further liabilities arose from pension shortfalls, environmental disputes and litigation surrounding nuclear plants exceeding a further $2 billion. Further sales and divesting followed, raising $10 billion. By the mid-1990s, the company was in better financial health and was returning profits, but the markets remained unimpressed, mainly due to a lack of a plan for growth, the central tenet of neoliberal market ideology.[121]

To give Westinghouse a new driver for growth, the-then (and last) CEO of Westinghouse, Michael Jordan (the fourth CEO since 1983) decided the best option was to strengthen the company's presence in broadcasting. Westinghouse had long had a presence in the broadcast sector, setting up some of the original commercial radio stations in the US and previously owning cable TV companies in the 1970s and 1980s, from which it understood that these had previously provided reliable revenue streams. In the 1990s, the markets saw broadcasting and media as a significant area of future growth. Therefore, Jordan decided to buy CBS amongst a range other media and cable channels, representing a total $15 billion in spending. To finance this, Jordan was forced to sell off the remainder of the engineering business units, effectively ending Westinghouse's existence as an energy engineering corporation. Most significant of these sell-offs from the viewpoint of the SOFC team was the sale of the fossil fuel energy and power generation business to Siemens for $1.53 billion.[122]

The sale of Westinghouse in November 1997, one of the global leaders in SOFC development to Siemens, home to one of Europe's leading industrial SOFC development programmes, raised a few eyebrows across the SOFC community. However, most in this community understood that in a deal of this size the SOFC aspects would have been lost in the very small print and formed little if any part of the negotiations.[123] Singhal recalled that as the Westinghouse SOFC project was not formally aligned with any particular business group and existed as an internal

120 Singhal Interiew.
121 Massey "Who Killed Westinghouse - a Special Report in Six Parts".
122 Ibid.
123 Here I draw from my own recollections of conversations amongst SOFC community members at the time of the sale when announced in 1997.

venture within the R&D centre, it had actually not even been considered at all within the sale of the power generation business to Siemens. By this time, the 230 members of the SOFC team were almost the only remaining members of the once-3000 strong Westinghouse R&D centre and having existed for some time mainly on DOE and other external funding, and not being part of this sale, they were now facing an uncertain future.[124]

This "loss" of the Westinghouse SOFC programme in negotiations also reflects one of the issues of such technologically specific development within such a large and varied organisation such as Westinghouse. The very small size both in terms of resource and value compared to the operations taking place in the main business units meant that while SOFC was high up in the minds of those actors actively engaged in its promotion and development, it did not figure in the thinking and considerations of others higher up the corporate ladder. It appeared too small to be of major consequence. This is the opposite to what was being seen in the emerging start-up companies and university spinouts. Here the SOFC was at the front and centre of corporate strategy, being intimately linked to constructing company identity and value. Rather than being a relatively small laboratory within a massive company as was the case in Westinghouse, in the case of the start-up the laboratory was the company, and the company was the laboratory.

While the initial Siemens negotiators had not considered the SOFC project within the deal, Singhal was aware of the Siemens development programme at Erlangen in Germany and that there were some development issues with the Siemens planar design. He therefore suggested to his own senior management that the Westinghouse SOFC programme should be rolled into the deal at no extra cost. Both parties accepted this proposition. It was cheaper for Westinghouse than paying off the SOFC team and Siemens appeared to like what they saw of the Westinghouse tubular approach, as they decided to maintain the SOFC programme as a separate venture and paid a rent for space at the R&D centre to continue the work. After evaluation of both the planar and tubular programmes, Siemens decided to settle on the tubular approach, cancelling their own planar programme.[125]

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[124] Singhal Interiew
[125] Ibid..

The decision to maintain the tubular over the planar reflected the significant investment that Westinghouse had already made in the larger vapour deposition process infrastructure and the recent 100-kilowatt tubular system demonstration in the Netherlands which had been promoted as highly successful. Together, these factors suggested Westinghouse was on the cusp of commercialisation.[126] The decision also acknowledged the technical difficulties that the Siemens Erlangen-based planar programme was experiencing in both sealing and cell cracking which had held back progress. Later, on reflection, Singhal felt that cancelling the planar programme was a mistake and that he would have preferred both programmes to run in parallel for longer to see if the issues with the planar programme could have been worked through with the benefit of the joint endeavours of both the US and German teams.[127]

Thick-Film Cells Promise New Opportunities

While the now Siemens-Westinghouse team continued development of the vapour deposited tubular cells focused on high temperature, pressurised operation, many of the new entrants to the SOFC field in the early to mid-1990s looked to the promise and opportunities they saw in thick-film processing. Allied Signal had become a leading exponent of thick-film processing for SOFC the anode-supported planar approach. With their early work on the tape casting and rolling processes, which was named “tape calendering”, Allied Signal had produced a cell with an electrolyte thickness of 5-10 microns, supported on a thicker anode, which showed acceptable performance at the new target temperatures of around 750°C.[128] However, Allied Signal was not alone in identifying the potential benefits of reducing the operating temperature from 1000°C to around 700-800°C or the relative ease with which demonstration cells could be fabricated using thick-film methods. Very soon, several other research groups were beginning to develop their own approaches for replicating

[126] Ibid. and Anonymous Interview 29th Apr 21.
[127] Singhal Interiew.
[128] Minh, Nguyen Q., 'Productionof Reduced-Temperature Solid Oxide Fuel Cells by Tape Calendering', in *First European Solid Oxide Fuel Cell Forum*, ed. by Ulf G. Bossel (Lucerne: European Fuel Cell Forum, 1994), pp. 587-596.

the merits the anode-supported cell by other means, which resulted in a growth of activity across the field.[129]

The examples discussed here are not exhaustive, they merely illustrate the multitude of different designs and forms of the zirconia-based SOFC. They demonstrate how the affordances of a particular set of materials and an agenda built from the consensus of a knowledge community around a reverse salient can lead to many different sets of development pathways being constructed. Scientists and engineers could apply their skills, ingenuity and creativity to the problem of how to drive the agenda within the constraints of the material logics they faced. Where existing logics proved too limiting, they could explore new materials or designs, and investigate how these could change the logics and open up new avenues of development.

By targeting lower operating temperatures researchers looked to reduce demands on the level of engineering required around associated components such as gas manifolding, sealing and electrical interconnection. In Europe, the national laboratories of a number of nations, particularly Denmark, the Netherlands and Germany, increased their SOFC research activities, and were joined by a number of new academic actors also entering the field.[130] In Australia, activities at the national research centre CSIRO led to the eventual spin out of a company called Ceramic Fuel Cells Limited (CFCL) who although initially investigated electrolyte supported cells, also eventually moved towards anode-supported cells.[131]

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[129] Cassidy, Lindsay, and Kendall, "Production of Ysz Based Planar Solid Oxide Fuel Cells with Operating Temperatures of 750-800c by Thick-Film Methods"; Ivers-Tiffée, "The Materials and Technology Development of Ceramic Components for a Reduced Temperature Sofc ", pp. 1042-1043; Buchkremer, H. P., U. Diekmann, and D. Stover, 'Components and Stack Intergration of an Anode Supported Sofc System', in *Second European Solid Oxide Fuel Cell Forum,* ed. by Bernt Thorstensen (Oslo: European Fuel Cell Forum, 1996), pp. 221-228; de Souza, Selmar, Steven J. Visco, and Lutgard C. De Jonghe, 'Ysz-Thin-Film Electrolyte for Low-Temperature Solid Oxide Fuel Cell', in *Second European Solid Oxide Fuel Cell Forum,* ed. by Bernt Thorstensen (Oslo: European Fuel Cell Form, 1996), pp. 677-685; Bagger, C., 'Status of Danish Solid Oxide Fuel Cell R&D', *ECS Proceedings Volumes,* 1999-19 (1999), p. 33.

[130] For European National Laboratory see for example Knudsen, Bagger, and Mogensen, "Combining Science and Practice in the Danish 'Dk-Sofc' Program"; Tietz Interview 17 Oct 22 Kilner Interview 30 Mar 22, Interview with John Irvine Conducted by Author on 31st Oct 2022. The early 1990s also marked my own entry into the field, key reasons for this being those described here and detailed in the introduction to this chapter.

[131] Badwal, S. P. S., et al., 'Market Targets and State of Product Development at Ceramic Fuel Cells Limited', in *Second European Solid Oxide Fuel Cell Forum,* ed. by Bernt Thorstensen (Oslo: European Fuel Cell Forum, 1996), pp. 55-64; Godfrey, B., 'Competitive Positioning of Planar Sofc Technology – Cfcl's Experience', *ECS Proceedings Volumes,* 1999-19 (1999).

The move towards the anode-supported cell in the 1990s was also accompanied by the construction of ideas around potential new markets for the SOFC. One such market was that of domestic cogeneration, which took the idea of combined heat and power (CHP), initially envisaged at a small industrial or district level of several hundred kilowatts or a few megawatts electrical output. In such a system an individual dwelling could meet all of its heat and electrical needs from an SOFC of one to five kilowatts electrical output. With the high volumetric power densities (the number of kilowatts per cubic metre) potentially offered by the planar SOFC, developers and promoters of such systems suggested these would be similar in size to a small refrigerator or washing machine.[132]

Such ideas gained the attention of several utilities, especially in Europe where many houses were already connected to gas grids. A number of European utility companies, such as British Gas and Gaz de France, became active in SOFC research, participating in European Commission programmes looking to explore how the SOFC would be situated within their energy interests.[133] Whereas previous attempts to explore fuel cells on the gas grid such as the TARGET programme in the US, which ran from the late 1960s to the early 1980s, were often seen as a way for the gas utilities to gain market share from the electricity utilities by using the gas grid to circumvent the electricity grid, this new interest, especially in Europe, was taking place in an energy market where deregulation was blurring the old boundaries between the supply of gas and electricity with utilities beginning to supply either or even both to customers and there were some who saw domestic CHP as a way to further disrupt the old certainties and create new market opportunities.[134]

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[132] Badwal, et al., "Market Targets and State of Product Development at Ceramic Fuel Cells Limited", p. 56; Diethelm, R., 'Status of the Sulzer Hexis Solid Oxide Fuel Cell (Sofc) System Development', *ECS Proceedings Volumes,* 1997-40 (1997); McCall, William, 'Boom in Fuel Cell Research Spells New Future for Alternative Energy ', *LA Times,* (2001); Interview with Michael Pastula, Conducted by Author 5th April 2022

[133] Taylor, Mark R. and Daniel S. Beishon, 'A Study for a 200kwe System for Power and Heat', in *First European Solid Oxide Fuel Cell Forum,* ed. by Ulf G. Bossel (Lucerne: Erupean Fuel Cell Forum, 1994), pp. 849-873; Dicks, Andrew L., 'Hydrogen Generation from Natural Gas for the Fuel Cell Systems of Tomorrow', *Journal of Power Sources,* 61 (1996); Ponthieu, E., 'Status of Sofc Development in Europe', *ECS Proceedings Volumes,* 1999-19 (1999).

[134] Wald, Matthew L., 'State Outlines a Far Different Lilco', *The New York Times,* (1994); Drenkhahn, Wolfgang, 'Solid-Oxide Fuel Cells and Chp- an Environmental Solution in the Making', *Power Engineering Journal,* (1996); Godfrey, "Competitive Positioning of Planar Sofc Technology – Cfcl's Experience", p. 78; Dunn, Seth, 'Micropower: The Next Era', *Worldwatch Papers,* ed. by Jane A. Peterson (Worldwatch Institute, 2000), pp. 1-94.

Prominent promoters of the home cogeneration system included Ceramic Fuel Cells Limited (CFCL) from Australia and Sulzer Hexis from Switzerland. Both had been spun out from larger more established organisations with CFCL originating from the SOFC work carried out by the Australian National Labs CSIRO and Sulzer Hexis starting out as a project within Sulzer Innotec, the research arm of the parent company Sulzer, which spun out as a separate entity in 1997.[135] Both companies looked to operate their respective stacks between 750 and 800°C, but both took slightly different approaches to achieve this aim. CFCL adopted the anode-supported electrolyte route, utilising a thinner yttria-stabilised-zirconia electrolyte to lower the resistive loss across the layer.[136]

Sulzer Hexis on the other hand remained with the thicker electrolyte using this as the supporting structure within their cell. Following the materials logic proposed by Steele, Sulzer Hexis looked to use an electrolyte material with higher conductivity to reduce the resistive loss, but rather than the ceria-based systems proposed by Steele, researchers at Hexis adopted a scandium doped zirconia.[137] This avoided the electronic conductivity issues of the ceria systems, exhibiting the almost pure ionic conductivity of the yttria-stabilised-zirconia. Changing the dopant to scandium as opposed to yttrium increased conductivity to an acceptable level, but also increased cost with scandium being more expensive than yttrium.[138]

Designers at Hexis looked to counter this cost implication through their novel design. Whereas designs such as the CFCL stack, in common with many planar stacks, required tricky edge sealing around the periphery of their cells and interconnects, the Hexis developers simplified the sealing requirement, which in turn,

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[135] Badwal, et al., "Market Targets and State of Product Development at Ceramic Fuel Cells Limited"; Diethelm, "Status of the Sulzer Hexis Solid Oxide Fuel Cell (Sofc) System Development"; Behling, *Fuel Cells : Current Technology Challenges and Future Research Needs / [Internet Resource]*, p. 345.
[136] Godfrey, Bruce, et al., 'Planar Solid Oxide Fuel Cells: The Australian Experience and Outlook', *Journal of Power Sources,* 86 (2000).
[137] The inference to scandia stabilised zirconia is drawn from the mention of partially stabilised zirconia in Batawi, Emad, 'Cell Manufacturing Processes at Sulzer Hexis', *ECS Proceedings Volumes*, 2001-16 (2001), p. 142.and cross-referencing to the later paper which reference the partially stabilised form of scandia doped zirconia (6ScZrO2) Price, et al., "Upscaling of Co-Impregnated La0.20sr0.25ca0.45tio3 Anodes for Solid Oxide Fuel Cells: A Progress Report on a Decade of Academic-Industrial Collaboration", p. 3.
[138] Irvine, John T.S. and Paul Connor, 'Alternative Materials for Sofcs, Opportunities and Limitations', in *Solid Oxide Fuels Cells: Facts and Figures,* ed J.T.S Irvine and P. Connor (London: Springer-Verlag, 2013), pp. 163-180 (p. 168).

they hoped would result in lower manufacturing costs.[139] Theirs was a radial design with a central hole, the electrolytes resembling a compact disc, both in size and shape. Fuel would travel up the central channel made by the central holes of a stack of cells and move radially out to the edge. On the other side of the cell, air would be routed through a series of channels and also end up at the outer edge of the cell. There were no seals on outer edges of the stack and excess fuel and air were allowed to combust.

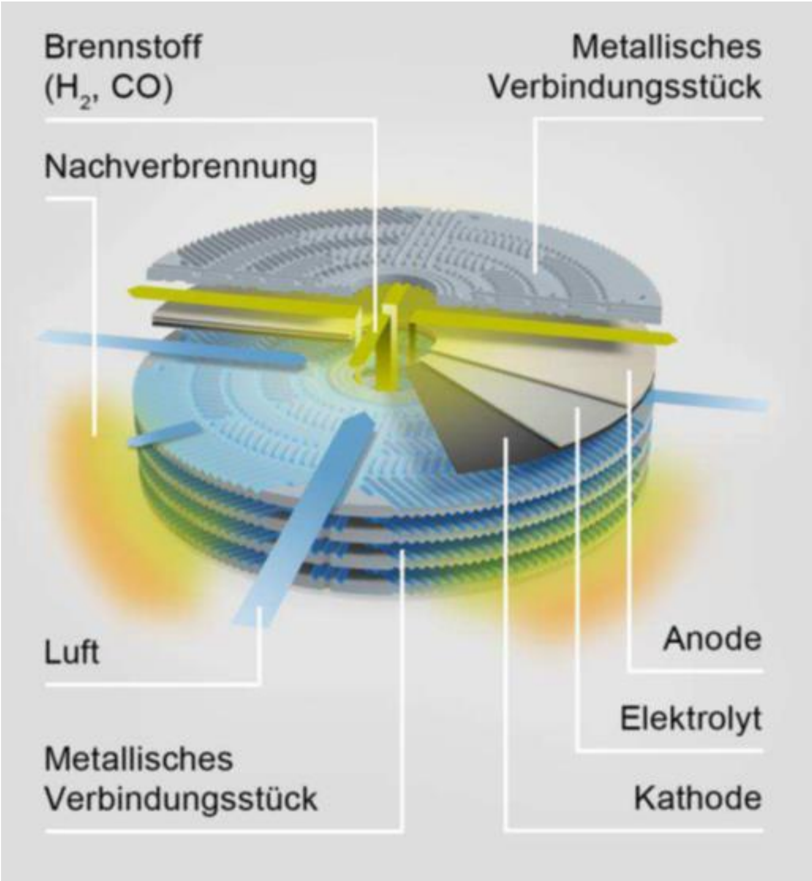

Figure 8; Schematic representation of the Hexis planar SOFC concept. Reproduced with permission from Mai, Andreas, Jan Gustav Grolig, Michael Dold, Felix Vandercruysse, Roland Denzler, Bernhard Schindler, and Alexander Schuler, 'Progress in Hexis' Sofc Development', ECS Transactions, 91 (2019), 63-70, p.64.

This created a system where heat rather than electricity was the main energy output, reflecting the energy requirements of many European homes, where heat

[139] Diethelm, Roland, 'Status of the Sulzer Hexis Sofc Stack and System Development', *ECS Proceedings Volumes*, 1993-4 (1993).

demand was generally greater than electricity.[140] Such design considerations placed the Hexis system as firmly targeting the domestic energy market and combined with the activities of other companies, such as Australian CFCL and Global Thermoelectric in Canada, would see the potential and promise of this sector grow in the eyes of investors who envisaged smaller domestic based consumer units as a quick route to market and investment returns.[141]

While much of the emergence of thick-film processing focussed on the development of smaller planar systems there were other SOFC developers who were still in favour of tubular systems. These were not the large bulky two-metre-long tubes of Westinghouse: rather it was a far smaller version, whose size and shape were often likened to a drinking straw.[142] A key proponent of what became termed the “microtubular SOFC” was Kevin Kendall, now established in his chair of chemistry at Keele University in the UK. His enthusiasm for this design revolved around the mechanical robustness that was common to tubular designs allied to the disappointing mechanical robustness of the flat plates he had observed in some of his early work on the early European projects while working at ICI.[143] The distribution of stresses and strains around ceramic tube were always more forgiving than those across a ceramic plate, something well recognised thirty years previously when many early designs adopted a tubular approach.[144] However in his micro-tubular design Kendall saw these advantages as allowing for rapid heating or tolerance to thermal gradients. He would enthusiastically demonstrate this point at talks and conferences using a small gas torch to rapidly heat the end of a small tube to red heat, with no apparent damage, and then repeat the process by heating the edge of a tape cast flat plate, resulting in the shattering of the plate.[145]

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[140] Robert, Gilles, et al., 'Swiss Sofc Integration Activities: Stacks, Systems, and Applications', *Chimia*, 58 (2004), p. 883.
[141] Dunn, Seth, 'Micropower: Electrifying the Digital Economy', *Greener Management International*, 32 (2000); Ruef and Markard, "What Happens after a Hype? How Changing Expectations Affected Innovation Activities in the Case of Stationary Fuel Cells", p. 327.
[142] Haydock Interview 24 Oct 22.
[143] Kendall Interview 9 Mar 22.
[144] Rohr, "High Temperture Solid Oxide Fuel Cells: Present State and Problems of Development". Doenitz and Schmidberger, "Concepts and Design for Scaling up High Temperature Water Vapour Electrolysis☆"; Feduska and Isenberg, "High-Temperature Solid Oxide Fuel Cell — Technical Status".
[145] Haydock Interview 24 Oct 22. I also remember seeing this demonstration of many occasions, always carried out with Kevin Kendall’s characteristic high level of enthusiasm.

With his micro-tubular approach Kendall also targeted the smaller end of SOFC applications, with prototypes aimed at around 1kW electrical output. With this arrangement Kendall was looking to use the thermal robustness of the tubes to accommodate the rapid heating and cooling cycles that he envisaged would be required for use as a small, portable power supply for remote applications that could be repeatedly switched on and off again. While the size was also suitable for a domestic power supply his initial assessments were that the remote and portable markets would be more willing to carry the greater expense that an early generation SOFC would very likely entail. Kendall managed to gain a patent on his design and published a number of papers from which he hoped to generate interest in his ideas.[146] He formed the company Adelan in 1996 and as such was an early exponent of the small SOFC spin-out from university research.[147] While Adelan still continues to trade in the UK, its micotubular technology found more interest in the US. Companies such as Accumentrics and later AMI (now Adaptive Energy) used micro-tubular concepts as a basis for smaller SOFC systems based around ideas on niche applications in defence or remote, portable power.[148]

While Europe was witnessing a surge in growth of SOFC activity from new actors across the 1990s, growth in the US was slower. In the US the SOFC continued to be viewed within the context of the larger central generation facility or as distributed industrial power, but still in the megawatt scale, with Westinghouse continuing to gain most of the DOE funding for SOFC development. The Gas Research Institute (GRI) and Electrical Power Research Institute (EPRI) did have limited funding available and supported some smaller ventures, as did military interests via the Defence Advanced Research Projects Agency (DARPA), but these

[146] Kendall, Kevin and Mirjana Prica, 'Integrated Tubular System for Small-Scale Cogeneration', in *First European Solid Oxide Fuel Cell Forum,* ed. by Ulf G. Bossel (Lucerne: European Fuel Cell Forum, 1994), pp. 163-170; Kendall, Kevin, "Solid Oxide Fuel Cell Structures", European Patent Office, EP0689724B1, Keele University, 2000; Alston, T., et al., 'A 1000-Cell Sofc Reactor for Domestic Cogeneration', *Journal of Power Sources,* 71 (1998).
[147] Kendall Interview 9 Mar 22
[148] 'Acumentrics, Sumitomo Form Sofc Joint Venture', in *Fuel Cells Bulletin,* (Elsevier, 2003), p. 1; 'Ultra Electronics Ami Fuel Cells for Uavs, Critical Military Tech', in *Fuel Cells Bulletin,* (Elsevier, 2013), p. 3.

projects were small in comparison to the support the DOE was giving Westinghouse.[149]

Companies such as Ztek, which emerged from MIT's Lincoln Labs in the late 1970s, along with Ceramatec and SOFCo, both of which originated from the University of Utah, were some examples of smaller enterprises emerging from US universities from the late 1970s through to the 1990s with these alternative, more limited funding steams. Both companies did make contributions to the field, Ztek was one of the first embodiments of a planar stack that would become so common over the following decades, while Ceramatec had visions of producing smaller compact planar systems, sized from small industrial down to domestic applications. Ceramatec also developed as a technology provider and supplied early tape cast electrolytes to Sulzer Innotec to aid their early system development, but neither Ztek or Ceramatec were able to cross the boundary to become a fully-fledged manufacturing company and remained orientated around the research and development of materials, processes and system modelling.[150]

Outside of Westinghouse, Minh's group at Allied Signal were probably the most prominent group developing smaller planar systems in the US. Their anode-supported system captured a lot of attention in Europe and beyond, shaping a lot of the development thinking. Further, Minh's classic 1993 review paper "Ceramic Fuel Cells" in the *Journal of the American Ceramic Society*, a general review of the state of the art in SOFC design, brought his work to a wider fuel cell audience reinforcing his position as a prominent figure in SOFC research.[151] However, the early progress and potential lead of this group was hampered by continued corporate buyouts over the 1990s with Allied Signal first changing to Honeywell, then Honeywell being purchased by General Electric.[152]

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[149] Kinzey, B.R. and R.K. Sen, 'Us Fuel Cell Research and Applications, 1960--1989', (Office of Scientific and Technical Information (OSTI), 1989); Krist, Kevin, 'Fabrication Methods for Reduced Temperature Solid Oxide Fuel Cells', *ECS Proceedings Volumes*, 1993-4 (1993); Williams, Mark C., 'U.S. Solid Oxide Fuel Cell Powerplant Development and Commercialization', *ECS Proceedings Volumes*, 1997-40 (1997).
[150] Hsu, M., 'Zirconia Fuel Cell Power System Planar Stack Development', in *Fuel Cell Seminar*, (Tucson, AZ: Courtesy Associates Inc., 1986), pp. 84-87; 'Fuel Cell Technology Promises Cost-Efficient, Environmentally Safe Energy Sources for Commercial and Household Applications', *Business Wire*, (1992); Diethelm, "Status of the Sulzer Hexis Sofc Stack and System Development".
[151] Minh, "Ceramic Fuel Cells".
[152] Minh Interview 18 May 21.

The sale of Honeywell to General Electric brought one of the original developers of the SOFC in the US back into the field, although as it was via the buyout of a larger corporate entity, it was by a tangential route rather than a specific corporate desire re-enter the field of SOFC technology development. It also emphasises, in a similar vein to the transfer of the Westinghouse project to Siemens, how the fortunes of smaller technological development groups get lost and in some ways become hostage to fortunes within the wider business machinations of the parent corporation.[153]

It could be argued that the mid-to late 1990s marked a distinct change in the direction of SOFC development. In their study of hype cycles in stationary fuel cells in German-speaking Europe, STS scholars Annette Ruef and Jochen Markard termed this period of time, from 1993 to 1997, as “the rediscovery period”, a time where their investigation of German language newspapers revealed the start of an upturn in interest in fuel cells.[154]

The historical analysis carried out within this thesis shows that research groups had begun to move toward thick-film processing in the late 1980s and early 1990s, a trend which continued a trend which continued across the 1990s. This shift was especially visible in Europe with many research groups entering the field. Therefore, it seems fair to contend that the move to thick-film processing was a significant enabling factor in the growth of interest in stationary fuel cells observed by Ruef and Markard in the mid-to late 1990s. It must be stressed that not only did Ruef and Markard focus just on the German speaking press, they also considered other types of fuel cell such as the PEM and the PAFC as well as the SOFC, so their results may reflect an amalgam of agendas and not just those arising from the reverse salients of the SOFC technical community.

Such analytical constructs, again highlight how different fuel cell types were often aggregated together, lessening awareness of how the individual characteristics

[153] It is of interest to note that in the 2000s, both Rolls-Royce and GE attempted to create spin out companies of their SOFC activities. Possibly to allow more autonomous decision making by the respective SOFC management teams to respond to changing conditions across the SOFC and fuel cell landscape as opposed to being swamped by wider corporate concerns. However, both remained wholly owned by parent companies.
[154] Ruef and Markard, "What Happens after a Hype? How Changing Expectations Affected Innovation Activities in the Case of Stationary Fuel Cells", p. 324.

of each type influenced the actor logics around development decisions and pathways. While the aggregations in this analysis is likely a reflection of the conflations that were taking place in their analysis data, it echoes the lack of awareness of the nuance in such press reports between fuel cell types and their different characteristics and potential applications. Nevertheless, the results of Ruef and Markard do indicate a wider trend that occurred in the energy markets over the same time, a move towards smaller generation units and the integration and utilisation of heat.[155]

This trend towards smaller more distributed forms of generation allowed the construction of new imaginaries concerning electricity generation and energy provision which had not been which had not been present a decade or so earlier when Westinghouse were first envisaging their large tubular system. The affordances offered by thick-film processing had allowed some developers of the SOFC to reframe and reposition their technology to synergistically align with the new set of market imperatives emerging from the trends towards applications around smaller distributed cogeneration. The new, more compact SOFC designs that were appearing from developers adopting thick-film processing lent themselves to meeting the needs and challenges that were emerging from these potentially lucrative energy markets.[156]

This new development activity also attracted the attention of entrepreneurial investors. Recent successes around investments in emerging digital technologies, allied with government policies around deregulation of energy markets and an increasing awareness of environmental effects of fossil fuels suggested that new energy technologies might be the next big opportunity for investment. This led to a rapid growth of stock values for SOFC companies, with investors speculating on the size of imagined markets, just the same way that many had witnessed in the digital domain.[157] Such excitement was heightened by related activities in low-temperature fuel cells for automotive activities and the rapidly increasing valuations of companies such as Ballard in Canada which was in the process of developing fuel cell stacks to

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[155] Ibid. p. 325.
[156] Dunn, "Micropower: Electrifying the Digital Economy".
[157] Wheale, Peter Robert and Laura Heredia Amin, 'Bursting the Dot.Com "Bubble': A Case Study in Investor Behaviour', *Technology Analysis & Strategic Management*, 15 (2003); Goodnight, G. Thomas and Sandy Green, 'Rhetoric, Risk, and Markets: The Dot-Com Bubble', *Quarterly Journal of Speech*, 96 (2010).

meet this potential need.[158] Increasing policy imperatives around emissions for both vehicles and other combustion processes from various levels of government also helped legitimise belief that devices such as fuel cells would become increasingly relevant and important.[159]

Within these contexts, the domestic co-generation market appeared to be a highly probable area of growth for the SOFC. The promise of a clean, super-efficient cogeneration unit no larger than a refrigerator providing a household’s complete heat and electricity was a tantalizing prospect. The new designs of SOFC that were being imagined in the second half of the decade were framed around this this promise, and by the year 2000 several emerging SOFC companies were riding the wave of enthusiasm, with rising share prices driven by investor optimism that a product and a profit were just around the corner. All that was needed was to translate the promising cell and stack results into a neatly packaged system, a task that would prove exceedingly difficult to realise.

In the next Chapter I follow the history of one such company, Global Thermoelectric as those within it worked to realise the goal of developing the small SOFC systems described above. My associations with the company permitted me access to various actors and communications which allowed the development of a microhistory which sits in parallel to the meso and macro historical accounts of this chapter. Together they paint a picture of scientists and engineers undertaking demanding technical development while attempting to reconcile the demands and expectations of investors excited by the promise.

[158] Koppel, *Powering the Future : The Ballard Fuel Cell and the Race to Change the World*.
[159] Lloyd, Alan C., Jonathan H. Leonard, and Ranji George, 'Fuel Cells and Air Quality: A California Perspective', *Journal of Power Sources,* 49 (1994). Serfass, Jeffrey A., Michael K. Bergman, and Wendy Rodenhiser, 'Commercial, Environmental and Legislative Factors That Influence the Implementation of Fuel Cells', *Journal of Power Sources,* 49 (1994).

Chapter 6: Bubbles of Expectations and Pins of Reality: The Global Thermoelectric Story

I first arrived in Canada in the spring 2000 and I was presented with what felt like a very strange world. It was a bright day, and the sun was prominent in the sky giving off a slight warmth, but a definite chill remained when out of its direct glow. While some patches of snow remained on shady embankments, where it had melted it revealed the grass beneath, brown and dishevelled looking, after months smothered by the snow. Some streets were coated with dust and gravel, used to improve traction on the roads in the cold Alberta winter where the frigid temperatures make the use of salt pointless. Other streets less so, as mechanical street sweepers went around the city rapidly cleaning away the detritus of winter. Around the streets old vans and pick-ups dominated the traffic, many worn and dented, often with cracked windscreens, another consequence of the use of gravel in winter. In the downtown core glass walled skyscrapers seemingly huddled together, the glass glinting and gleaming in the cool spring sunlight. Approaching in the aircraft this effect was exacerbated, a tight city metropolis rising out of the surrounding prairie, and island of urbanisation in a sea of flat grassland, extending eastwards as far as you could see and westward to the faint snowy peaks of the Rocky Mountains piercing the distant horizon. The city had its origins and heritage in the cattle ranches of these expansive grasslands, but it was oil that pumped through the beating heart of the downtown core. A city whose fortunes and prosperity were built on that black lifeblood of the 20th century.

I was visiting Calgary, Alberta to interview for a position with Global Thermoelectric (GTE), a company which was rapidly expanding its solid oxide fuel cell activities. I would go on accept a position within the company, being hired by Dave Ghosh in mid-2000 as part of the company's initial expansion into their new premises. I was part of the cell development team from July 2000 to August 2002 as the company struggled to deal with the rapid growth demanded of it to meet the promise and expectation generated by the fuel cell hype cycle of that time. This gave me familiarity with many of the actors through being colleagues and managers allowing me privileged and intimate access through their oral histories to life inside a company in the throes of a technology hype cycle and as such made Global Thermoelectric a natural choice for a detailed case study of such a company.

The pattern of fuel cell development in GTE was not unique. Other fuel cell companies have seen similar patterns of varying levels of optimistic investment and disappointing outcomes at various times. It does however epitomise the cycle of expectation and disillusionment common across many SOFC developers and investors. The story of GTE also encompasses a more general level of excitement and expectation that some placed on technology at the turn of the millennium. This expectation was energised through the seemingly unflinching confidence of investors in the ever-increasing value of communications and internet companies and, in-turn, created a wider optimism around companies with early-stage technologies at laboratory scale that seemed ripe for commercial growth. This chapter explores the events at GTE as an exemplar of dynamics within the SOFC field. It is a case study of a small company which initially looked to the SOFC with a very specific application in mind but rapidly realised that in order to develop the technology it would need far greater resources than this initial application could bring to bear.

In this chapter I draw from oral history interviews of GTE employees to show how the solid oxide fuel cell became integrated into GTE product development portfolio and then went on to dominate the company identity and direction. I also engage with posts to an on-line investor discussion board focussed on GTE, hosted within the website Siliconinvestor.com.[1] This discussion board contains over 6000 posts covering October 1997 until May 2005, which reveals not only the concurrent views and opinions of multiple smaller and private investors, but also texts of GLE press releases and announcements which had material impact on the tenor of these views and opinions.

I build on the arguments presented in the previous chapter, in that the emergence of thick-film processing as a significant enabler which allowed new actors, such as GTE, to enter the field. The apparent simplicity of the thick-film technology allowed the company to make rapid inroads into developing and testing cells and stacks. These initial advances created excitement and expectation for the

[1] https://www.siliconinvestor.com/subject.aspx?subjectid=17464&LastNum=4916&NumMsgs=25

prospects of the technology within the company, while other external events acted to legitimise both the excitement and expectation in the minds of many actors. While GTE produced cells and stacks with state-of-the-art performance, this technology still required considerable further development before it could be commercialised. The realisation that the road to a commercial product was far more convoluted and complicated than producing the cells and stacks themselves created disillusion among investors which, when combined with other wider events eventually led to the sale of the company.

A Company Built on Solid State Energy Conversion

As with many Albertan technology enterprises, GTE owed a lot to oil and gas. The main application for GTE's foundational product, the thermoelectric generator, was providing corrosion protection of oil and gas pipelines by supplying a small electric current to counteract the effects of corrosion, known as cathodic protection. In a similar way to the fuel cell, the thermoelectric generator can trace its roots to the NASA space programme, originally being developed by 3M and used by NASA to provide electrical power on the moon as part of the Apollo missions. With the end of the Apollo program, 3M decided that thermoelectric generator technology did not align with company priorities and looked to sell it. Seven 3M employees who had worked on the technology decided that they would buy it, and one of those scientists, while on a hunting trip to southern Alberta, discussed their plans and sparked interest amongst his fellow hunters. This led to the creation of a group of around 35 local investors from the area around Bassano in southern Alberta who injected Can$250,000 into the project with a further Can$750,000 being secured from an Alberta provincial government loan allowing a company to be set up in 1975. This formed the basis of Global Power Technologies, which acquired and went on to found GTE in 1975.[2]

[2] Crawford, Anne, 'Global Thermoelectric Wins National Exporting Award', *Calgary Herald,* (1998); Nelson, Barry, 'Self-Powered Furnace a Hot Item', *Calgary Herald,* (1998); Pastula Interview 5 Apr 22

For the first 20 years of the company's existence, the thermoelectric generator was the central product around which it developed and grew. Over this time, the company remained relatively small and stable, with around 40 employees split across two sites. The main headquarters was situated in the southeast of the city of Calgary, while a manufacturing group was located in the small town of Bassano, approximately 140km southeast of Calgary. The thermoelectric generator formed a core part of the company identity. The name "Global Thermoelectric" not only connected the company with the product, but also related the idea that this small Canadian company had installed thermoelectric generators not just in the Canadian oilfields but also oilfield and pipeline installations around the world, often in the remotest of locations operating under the harshest of conditions. GTE's market for the thermoelectric generator extended beyond the Canadian oilpatch, to many of the world's remote oilfield well heads and pipeline routes such as Kazakhstan, Siberia and the Andes.[3]

Like the SOFC, the thermoelectric generator is a solid-state device which due to its lack of moving parts makes it ideally suited for such remote or rugged locations where minimum maintenance will be available. The principles of the technology are based on the Seebeck effect, where an electrical potential (voltage) is created between hot and cold junctions of two different conducting materials.[4] In the GTE technology, the semiconductor lead telluride was used as the thermoelectric material.[5] When such a material was heated on one side and cooled on the other it created a small electrical potential (voltage) between the hot and cold sides. Through chemical modifications to the thermoelectric material the carriers of electrical charge could be engineered to flow from hot to cold or vice-versa. By repeating these alternating elements in a larger array, a usable voltage could be built up, which when connected to an external circuit would provide a useful electrical current.

Of the disadvantages with the thermoelectric generator, one was its relatively low efficiency, which was of the order of 4-6%. This had generally not been too much of a concern when smaller units were being used in the cathodic protection

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[3] Anonymous Interview, Conducted by Author on 12 March 2022; Pastula Interview 5 Apr 22.
[4] Rowe, D.M., 'Thermoelectric Power Generation', *Proceedings of the Institution of Electrical Engineers*, 125 (1978).
[5] Anonymous Interview 12 Mar 22.

role, as it was a simple matter to take a small bleed of gas or oil from the pipeline to use as the fuel to heat the hot side of the thermoelectric generator. In terms of the percentage of fuel in the pipeline, the amount going to the thermoelectric generators was negligible and the role they played in protecting the infrastructure from corrosion more than compensated for the tiny amount of gas used.

However, where thermoelectric generators were being used away from infrastructure such as oil or gas pipelines, low efficiency became more of an issue. One such use was remote communication towers. Here, fuel for the generators needed to be shipped in, often by helicopter, as the towers were beyond any road network or energy infrastructure. Unlike those generators adjacent to pipelines, these costs were not negligible, and therefore efficiency of energy conversion in these applications was a consideration of far greater importance.[6]

Another disadvantage of the thermoelectric generator concept was its footprint. As well as requiring a fuel to heat one side of the thermoelectric material, heat-sinks were required on the other side to remove heat and keep this side cool. In the early 1990s, part of this heat removal system comprised of extended cooling fins, which spread from the body of the device like metallic branches on an artificial tree, with a footprint of maybe several square metres. While this was not a problem for a 500-watt system, then the biggest single system on offer, customers were beginning to demand larger systems of 3-5 kilowatts to meet the increasing power demands of more sophisticated communications and telemetry. At this level, thermoelectric generators systems began to become unwieldy, and the costs of fuel supply was also more prominent.[7]

As GTE looked to expand into these larger power markets it faced competition from other companies using different technologies with higher efficiencies, such as Ormat Technologies, who had developed remote power generation systems based on the Organic Rankine Cycle.[8] Here, thermoelectric technologies faced the further disadvantage of high capital cost. Thermoelectric generators cost in the region $25,000 per kilowatt. While such a high outlay could be

[6] Interview with Dave Ghosh, Conducted by Author on 28th March 2022.
[7] Anonymous Interview 12 Mar 22.
[8] Ghosh Interview 28 Mar 22 for technical background to the Organic Rankine Cycle see Inc., Ormat Technologies, 'Organic Rankine Cycle-Orc', (2019) <https://www.ormat.com/en/company/news/view/?ContentID=8819>.

accounted for in smaller systems using negligible bleeds of fuel from adjacent major pipelines, the high initial costs became more difficult to justify at higher power ratings, especially when combined with the more significant fuel demands. The lower initial costs of competing technologies, coupled with their higher efficiencies, put the thermoelectric generator at an economic disadvantage, particularly when the overall cost of running the system over many years was considered. Therefore, for GTE to continue to grow and to develop generators with the power ratings increasingly demanded by customers, it would need a new technology. The solid oxide fuel cell appeared to fit the bill. [9]

Diversification is Key

The company had a relatively stable technological platform in the thermoelectric generator and was in a reasonable financial position. However, while sales could be lucrative, they were closely linked to the fortunes of the oil and gas business and so steady revenue was not guaranteed. Privately-owned GTE had retained the scientific focus of the original founders, but the Alberta government sold its stake in the company to a venture capital firm (Foundation Equity Corp. of Edmonton) causing GTE to first list shares on the Alberta Stock Exchange in 1994.[10] With this shift from private to public ownership, company directors now had responsibility to shareholders which changed the business outlook of the company significantly.

This shift to a more business-oriented viewpoint was emphasised by the appointment of Jim Perry as company president in 1997, who with previous board level appointments at both Schlumberger Canada and Computalog Ltd., brought considerable business experience.[11] Between 1993 to 1998, the company had managed to grow significantly increasing annual revenues from Can$3.4 to Can$16.3 million, but tied to large, individual contracts. For example, in 1997, the company sold Can$3.2M worth of generators to India and a further Can$2.25M to China. Perry believed that reliance on a single product in a single market carried business risks and that some form of diversification was essential to give a steadier stream of

[9] Ghosh Interview 28 Mar 22
[10] Chase, Steven, 'Global Fires up New Products', *Globe and Mail,* (1998).
[11] Nelson "Self-Powered Furnace a Hot Item".

revenue. GTE was now to some extent at the mercy of the markets where steady growth was seen as key to a company's continued success. This was highlighted by Michael Hill, a market analyst following GTE, who was quoted in a 1998 piece on GTE in the Toronto-based newspaper, *Globe & Mail* as saying, "The market doesn't like lumpy sales and lumpy earnings." [12]

The first significant move to diversification was the development of a stand-alone heater for military vehicles. This was based around an original idea from 1991 after the devastating ice storms of that winter which left many without power across the northeastern seaboard of North America. This idea combined the existing company knowledge from thermoelectric generation and fuel combustion. Heat generated from combustion of a logistical fuel, such as diesel or bottled gas, simultaneously providing heat to the hot side of the thermoelectric array, which provided electrical power to drive fans and blowers to distribute the combustion heat around the space to be heated. Although innovative and potentially useful, initial cost estimates suggested that such heaters would be too expensive for a domestic market.[13] However, following the first Gulf War in 1991, the US Army decided it needed better, more reliable heaters in its military vehicles and launched a competition for improved heater units. GTE entered this competition using their existing heater as the basis for the military unit. In 1996, it beat two US companies to be awarded an $18 million contract for 2000 heaters with potential options for 2000 more.[14]

This was a significant move towards developing a more diverse product line and creating a more consistent revenue stream, gaining the company a Canadian export award in 1998.[15] Although the military heaters appeared to be emerging as a lucrative product line for the company, they did not address some of the main issues surrounding expanding the use of thermoelectric generators in the remote power markets. Such a technology required higher power ratings which entailed unwieldy and expensive installations, and the inherent low efficiency of the thermoelectric conversion process meant high fuel replenishment costs when not directly linked to a

[12] Chase "Global Fires up New Products".
[13] Nelson "Self-Powered Furnace a Hot Item".
[14] Chase "Global Fires up New Products"; Crawford "Global Thermoelectric Wins National Exporting Award".
[15] Crawford "Global Thermoelectric Wins National Exporting Award".

fuel pipeline application. Both of these factors meant that other competing technologies threatened the market penetration of thermoelectric generations into wider remote power applications. New technologies were still required if these issues were to be addressed and GTE was to continue to look to increased penetration and increased revenues in the remote power sector.

SOFC Meets the Need

While there was some effort by GTE to look at new or improved thermoelectric materials which would yield better efficiencies, it was felt by many in the company that these were still not going to provide the order of magnitude improvement required to compete with the alternate technologies which were also prevalent in the remote power space.[16] In trying to address the above issues GTE appointed Jim Lumsden as vice president of research and development. Lumsden was given the remit to search for technologies that could work alongside and complement the existing line of thermoelectric based technologies and expand the range of products the company could field in the growing remote power sector. Described as a unique individual, Lumsden was very personable, strong in the "softer skills" which are invaluable in building relationships and negotiating partnerships.[17] Over the course of his first year in the company Lumsden attended trade shows and technical conferences to gain an in-depth appreciation of the landscape around various new energy technologies, especially technologies that provide a good complement to the existing thermoelectric generator portfolio. Lumsden was described as coming back from his travels as "pretty excited" about the SOFC, with its solid-state construction, minimal moving parts and the potential to utilise a wide range of available logistical fuels, he felt it appeared to fit the requirements very well. He presented the SOFC to the GTE management as the complimentary technology the company was looking for, they agreed, and decided to invest some money into investigating this technology further.[18]

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[16] Anonymous Interview 12 Mar 22; Ghosh Interview 28 Mar 22.
[17] Pastula Interview 5 Apr 22.
[18] Anonymous Interview 12 Mar 22; Pastula Interview 5 Apr 22

Through his conference attendances Lumsden had met representatives Forschungzentrum Jülich, a significant member of the Helmholtz Association of national laboratories in Germany. One of the largest interdisciplinary research centres in Europe, Jülich had extensive activities around energy research, and was home to one of the largest European SOFC research efforts being one of the national laboratories which had seen considerable expansion in SOFC research during the early 1990s. Jülich had developed an anode-supported electrolyte cell based around its proprietary "coat mix" process, involving vacuum slip casting to deposit the appropriate thicknesses of the various cell layers to result in a stack with an operating temperature in the region of 750-800ºC.[19] One reason this operating temperature range was attractive to the wider SOFC community was it allowed the utilisation of more cost-effective materials such as stainless steels in the stack components. This was doubly attractive to GTE as they had significant stainless steel fabrication experience through their thermoelectric generator construction.[20]

Further and most importantly to Lumsden, Jülich were very open to licensing their technology and transferring it to potential commercial developers. Lumsden approached the Alberta Research Council (ARC) to help assess the technology and in later 1997 a small Canadian team headed across to Germany to assess the Jülich technology in more detail. Over the course of late 1997 and 1998 GTE entered into an agreement to transfer the Jülich technology into their own labs.[21] In parallel to this, Lumsden assembled a team of young engineers to develop the cadre of skills he would require. Drawing not only from development engineers in house, he also recruited materials scientists from the programmes of University of Alberta and McMaster University in Ontario, and engineers who had graduated from the University of Victoria's Institute for Integrated Energy Systems which had a strong hydrogen and fuel cell emphasis.[22]

Progress was rapid over the initial months of the arrangement between Global and Jülich, with visits of the Canadians to Germany and Germans to Calgary and

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[19] Buchkremer, H P., 'Advances in the Anode Supported Planar Sofc Technology', *ECS Proceedings Volumes*, 1997-40 (1997); Stöver, D., 'Recent Developments in Anode Supported Thin Film Sofc at Research Centre Jülich', *ECS Proceedings Volumes*, 1999-19 (1999); Tietz Interview 17 Oct 22
[20] Anonymous Interview 12 Mar 22
[21] Ibid.; Ghosh Interview 28 Mar 22.
[22] Pastula Interview 5 Apr 22.

numerous detailed phone calls.[23] Initial cells and other components were shipped to Calgary from Germany for assembly in the GTE laboratory and in March 1998 the first planar SOFC stack was tested, exceeding performance expectations.[24] As well as supplying ready-made cells, Jülich also sent manufacturing equipment to GTE and trained the Calgary staff in production techniques required for the "coat mix" process. In addition to the technology licensing agreement with Jülich, Lumsden also paid Can$450,000 to ARC in November 1997, which funded research to help integrate and fine-tune the ceramic processing required into its nascent Calgary facility, mirroring the Jülich approaches. The main contact at ARC was Dave Ghosh, then manager of the manufacturing technologies group. Ghosh drew on the ceramics processing development experience within ARC, whose previous work had included supporting development of ceramic armour systems for another Calgary firm and silicon carbide and nitride-based materials important to the mining industry across Alberta.[25]

Rapid progress was made in manufacturing cells in Canada: within around six months SOFC stacks were being manufactured and tested in Canada which had at least equivalent performance to those whose components had come from Germany.[26] However, it soon became very clear to both ARC and GTE that while the Jülich system could produce high quality reproducible cells, it was very much a batch process which would struggle to achieve the low-cost, mass-manufacturing that would be required if an SOFC system was to move from the laboratory and emerge as a commercially viable prototype.[27] Therefore, GTE extended the remit of the ARC development contract to investigate other methods of ceramic processing which would be amenable to continuous, mass-manufacture of the anode-supported SOFC. Such techniques revolved around tape casting of anodes and screen printing of the electrolyte and some initial fabrication trials and cell tests using these techniques

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[23] Anonymous Interview 12 Mar 22 2
[24] Global Thermoelectric, 'Global Thermoelectric Press Release (Message 12)',Global Thermoelectric Discussion Board(Silicon Investor, 1998) <https://www.siliconinvestor.com/readmsg.aspx?msgid=3665602>
[25] Ghosh Interview 28 Mar 22
[26] Ibid.; Global Thermoelectric, 'Details of Sofc Progress from Global Thermoelectric 1998 Website (Message 213)',Global Thermoelectric Discussion Board(Silicon Investor, 1998) <https://www.siliconinvestor.com/readmsg.aspx?msgid=7019717>
[27] Anonymous Interview 12 Mar 22; Ghosh Interview 28 Mar 22.

were conducted over the course of August 1998 to November 1998. However, these were initially an adjunct to the main ARC activities of mirroring the Jülich manufacturing processes. It was not until Ghosh accepted an offer from GTE to take up a position as manager of the emerging fuel cell division that the efforts to develop a scalable process based around tape casting and screen printing really began in earnest.[28]

The move was a risk for Ghosh. He was well-ensconced with a senior position in ARC, a government organisation, well recognised in Canadian circles as an extremely stable and secure employment option. Giving that up was a big step and caused some tension in his family, but Ghosh saw potential in the SOFC technology and the growth potential of the company. GTE had been very active and had raised further funding on the Alberta Stock Exchange, with an ongoing offer of share warrants looking to raise of the order of Can$3 million in early 1998 for the further development of their SOFC technology.[29] Ghosh was convinced that by developing the screen printing and tape casting techniques the SOFC could be made commercially viable. He was also witnessing the on-going growth in the dot-com sector, which further persuaded him that there were potentially significant upsides from getting more involved in a technology at the earlier stages of growth. If he remained at ARC his involvement with SOFC would be far more limited. Ghosh recalled when being invited to join GTE, that Lumsden had said there was no way GTE was going to be continuously spending half a million dollars a year with ARC. So, Ghosh decided to take the risk and move, joining GTE fuel cell division in June 1998, which then consisted of three other people, 6000 square feet of empty warehouse space and a couple of test stations.[30]

The Bubble Begins to Inflate

While the development of the SOFC continued apace over 1998 and into 1999, it was the US Army heater product that helped solidify the financial foundation of the

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[28] Ghosh Interview 28 Mar 22.
[29] Global Thermoelectric, 'Global Thermoelectic News Release - 2nd March 1998 (Text) (Message 11)',Global Thermoelectric Discussion Board(Silicon Investor, 1998) <https://www.siliconinvestor.com/readmsg.aspx?msgid=3578468>
[30] Ghosh Interview 28 Mar 22.

company and seemed to please many shareholders, with the SOFC seen as something of a sideline - an interesting potential new product line but not something which was impacting the value, or at least the perceived value, of the company. Some investors referred to the SOFC work as “icing on the cake”.[31] The SOFC development activities did not seem to impact the stock price which hovered at around Can$1-2 on the Alberta exchange. There were some slight increases in value, mainly related to the US Army heater contract, but the slow pace of US military acceptance trials and ramping up of production during 1996 to 1998 frustrated some investors who saw the company as undervalued.[32] These investors attributed the low and stagnant value of the value of the stock to the limited exposure the company had received residing on the regional Alberta Exchange, and suggesting a listing on the larger Toronto Stock Exchange (TSE) would be beneficial for value.[33] Indeed, such sentiment was shared by Perry who sought to list the company on the TSE over the course of 1997-1998.[34]

In October 1998, GTE listed on the TSE under the symbol TSE:GLE, with trading starting on the 8th October.[35] At around the same time, the company received a Canadian export award in relation to the US Army vehicle heater contract. Both of these brought GTE further into the public eye, moving it from the relative provincial backwaters of Alberta business networks toward a more national and international stage. The export award resulted in favourable press articles in the prominent

[31] speculatingvalue, 'Comment of Fuel Cells Being "Icing on the Cake": Message Number 244',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=7532847>

[32] Chow, D.W, 'Comments on Undervalued Stock: Message Number 4',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1997) <https://www.siliconinvestor.com/readmsg.aspx?msgid=2577458>

[33] One of the earliest voices was Chow, D.W, 'Comment Refering to Lack of Exposure on Tse Impacting Value: Message Number 5',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1997) <https://www.siliconinvestor.com/readmsg.aspx?msgid=2588728> , however such calls became repeated across discussion board comments throughout 1998 as represented by Chow, D.W, 'Push for Tse Listing: Message Number 108',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1998) <https://www.siliconinvestor.com/readmsg.aspx?msgid=5223506> ; speculatingvalue, 'Comment on Need for Tse Listing: Message Nunber 109',Global Thermoelectric Discussion Board(Siliconinverstor.com, 1998) <https://www.siliconinvestor.com/readmsg.aspx?msgid=5225684>

[34] Chow, D.W, 'Response Fro Jim Perry on Tse Listing: Message Number 8',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1997) <https://www.siliconinvestor.com/readmsg.aspx?msgid=2677587>

[35] Chow, D.W, 'Text of Tse Announcement of Global Thermoelectric Listing: Message Number 158',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1998) <https://www.siliconinvestor.com/readmsg.aspx?msgid=5931773> ; speculatingvalue, 'Text of Gte Press Release on Tse Trading: Message Number 163',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1998) <https://www.siliconinvestor.com/readmsg.aspx?msgid=5942021>

Canadian national newspaper *Globe & Mail*.[36] Such coverage moved the share price up a little, but it did not match the lofty heights being enjoyed by Ballard, another Canadian fuel cell company, fast approaching iconic status by leading the charge in fuel cells for automotive applications, and to which GTE was being increasingly compared.[37]

Over the latter months of 1998 into 1999, GTE continued to publish encouraging results for the performance of their prototype SOFC cells and stacks, some based on the Jülich technology and on their own tape casting and screen-printing processes.[38] However, it was the production of the thermoelectric generators, with several large and valuable contracts being awarded over this time and the ramp up and delivery of the vehicle heaters for the US Army, which still defined how many saw the company and dominated its share price.[39]

Events would see this shift dramatically. On April 8th, 1999, GTE issued a press release on the performance of the keenly-anticipated SOFC prototype utilising their locally developed cell processing which would become known in-house as the "TSC cell" an acronym which represented the stages of processing **T**ape casting, **S**creen printing and **C**o-firing. This press release spoke of "materials breakthrough", "output…double the amount we have recorded on previous cells", "tremendous

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[36] Crawford "Global Thermoelectric Wins National Exporting Award".
[37] Several investor comments across 1998 discuss the feelings that the company is undervalued and begin to draw comparisons to Ballard and the potential of the SOFC development to add to the value of GE, these discussions are characterised by comments such as, Stephen O, 'Comment on Stock Price Linked to Current Products and Comparison to Ballard: Message Number 178',Siliconinvestro.com(1998) <https://www.siliconinvestor.com/readmsg.aspx?msgid=6317135> ; speculatingvalue, 'Comment on Undervalued Stock Linked to Current Product and Sofc Research as a Bonus: Message Number 179',Global Thermoelectic Discussion Board(Siliconinvestor.com, 1998) <https://www.siliconinvestor.com/readmsg.aspx?msgid=6318133>
[38] These results were mostly communicated by press releases and were often light on technical detail but served to relay progress to investors speculatingvalue, 'Text of Gte Press Release Announcing Successful Sofc Tests: Message Number 130',Global Thermoelectric Discussion Board(Siliconinvestor, 1998) <https://www.siliconinvestor.com/readmsg.aspx?msgid=5614208> ; Stephen O, 'Overview of Gte Fuel Cell Testsand Plans: Message Number 213',Global Themoelectic Discussion Board(Siliconinvestor.com, 1998) <: https://www.siliconinvestor.com/readmsg.aspx?msgid=7019717> ; speculatingvalue, 'Text of Gte Press Release Announcing Improved Sofc Perfomance: Message Number 291',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8781878> . Two papers which contained more technical information were pitched towards outlining the GTE approach to the SOFC technical community were Ghosh, D., 'Performance of Anode Supported Planar Sofc Cells', *ECS Proceedings Volumes,* 1999-19 (1999). and Potter, E. N., 'The Emergence of Viable Solid Oxide Fuel Cell Technology', *Fuel Cells Bulletin,* 3 (2000).
[39] Chase "Global Fires up New Products"; speculatingvalue, "Message Number 179".

improvement over anything previously reported", "highest power densities reported for commercial solid oxide fuel cells in the world to date" and "patent application on new composite material."[40]

Figure 9; Global Thermoelectric tape-cast, screen printed, cofired (TSC) cell. Image courtesy of Fuel Cell Energy.

The announcement of this successful test coincided with the impending shares warrant sale which was due to expire on the 17th April, a successful completion of which would raise over Can$3 million to fund further SOFC development. Through the listing on the TSE, the impending warrant expiry on the Alberta exchange, and recent press coverage, the company had been receiving wider interest than before and the press release further heightened expectations in the company. Over the coming days, the stock price began a steeper increase in price than had been previously witnessed with values of Can$3 and Can$4 being reached and there was talk of stock prices of Can$6 and even Can$10 in the near future.[41]

For the first time, the potential of the fuel cell development activities were driving the share price, as opposed to the previously situation where this price had been dominated by the real earnings from heater and thermoelectric generator sales. This was a complete reversal of the situation the company had been in. Whereas

[40] speculatingvalue, "Message Number 291".
[41] Plantinga, J., 'Comments on Future Share Price Potential and Gte Now Seen Foremost as a Fuel Cell Company: Message Number 314',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8815715>

before the company was described as a heater and generator company with an interesting side project in fuel cells, investors rapidly refocused to see it as a fuel cell company with some other product lines. Importantly, this pegged the value of the company to a share price based solely on the perceived future value of the fuel cell market, as opposed to the real and tangible value of product sales.[42]

This linked it squarely to the fortunes of not only other fuel cell companies such as Ballard, but also other speculative technology markets such as the multitude of internet and dot-com companies which were proliferating on various stock exchanges. This change in the estimation of the value of a company from real measurable results to perceived future technology performance is seen by some to mark the move into the "hype cycles," where investors can become more influenced by the promise of future expectations rather than critical analysis of the technical realities and challenges facing the company.[43] Even though a company may articulate these challenges to investors, the scale of these issues and the timelines to overcome them are often not well understood.

Such misunderstandings and disconnects between what the company said and what investors heard were reflected in some of the comments made by investors after the April 8th press release. Although the press release signified that remote power applications were going to be the main focus of the company's initial potential SOFC products, augmenting the company's other major product of thermoelectric generators, it was one single word that a number of investors latched onto, a word used in an almost careless fashion at the beginning of the release describing general applications where fuel cells may be used: "automotive". Very quickly thereafter, investors started posting with comparisons to Ballard, whose proton exchange membrane (PEM) cell was directly targeted at automotive drive train applications, with some even calling GTE the "next Ballard".[44] Over the following days, some commentators tried to bring some perspective to the discussion by pointing out that

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[42] Ibid.

[43] Konrad, et al., "Strategic Responses to Fuel Cell Hype and Disappointment", p. 1091.

[44] Plantinga, J., 'Comment Describing Gte as "the Next Ballard": Messgae Number 311',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8813184> ; Stephen O, 'Comments Comparing Gte to Ballard: Message Number 323',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8823981>

the operational principles of the PEM and SOFC technology were substantially different, so implied different markets and that expectations that GTE technology might threaten or displace Ballard were misplaced.[45] Some also pointed out that while the SOFC offered the potential to utilise a wider range of fuels than the PEM this was due to a far higher operating temperature which in itself brought another range of developmental challenges such as materials compatibilities and longevity issues neither of which were trivial. [46]

It is difficult to assess how well these words of caution resonated as the overall feel of many of the posts was unabated excitement. Many of the longer-term investors had stuck with the company while the stock price remained stubbornly low in their eyes and now the good times were coming. This feeling was only heightened when eight days after the press release, on the morning of 16th April, trading in GTE shares were halted pending an announcement by the company which would have a potentially material effect on the share price.[47]

Automotive Angles

If the press release of April 8th had begun to initiate excitement, such sentiments were legitimised and heightened by the announcement of the Friday April 16th. It related to an agreement between GTE and Delphi Automotive Systems the purchase a number of SOFC stacks. The text of the announcement framed the deal as an “initial commitment” from Delphi to the development of SOFC systems. Perry commented that this demonstrated a “major endorsement of our fuel cell work” and

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[45] Gulo, 'Comment Highlighting Differences between Gte and Ballard: Message Number 227',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=7627158> ; speculatingvalue, 'Comment on Business Diversification between Gte and Ballard: Message Number 272',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8477754>

[46] see clearly now, 'Comment on the Hight Temperature of Sofc: Message Number 349',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8862534> ; Fishfinder, 'Message Containing Cautioning Reference to Difficulties of High Temperature Operation: Message Number 400',Global Thermelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8881236>

[47] the Chief, 'Annoncement of Halt in Gte Trading Apr16th 1999: Message Number 453',Global Theroelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8962803>

described Delphi in the terms of a "strategic partner" helping to accelerate progress towards development milestones. The purchase order route was a means to expedite immediate development work while a more comprehensive agreement was negotiated, which would encompass "the entire solid oxide fuel cell project."[48]

Delphi was one of the largest suppliers of automotive components in the world, with an annual revenue of $28.5 billion. Although part of General Motors (GM), in 1999 it was being spun out from GM as a separate company. This echoed many of the corporate break-ups that had become increasingly common over the late 1980s and 1990s. The now-dominant market-focused business dynamics had driven the large vertically integrated corporations to divest large parts of their organisations into separate business units or even separate companies. Notwithstanding the details of the changes that were ongoing at Delphi, the news of a deal with a major supplier of automotive components sent a wave of excitement in the investor community. To some, this vindicated their assumptions about automotive use. Earlier comparisons of GTE to Ballard became even stronger while the remote power applications which were GTE's point of potential market entry were almost forgotten.[49]

The effect of this was to see a surge in the stock price when trading recommenced, with the stock jumping to Can$9, up from around Can$3.50 before trading ceased, this was accompanied by a huge increase in trading volume. The stock peaked around Can$15 an hour or so after trading began and eventually settled

[48] Stephen O, 'Text of Gte Press Release Announcing Delphi Sofc Purchase: Message Number 455',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8963036>

[49] The Global Thermoelectric discussion board became very busy and excited after the announcement with a high volume of posts. The flavour of these posts is captured by, the Chief, 'Comment on Potential for Gte after Delphi Announcement: Message Number 456',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8963055> ; the Chief, 'Comment That Delphi Announcement Is a Technology Endorsement and Comparison to Ballard: Message Number 468',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8963487> ; Jim P, 'Positive Comment on Dephi Announcement: Message Number 470',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8963564> ; Plantinga, J., 'Comments on Gte Automotive Angles: Message Number 477',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8963897> ; Hamlin, Kevin, 'Ballard Comparison: Message Number 517',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8969268>

at Can$10.70 at the close. Such volatile trading brought in new traders to the scene especially those looking to profit from the rapidly changing price.[50]

Over the course of that weekend, the many of the investors posting on the Siliconinvestor.com discussion board were in a highly bullish mood with some predicting prices of Can$20 and even beyond when trading was due to reopen on Monday. Some of this optimism was predicated against strong comparisons of the GTE technology with that of Ballard.[51] There were also some more restrained voices in making direct comparisons to Ballard pointing out some of the uncertainties around GTE's development.[52] In some cases a few of these commentators to the discussion board, in particular John Paquet, were accused by other contributors of trying to talk down the price and lumped in with day traders suspected of shorting the stock.[53] At times, these exchanges became quite abrupt and over the course of just a

[50] I make this claim looking at a rash of apparently new usernames and pseudonyms that started to post to the Siliconinvestor.com during this time period, often with very heightened expectation on potential returns illustrated by posts such as Chisy, 'New Poster on Website: Message Number 532',Global Termoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8972049> ; hx4, 'Post Showing Excitement in Gte Stockprice and Rapid Buying: Message Number 540',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8973104> ; Cameron, 'New Poster with High Expectations: Messgae Number 555',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8974527>

[51] Kubisz, Mark, 'Post with Optimistic Views and Ballard Comparison: Message Number 529',Global Thermoelectric Discussionn Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8971005> ; Jim P, 'Comment on Gte Being Competion to Ballard: Message Number 533',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8972226> ; Pugliese, Sal, 'Gte-Ballard Comparison against Heightened Expectation: Message Number 537',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8972666>

[52] Wiselight, 'Some Notes of Caution on to Direct a Comparison to Ballard: Message Number 531',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8971506> ; Paquet, John, 'Comments Talking Down Gte Stock: Message Number 606',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8981574> ; Paquet, John, 'Comments to Effect That Gte Stock Is Overpriced: Message Number 705',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8991028> ; Rowe, Michael A., 'Message Questioning Vagueness in Delphi Press Release: Message Number 612',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8982249>

[53] Rocket Red, 'Post Critical of J. Paquet: Message Number 709',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8991113> ; Hamlin, Kevin, 'Post Critical of Talking Down Stock Price: Message Number 716',Global Thermoelectric Discussion Board (Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8991212>

few days the nature and tone of discourse on the discussion board seemed to have changed with a few old animosities appearing.[54]

Previously, it had appeared that the contributors to the discussion board were largely a collection of people who had been invested or following GTE for some time. However, from the comments over the weekend of the 16th to 18th April it appeared that this had changed to a wider mix, including those who seemed to have less interest in the fortunes of the company or the technology other than where short-term speculation could net a profit either on a rising or falling stock price. It could also be suggested from the content of a number of the posts, that there were a considerable number of investors new to this area who did not fully understand either the technology or its developmental position and were jumping onto a bandwagon on the strength of the announcement of the 16th April, the subsequent press coverage, the rapid stock price fluctuations and a fear of missing out.

The following weeks of trading followed a volatile trend and there was a drop from the highs of initial trading. To be sure there was also a reasonable amount of institutional buying which steadied the price somewhat and led to a slow recovery to around a value of Can$8-10 and although not quite the Can$20 some were hoping for, it was still of the order of three times the value before the initial Delphi press release on the 16th of April. However, rumours of further press releases or announcements continued to circulate amongst investors and the wider mood of the discussion board remained positive. This positivity was heightened by press releases from Delphi and BMW on the 26th of April, linking the world’s largest manufacturer of auto parts to one of the leading luxury car brands through a joint venture to develop an SOFC unit to provide auxiliary power in larger and luxury vehicles, where more and more on-board electronic equipment was placing increasing

[54] marcos, 'Attack on J. Paquet's Comment: Message Number 614',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8982541> ; Rowe, Michael A., 'Defensive Comment after Being Challenged: Message Number 629',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8985148> ; 1st.mate, 'Comment Attacking Paquet: Message Number 712',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=8991147>

demands on the standard twelve volt battery .[55] This led some investors to draw parallels to Ballard and their partnerships with Daimler.[56] However, neither of these press releases specifically mentioned GTE as the manufacturer of the fuel cells utilised, which created some speculation amongst investors to the role of GTE and the nature of their relationship with Delphi.[57] Of course, the cells used were to be supplied by GTE under the purchase order agreement, yet the downplaying of GTE involvement did suggest some potential underlying tensions in the relationship.[58]

While the use of the purchase order did expedite the process of transfer of cells and stacks between Global and Delphi, it also brought forward a number of intellectual property concerns for GTE. The purchase order gave Delphi a lot more leeway than they possibly would have had if a collaborative developmental contract had been negotiated from the start. As part of the purchase order due diligence, Delphi required their staff members to inspect the complete GTE process and while there were confidentiality agreements in place Ghosh mentioned that this did cause some nervousness in GTE.[59] There was a fear within GTE that Delphi might just use the arrangement to gain technological knowhow and then use this to develop their own SOFC technology, cutting out GTE, with "the big company learning from the small company".[60] Such fears were not entirely unfounded as similar types of predatory practice by larger companies towards technologies developed by smaller companies, often framed as "David and Goliath" encounters, had been seen in battery development for electric vehicles. One such asymmetrical struggle was illustrated by the travails of the smaller US Ovonic battery company, not only in trying to hold off the Japanese battery giant Matsushita, but also in its negotiations

[55] blue_chip, 'Text of Delphi Bmw Sofc Apu Press Release: Message Number 1482',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=9155105> ; Ponthieu, "Status of Sofc Development in Europe", p. 24.
[56] Jim P, 'Comparison of Gte- Delphi to Ballard-Damler Benz: Message Number 1488',Global Thhermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=9155615>
[57] Houle, Michel, 'Post Question Role of Gte in Delphi/Bmw Arrangement: Message Number 1509',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=9160539> ; blue_chip, 'Post Underlining Facts around Gte Relationship with Delphi: Message Number 1604',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=9200011>
[58] Ghosh Interview 28 Mar 22.
[59] Ibid.
[60] Pastula Interview 5 Apr 22.

with its far larger US partner General Motors.[61] While GTE had applied for patents on some aspects of their fuel cell, such as materials compositions and specific component structures, there were some aspects that were kept as trade secrets and involved significant levels of tacit knowledge.[62] While patenting can be important in some aspects of intellectual protection, with respect to processing, the patent process can give away important pieces of knowledge which are in themselves difficult to protect within the patent.

Global had expended significant effort in constructing and developing this tacit knowledge and did not just want to give it away. When development stacks were to be shipped to the Delphi research centre in Rochester US there was some worry that the shipping process could damage completed stacks. After stacks were conditioned, a first heat treatment to form cell-to-cell contact and set the seals, they could be fragile after being returned to room temperature. So, to avoid damage Global insisted that they shipped individual cells for assembly into stacks at Delphi's facility. Further, Global demanded that the stacks were assembled and conditioned by Global personnel in a closed room, thereby preserving some of the important tacit knowledge they had developed around their stack processing.[63]

Ghosh feared that through knowledge gained from GTE, Delphi could potentially patent very similar processes which could potentially lock Global out of their own processes and a company the size of Global would not have the wherewithal to engage in a patent battle with a company the size of Delphi.[64] Such fears were not allayed by the lack of any mention of GTE in the 26th April press releases from Delphi and BMW. One Global staff member who was involved in the process commented on Delphi that "[I] can't say they were incredibly ethical through that whole thing".[65] Global did supply stacks under the purchase order agreement and

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[61] Eisler, *Age of Auto Electric : Environment, Energy, and the Quest for the Sustainable Car* pp. 91-99.

[62] For example, Ghosh, Debabrata, Frank. Martel, and Zheng Tang, "Composite Electrodes for Solid State Devices", US Patent Office, Global Thermoelectric, 2022.I also draw on my own recollections of working for GTE during 2000-2002 and a number of patent strategy discussion that were held across this time.

[63] Ghosh Interview 28 Mar 22.

[64] Ibid..

[65] Anonymous Interview 12 Mar 22

these were tested on the bench top rigs and also integrated into Delphi prototype systems and tested both stand-alone and in a trial BMW seven series.[66]

With the tensions created between the companies, the developmental relationship was described as having “fizzled out” after a year or so.[67] Delphi went on to continue to develop SOFC-based auxiliary power units for various sizes of truck across the early 2000s and became an industrial member of the Department of Energy’s SECA (Solid State Energy Conversion Alliance) programme around the same time.[68] While the relationship could not be described as a long-term success for GTE, the company could say that their stacks did work in a real work application, such as the vehicle APU, which brought technical credibility. The automotive aspects had also captured a significant amount of interest across wider interest groups together both aspects legitimised GTE as a serious actor in the solid oxide fuel cell field.

Enbridge Invests

While the Delphi order continued to draw a lot of interest from many shareholders and investors, many within GTE were aware that Delphi was developing its own SOFC programme and suspected that the order of stacks from Global was really a way for Delphi to acquire some early stacks to help produce initial prototype demonstrations and expedite learning.[69] It was also clear to a number of people in GTE that while the remote power sector was a specialist market able to tolerate high costs and therefore attractive for more costly, early SOFC applications, the overall size of that market was not going to be large enough to fund the development of the SOFC to a suitable stage where it would drive down costs significantly. Further, earlier models of SOFC systems were not going to be the equivalent of the highly

[66] BMW Group, 'Bmw Group Presents First Car with Petrolfuel Cell for on Board Electricity Supply ', (2001) <https://www.press.bmwgroup.com/united-kingdom/article/detail/T0020248EN_GB/bmw-group-presents-first-car-with-petrol-fuel-cell-for-on-board-electricity-supply?language=en_GB>.
[67] Anonymous Interview 12 Mar 22.
[68] Mukerjee, S., 'Solid Oxide Fuel Cell Auxiliary Power Unit – a New Paradigm in Electric Supply for Transportation', *ECS Proceedings Volumes*, 2001-16 (2001).
[69] Anonymous Interview 12 Mar 22.

dependable and rugged thermoelectric generators systems requiring 10-20 years low or no maintenance in the field.[70]

Therefore, the company needed a further potential market that would yield investment interest to fund continued development. With this in mind, Ghosh and a number of the team had, in parallel to the remote power markets and the deal with Delphi, also been pursuing ideas around domestic combined heat and power.[71] While company press releases had included “home power applications” as one of the potential uses of its SOFC system, it had so far failed to gain traction as the main driving force for potential revenue generation. This role had been taken by the remote and automotive possibilities. The company was aware that it needed to raise more funding to finance the scale-up of its tape casting and screen-printing processes and to try to move the cell production from the laboratory, batch-based processing they had acquired from Jülich.

In October 1999, the company tried to raise Can$25 million in a special warrants issue and although this only raised Can$12.75 million, it was followed later in the year by a second closing which raised a further Can$15.3 million. This gave Global the revenue required to lease new premises which would give them 32,000 square feet of space and form the basis for a pilot manufacturing facility and to order equipment to populate it. This physically relocated the fuel cell activities out of the existing GTE operations at their original location. As part of this separation of the fuel cell business, Dave Ghosh was also promoted from manager to vice president of the fuel cell division which further emphasised the growing role of the SOFC in not only the operations of GTE, but also in its identity as a company.[72]

Meanwhile, Perry continued to discuss the importance of domestic CHP as a potential product for the company at the September 1999 annual general meeting and

[70] Anonymous Interview 12 Mar 22
[71] Ghosh Interview 28 Mar 22.
[72] blue_chip, 'Text of Gte Press Release Announcing Warrents Sale Closure and Promotion of Ghosh to Vp Fuel Cell Division: Message Number 4221',Global Thermoelectric Discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=12145344>

in press interviews.[73] While this saw some increased discussion of this topic amongst investors, it was the links to automotive applications and comparisons to Ballard through the Delphi order that still appeared to dominate discussions, share price and by implication the perception from investors as to progress within the company. Evidence of this link is suggested by stock price response to Global-Delphi announcements of successful prototype testing on gasoline fuels at the end of 1999 which pushed stock price towards $15 followed by a steady climb across January 2000 to Can$27.

In March 2000 BMW announced that the successful integration an SOFC auxiliary power unit into an experimental seven series automobile.[74] This returned investor focus back to automotive applications and boosted the stock price to a high of just over Can$51. However this was just temporary and the price quickly stabilised to float around Can$25.[75] Although the bullishness of some investors was based on these recent announcements, the value of the company was also being bolstered by rises in other fuel cell stocks such as Ballard, so it could also be argued that a proportion of this general rise was linked to increasing valuations across many technology companies at the time. Many of these rises were based around ambitious expectations of returns from internet and telecommunications sectors, what many would later refer to as the “dot-com bubble.”[76]

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[73] StockPro, 'Comment on Perry Emphasising Market Potential of Co-Generation in Response to Automotive Interest: Message Number 3430',Global Thermoelectric discussion Board(Siliconinvestor.com, 1999) <https://www.siliconinvestor.com/readmsg.aspx?msgid=11208382> ; slick stevens, 'Post Discussing Perry's Focus on Residential Co-Generation Applications for Sofc: Message Number 3949',Global Thermoelectric Discussion Board(Siliconinverstor.com, 1999) <https://www.siliconinvestor.com/readmsgs.aspx?subjectid=17464&msgnum=3941&batchsize=10&batchtype=Next>

[74] BMW Group, "Bmw Petrol Fuel Cell Apu".

[75] The varying GTE stock price can be seen through posts to Siliconinverstor.com such as Vitalsigns, 'Comment on Gte Reaching $17 Share Price: Message Number 4448',Global Thermoelectric Discussion Board(Siliconinvestor.com, 2000) <https://www.siliconinvestor.com/readmsg.aspx?msgid=12578567> ; the Chief, 'Post Relating to $27 Share Price: Message Number 4488',Global Thermoelectric Discussion Board(Siliconinvestor.com, 2000) <https://www.siliconinvestor.com/readmsg.aspx?msgid=12637823> ; Vitalsigns, 'Text of Reports of Gte Stock Price Boost in Relation to Bmw Announcement: Message Number 4825',Global Thermoelectric Discusion Board(Siliconinvestor.com, 2000) <https://www.siliconinvestor.com/readmsg.aspx?msgid=13113244> ; the Chief, 'Post on Gte Stock Price at Beginning Od May 2000 on Parallel Discussion Board Related to Day Trading: Message Number 36470', Daytrading Canadian stocks in Realtime(Siliconinvestor.com, 2000) <https://www.siliconinvestor.com/readmsg.aspx?msgid=13571486>

[76] Wheale and Amin, "Bursting the Dot.Com "Bubble': A Case Study in Investor Behaviour".

Despite the investor focus on automotive applications, GTE continued to harbour ambitions to apply their system in residential CHP. In May 2000, GTE announced the successful test of a prototype domestic CHP system, which due to its resemblance in size and shape to a common domestic appliance was nicknamed “the fridge” by some in the company.[77] The importance of residential CHP as a potential application for the GTE SOFC was emphasised in July 2000 when the *Globe and Mail* reported that GTE had confirmed industry speculation about discussions with a major utility, which led to a rapid rise in stock price to Can$36.[78] The utility was later revealed to be Enbridge, a major Canadian actor in natural gas distribution which had agreed to invest Can$25 million in GTE. On the back of this news, GTE raised a further Can$100 million of funding through a combination of special warrants.[79]

It was an exciting time for those involved in the company. In addition to the 32,000 square foot building that they had already occupied, GTE now expanded into the adjacent building, creating an additional 100,000 square feet of space for new staff and accelerated expansion of testing facilities. They felt they had come a long way in just two years from small single-cell tests to one kilowatt prototype systems, which created a sense of optimism around the building. It was still a relatively small team at that time, around 30-40 people, mainly consisting of younger engineers and scientists taking a highly collaborative and energetic approach to problem-solving that employees of that time believed was, in part, responsible for the early rapid progress of the group.[80] GTE was also attracting skilled and experienced SOFC engineers and scientists from other SOFC communities, often coming from within larger organisations where the commitment to the technology always felt rather

[77] blue_chip, 'Text of Gte Press Release Announcing Rest of Residential Fuel Cell Unit: Message Number 4935',Global Thermoelectric Discussion Board(Siliconinvestor.com, 2000) <https://www.siliconinvestor.com/readmsg.aspx?msgid=13535928> , Pastula Interview 5 Apr 22
[78] Barnes, Angela, 'Global Thermo Jumps on Deal Talks', *Globe and Mail*, (2000); caveat, 'Text of Gte Comments around Deal with Major Utility: Message Number 5042',Global Thermoelectric Discussion Board(Siliconinvestor.com, 2000) <https://www.siliconinvestor.com/readmsg.aspx?msgid=14029212>
[79] blue_chip, 'Text of Gte Press Release Announcing the Deal with Enbridge: Message Number 5058',Global Thermoelectric Discussion Board(Siliconinvestor.com, 2000) <https://www.siliconinvestor.com/readmsg.aspx?msgid=14136004> ; the Chief, 'Text of Gte Press Release of 8th August Announcing Further Financing: Message Number 5086',Global Thermoelectric Discussion Board(Siliconinvestor.com, 2000) <https://www.siliconinvestor.com/readmsg.aspx?msgid=14179395>
[80] Anonymous Interview 12 Mar 22.

tenuous, attracted not only by the technical progress but also the commitment of the company towards taking the SOFC forward.[81]

The delivery and installation of the 60-foot tape caster, the 60-foot tunnel kiln and an improved clean room for screen printing as part of the move towards processes for increasing levels of manufacture heightened the feelings of progress and that a product could not be too far away. As systems engineer Michael Pastula recalled, it felt like "good times."[82] However, while the team was technically talented and enthusiastic about the tasks ahead, there was also limited product development experience, which led to a certain level of naivety about the tasks ahead and the difficulties of taking a generally successful system from a laboratory test bed to something which could be sold as a product. These difficulties would become more apparent as the injection of financing from Enbridge led to increased stockholder expectation and the resulting accelerated rates of growth would change team dynamics and cultures.[83]

Growing Pains & Bursting Bubbles

"Growth is Painful." This was the opinion of Michael Pastula when discussing the events following the backing of Enbridge and the significant funding that followed.[84] The pressure was now on, and the various shareholders would now be looking for a return on their investment through the share price. Like Westinghouse before them, GTE was in some way hostage to the markets. Although while the SOFC group at Westinghouse did not have any influence on the overall financial situation of Westinghouse itself, or its demise, caused by events at corporate boardroom level, the SOFC division at GTE were fully exposed to the vagaries of the various investors who had put money into the company. Overall, the effects were similar: time horizons began to revolve around quarterly reports and the aim was to sustain or increase share price to maintain stockholder value. This meant that it was no longer sufficient to just maintain progress: rather the company needed to be seen to be

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[81] Anonymous Interview 29th Apr 21, Wood Interview 28 Nov 22. I also draw on my own experiences and reasons for moving to Calgary to Join Global in July 2000.
[82] Pastula Interview 5 Apr 22 Ghosh Interview 28 Mar 22.
[83] Ghosh Interview 28 Mar 22 Pastula Interview 5 Apr 22 Anonymous Interview 12 Mar 22
[84] Pastula Interview 5 Apr 22

accelerating development towards a product.[85] Paraphrasing one Global insider, the stockholders wanted to see action: the company had just raised all this cash, now they wanted to know what it was doing with it. They wanted to see action and they wanted results.[86]

To achieve this accelerated development the company needed to grow. Like the heads of many SOFC projects before him, Ghosh went on a hiring spree. Over the next year, the company expanded from the 30-40 people in the summer of 2000 to over 180 people by the next summer. Ghosh could not hire everybody personally, so he took the approach of hiring senior managers or team leaders and letting them hire people to populate their teams. This created a number of cultural issues. The integrated, collaborative approach to design and problem solving previously described began to dilute and the newly formed teams and groups would begin to focus on their own individual priorities, rather than those of the SOFC division as a whole. As new managers came in, many with no fuel cell or SOFC background, the culture within the company became disjointed. Some insiders suggested that there were now a number of different cultures around research and development within GTE, none of which were well integrated.[87]

These new teams were bringing in ideas shaped by their own context, and while a fresh perspective can be informing and bring valuable insight, in this case it appeared to exacerbate the misalignment and divergence of priorities and challenges. Crucially, a large proportion of the new workforce neither understood the underlying development needs of the SOFC technology nor had an accurate perception of the where the SOFC actually stood in terms of the maturity of the technology development around it. Many of the teams being created within the company were felt by some to be getting ahead of where the technology actually lay, forming large complex structures around a product that did not really exist.[88] It is arguable that the formation of such product-oriented teams fed a perception both amongst investors and across the business development functions of the company that the technology was more advanced that it was. It was in fact a laboratory-based demonstrator for

[85] Ghosh Interview 28 Mar 22.
[86] Anonymous Interview 29th Apr 21.
[87] Ghosh Interview 28 Mar 22 Anonymous Interview 12 Mar 22.
[88] Anonymous Interview 12 Mar 22 Anonymous Interview 29th Apr 21.

technology learning, and the misalignment between this actual technology and the commercial imaginary informed construction of unrealistic milestones for roll out of prototype development.[89]

The board of the GTE now contained a number of institutional investors and these board members along with representatives of Enbridge were keen to see a demonstration SOFC system tested at Enbridge. Therefore, in May 2001, a first prototype system was sent to Enbridge for testing.[90] This prototype was rated at 2.3 kilowatts, almost double the power of the first residential development unit of 1.35 kilowatts run in Calgary just a year earlier.[91] Ghosh reflected that this unit was sent out too early and it would have been better to have completed more testing and refinement of the first prototype at Calgary, then using this knowledge, to build and send an improved SOFC system to Enbridge. However, with the pressures of the aggressive timelines being pushed by some in the company, the first prototype was sent, as there was not deemed to be time available for development of an improved system. Ultimately this first prototype had numerous issues around the system and stack which resulted in lower performance and durability than had been seen in the more protected environment of GTEs Calgary facility. These disappointing results revealed to those in the company new to SOFC development the true maturity level of the technology and the amount of work required to bring it towards a product.[92]

In March 2000, the stock price of GTE reached its highest level of Can$51: this was also the peak of the Nasdaq technology stock exchange. Young, brash internet companies were buying 30-second advertising space at Superbowl XXXIV for $2.2 million and investing in technology stocks seemed like an excuse to print money. However, such euphoric times were not going to continue. The US Federal Reserve’s interest rate rises in 1999 and 2000, accompanied by poorer than expected internet sales over the 1999 Christmas period had begun to chip at the confidence of some technology investors. This confidence was given another blow in March of 2000 with the joint announcement from US President Bill Clinton and UK Prime

[89] Ghosh Interview 28 Mar 22.
[90] Stephen O, 'Text of Gte Press Release of May31st 2001 Announcing Delivery of Sofc Prototype to Enbridge: Message Number 5328',Global Thermoelectric Discussion Board(Siliconinvestor.com, 2001) <https://www.siliconinvestor.com/readmsg.aspx?msgid=15877530>
[91] Ibid.; blue_chip, "Message Number 4935".
[92] Ghosh Interview 28 Mar 22 Anonymous Interview 29th Apr 21.

Minister Tony Blair that human genome mapping research should remain public, which caused a downturn in biotechnology stocks. Together, these factors precipitated a decline in the value of the Nasdaq which would continue until late 2001, never recovering the heights at the turn of the millennium.[93]

This slide in stock value was also felt by investors in GTE, although the announcement of the Can$25 million investment by Enbridge and the successful Can$100 million issue of special warrants brought the company stock price back to values in the mid Can$30s, it still some way short of Can$51 earlier in the year, and from which it would then fall again over the coming months. By 2001, the stock was trading at between Can$8 and Can$7 and the lack of news or announcements from the disappointing Enbridge prototype testing further dented investor confidence. As with many other companies which had raised significant finances through share offers during the inflating bubble, investors started to ask about "burn rate," the amount of money and time required to get a profitable product out into the market and whether there was enough money to cover the time it would take to get there.[94] Whereas previously bullish investors were keen to see money spent and progress made, that attitude began to change, with investors becoming more bearish, questioning the rate at which money was being spent.[95]

The Garrett Era

As part of a plan to address some of the issues that were emerging within the GTE and to move towards a focus on product development and manufacturing, the fuel cell division was split. Ghosh became the chief technology officer and in November 2001, an outsider, Peter Garrett, was appointed as chief operating officer. Garrett had previously been a vice president of Nortel Networks, the storied Canadian telecommunications company, which had also seen rapid growth during the 1990s optical and digital telecommunication technologies boom.

[93] Goodnight and Green, "Rhetoric, Risk, and Markets: The Dot-Com Bubble"; Wheale and Amin, "Bursting the Dot.Com "Bubble': A Case Study in Investor Behaviour".
[94] Goodnight and Green, "Rhetoric, Risk, and Markets: The Dot-Com Bubble", p. 129.
[95] Anonymous Interview 29th Apr 21.

Nortel had been spun-out of Bell Canada Enterprises in 1998 to take advantage of the potential growth in in new internet technologies, and it became the epitome of the dot.com bubble. Rapid growth through aggressive acquisitions and supportive regulatory and market conditions saw the share price rising to over Can$200, more than tripling its value in just four years.[96] Investors were ecstatic at this performance, with many institutional investors buying into the company. Management academic Timothy Fogarty and co-authors described a fevered atmosphere around investment and suggested that many analysts became "lazy" and did not question the acquisitions that Nortel were making: "everyone wanted to believe in the Nortel Supernova."[97]

At the beginning of 2001, Nortel had promised investors that they were in a strong position to withstand the downturn that had been seen across the US technology sector in 2000. However, this promise was based on opaque accounting and financial practices which could no longer hide the precarious position of the company. In February 2001 a Nortel press release projected earnings growth of 10%, down from a 30% projection issued just a month previously.[98] This sent shockwaves through the investment community, many rushed to sell shares and the price collapsed forcing Nortel to cut thousands of jobs.[99] At its peak, Nortel was valued more than Can$350 billion, representing more than 37% of the total value of the Toronto Stock Exchange (TSE) by mid-2002 Nortel shares would be trading for under a dollar.[100] Such a fall from grace created a shock on the wider markets, sent the TSE into a tailspin, weakened the Canadian dollar and had massive detrimental impact on the savings and pensions of many Canadians.[101] It also influenced technology investor confidence across the board and insiders at GTE felt that the drop in value they were seeing in their own shares was in many ways exacerbated by the events around Nortel as well as the wider downturn in technology investments.[102]

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[96] Fogarty, Timothy, et al., 'Inside Agency: The Rise and Fall of Nortel', *Journal of Business Ethics,* 84 (2009), p. 167.
[97] Ibid.
[98] 'So What Happened at Nortel Networks?', *Globe and Mail,* (2001).
[99] Bourette, Susan and Simon Tuck, 'Nortel Cuts Back: Nortel Cuts, Investors Run. Stock Blasted as Tech Giant Slashes Jobs and Warns of Falling Profit.', *Globe and Mail,* (2001).
[100] Fogarty, et al., "Inside Agency: The Rise and Fall of Nortel", p. 167.
[101] Bell, Andrew, 'Nortel Swamps Markets: Selloff Triggers Global Tailspin, Paralyzing Trading Systems and Pushing Dollar Down Further', *Globe and Mail,* (2001).
[102] Ghosh Interview 28 Mar 22; Anonymous Interview 12 Mar 22

As the downturn started at Nortel, Garrett was unhappy at having to lay off large numbers of people and dismantle what he had considered that he had built, so at just 44 years of age he left to consider retirement, however ideas of retirement did not last long before he was headhunted to join GTE.[103] Garrett described himself as a "specialist in building and commercialising ground-breaking technologies" and was seen as bringing strong project management practices and a far greater focus on product development.[104]

Garrett drove for better alignment between the some of the disparate teams, trying to integrate their divergent priorities, which over time did begin to converge. Stronger development plans were produced as teams were brought to understand the overall goals of the company and to prioritise and work towards these wider goals as opposed to looking just at their local issues.[105] By 2002, some felt that GTE was beginning to get its act together again, however both internal and external events over the early 2000s had shaken investor confidence and this was beginning to catch up with the company.[106]

The management at GTE had restructured the company across 2001 and 2002, but the share price continued to fall, and by mid-2002 was trading at between Can$4 and Can$3. One technical manager commented that while Garrett's product focus was important, it was at the expense of technology development, a significant amount of which was still required to overcome some of the underlying technology challenges that still remained.[107] Garrett himself admitted that he knew nothing about fuel cells but felt his knowledge of technology commercialisation in itself brought value.[108] As part of his drive towards commercialisation, Garrett brought a number of former colleagues from Nortel with him, who now sat at various senior management positions and shared Garrett's ideas and visions. This created an underlying tension within the company, between those more technically focussed engineers and

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[103] Konotopetz, Gyle, 'Text of Interview with Peter Garrett on Biz.Yahoo.Com, Posted on Siliconinvestor.Com by Username Vitalsigns: Message Number 5721',Global Thermoelectric Discussion Board(Siliconinvestor.com, 2002) <https://www.siliconinvestor.com/readmsg.aspx?msgid=18212344>
[104] Ibid.; Anonymous Interview 12 Mar 22
[105] Anonymous Interview 12 Mar 22
[106] Pastula Interview 5 Apr 22; Anonymous Interview 12 Mar 22
[107] Anonymous Interview 12 Mar 22
[108] Konotopetz, "Message Number 5721".

scientists who wanted to understand and drive out underlying issues, and those from the business side who were frustrated that the technology development was not moving fast enough and saw it as imperative to get a product out to market as soon as possible. It was a misalignment of expectation which was never fully reconciled.[109]

The low stock price created further tensions within the company. By mid-2002 Global was sitting on over Can$100 million of cash reserves, which equated to a value of Can$3.70 per share. However, at this time the shares were trading around Can$2.20 which meant GTE had more money in the bank than it was valued at through its stock price.[110] This made it vulnerable to predatory investors looking to asset strip the company. These tensions around share price, along with the perceived lack of technical progress and pressure from different quarters both within and out with the company eventually forced Perry to resign as CEO on 16th July 2002 to be immediately replaced by Garrett. A move which Ghosh commented as being conducted in a way highly disrespectful to Perry and what he had done for the company.[111]

Garrett suggested to the board that he considered the Can$125 million of cash reserves the company held in the bank was insufficient to commercialise the SOFC and he recommend that the board looked to sell the company. Ghosh did not agree with Garrett's assessment of the situation and argued that with careful control of the burn rate there were enough cash reserves to allow for ten years of continued technological and product development.[112] Ghosh's appeals were ignored, and the board committed to sell the company. Ghosh and others thought this could be perceived as a cash out for those with vested interests, which they felt had uncomfortable echoes of the events which had occurred at Nortel several years

[109] Pastula Interview 5 Apr 22 Anonymous Interview 12 Mar 22.
[110] Vitalsigns, 'Post Relating to More Cash Reserves Than Value Via Stock Price: Message Number 5571',Global Thermoelectric Discussion Board(Siliconinvestor.com, 2002) <https://www.siliconinvestor.com/readmsg.aspx?msgid=17870353> ; Al Collard, 'Text of Gte Press Release Refering to Cash Reserves and Undervaluation of the Company with Respecct to Share Price: Message Number 5770',Global Thermoelectric Discussion Board(Siliconinvestor.com, 2002) <https://www.siliconinvestor.com/readmsg.aspx?msgid=18252911>
[111] caveat, 'Text of Gte Press Release Announcing Resignation of Jim Perry: Message Number 5530',Global Thermelectric Discussion Board(Siliconinvestor.com, 2002) <https://www.siliconinvestor.com/readmsg.aspx?msgid=17746353> ; caveat, 'Text of Gte Press Release Announcing Appointment of Peter Garrett as New President and Ceo: Message Number 5531',Global Thermelectric Discussion Board(Siliconinvestor.com, 2002) <https://www.siliconinvestor.com/readmsg.aspx?msgid=17746381> ; Ghosh Interview 28 Mar 22
[112] Ghosh Interview 28 Mar 22

earlier.[113] For Ghosh, the decision to sell the company, rather than to try to continue developing the technology, was a final straw and he also tendered his resignation on 31st August.[114]

The decision to sell rather than continue development with a lower burn rate indicated to some in GTE that the new board were the wrong individuals to run a fuel cell company that needed to refine its technological offering and extend its time to market. They pointed to the plentiful reserves of cash in the bank and that their strategic partner Enbridge still seemed keen, which they suggested showed Enbridge could see beyond the short termism of the market and understood the challenges thrown up by early-stage prototype demonstrations.[115] Garrett continued to profess support for continued development of the technology towards a future product in an August 2002 interview to the *Calgary Herald* and other press announcements.[116] Although it appeared to some in the company that the senior management did not seem to have the stomach for a long technical campaign of slower hard-won progress and preferred to position the company for a quick sale.[117] Over the coming months, management made several approaches to various other companies about options for strategic alliances, mergers or buy-outs before finally agreeing to the acquisition of GTE by US company Fuel Cell Energy in early August 2003.[118]

While it could be postulated that Fuel Cell Energy were attracted by the significant bank balance of GTE, it was not as predatory as it could have been. Fuel Cell Energy were interested in keeping the core development of the SOFC active as it complimented their developments of the other high temperature fuel cell variant, the Molten Carbonate Fuel Cell (MCFC). Further with Fuel Cell Energy having been selected as a lead contractor on the US Department of Energy Solid-State Energy

[113] Ibid.; Wood Interview 28 Nov 22
[114] Stephen O, 'Text of Gte Press Release Announcing Resignation of Dave Ghosh: Message Number 5581',Global Thermoelectric Discussion Board(Siliconinvestor.com, 2002) <https://www.siliconinvestor.com/readmsg.aspx?msgid=17872917> ; Ghosh Interview 28 Mar 22
[115] Ghosh Interview 28 Mar 22; Pastula Interview 5 Apr 22, Anonymous Interview 12 Mar 22.
[116] Stephen O, 'Post of Text of Calgary Herald Interview with Peter Garrett Published on Aug.19th: Message Number 5592',Global Thermoelectric Discussion Board(Siliconinverstor.com, 2002) <https://www.siliconinvestor.com/readmsg.aspx?msgid=17895113>
[117] Pastula Interview 5 Apr 22 Anonymous Interview 12 Mar 22; Wood Interview 28 Nov 22, Anonymous Interview 29th Apr 21.
[118] russet, 'Text of Press Release Announceing Sale of Gte Tpo Fuel Cell Energy: Message Number 5951',Global Thermoelectric Discussion Board(Siliconinvestor.com, 2003) <https://www.siliconinvestor.com/readmsg.aspx?msgid=19178773>

Conversion Alliance programme (SECA) which focussed on SOFC development, the acquisition of GTE to gain both the technology and the expertise of staff made significant sense.[119]

However, the way in which Fuel Cell Energy structured the integration of GTE activities was rather complex. The cash reserves were absorbed by the main company of Fuel Cell Energy, the thermoelectric generator business was sold, as it did not align with Fuel Cell Energy's core competencies, and Fuel Cell Energy invested a stake in Versa Power, a joint venture conglomerate formed from the Gas Research Institute (GRI), Electric Power Research Institute (EPRI), the University of Utah, and Materials and Systems Research, Inc. (MSRI) a spin out from University of Utah.[120] The GTE SOFC activities were then placed within Versa Power, which turned the former Canadian company into a US company headquartered in Golden, Colorado. Versa Power then became part of the Fuel Cell Energy SECA team with their SOFC development now funded by Department of Energy.[121]

In effect, Global had been separated from its Can$100 million nest-egg and now had to survive by chasing government project funding, effectively as a contract research organisation. This process also realigned the activities within the company back towards technology and process development and away from the demands of developing and releasing a commercial product in the shorter term. This resulted in further loss of staff with the Calgary team shrinking back towards 40-50 people housed in the initial 32,000 square foot pilot facility.[122]

This rebranding of Canadian GTE as US Versa Power would also place the reframed company in the centre of a new US energy policy vision which would shape the view of fuel cells and SOFCs in the US for at least the next decade, the description of which forms the basis of the next chapter. Here I return to more meso and macro historical frames where I investigate how the enduring need for clean

119 Casaubon, 'Text of Press Release Announcing Fuel Cell Energy as Contractor in Us Doe Seca Programme: Message Number 5898',Global Thermoelectric Discussion Board(Siliconinvestor.com, 2003) <https://www.siliconinvestor.com/readmsg.aspx?msgid=18891129>
120 Pastula Interview 5 Apr 22
121 Casaubon, "Message Number 5898".
122 Ghosh Interview 28 Mar 22 Pastula Interview 5 Apr 22, Wood Interview 28 Nov 22 Anonymous Interview 29th Apr 21, Anonymous Interview 12 Mar 22.

energy conversion maintained the legitimacy of the promise of SOFC technology in the minds of the US Department of Energy. However, the account also reveals how misconceptions and misunderstandings around the attributes and roles of differing types of fuel cell led to tensions around the positioning and funding of US SOFC development.

Chapter 7: Changing Landscapes, Multiple Contexts

> “Tonight I'm proposing $1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles. A single chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car -- producing only water, not exhaust fumes.”[1]

This statement was made by President George W Bush during his 2003 State of the Union Address. It was a statement that would have implications for the perception of the place of fuel cells and in particular solid oxide fuel cells in the imaginaries of future US energy systems. Such imaginaries would propose transportation systems free of greenhouse gasses and other harmful pollutants, creating optimistic rhetoric around the power of technology to deliver such utopian systems, free and independent from the shackles of foreign oil, drawing on past glories of the 1960s space programme while tethering them to present concerns through rhetorical programme titles such as “FreedomCAR”, creating strong links to the post September 11th sensibilities still prominent in American minds.

While it was rooted to contextual shifts around energy and the environment which had occurred in the late 1990s, President Bush’s announcement was deeply embedded within issues of electromobility and air quality concerns around transportation. The apparent shortcomings of the battery electric vehicle claimed by some automobile manufactures, such as GM, had shifted attention towards hydrogen and fuel cells as a potential future solution to the perceived problems of vehicle electrification.[2] The seeming enthusiasm of companies such as GM for fuel cells and hydrogen had convinced President Bush that this was the way forward and he threw the full weight of the DOE onto it. This created an energy imaginary so powerful, that in the minds of policymakers and public alike the fuel cell and hydrogen became inextricably linked. This drew the hydrocarbon fuelled SOFC into the hydrogen nexus eventually realigning to the needs of President Bush’s hydrogen initiatives.

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[1] Bush, George W., '2003 State of the Union Address to Congress 28th January 2003', 2024 (2003) <https://georgewbush-whitehouse.archives.gov/news/releases/2003/01/20030128-19.html>.

[2] For background into the role of the automobile companies in undermining the battery electric vehicle see Eisler, *Age of Auto Electric : Environment, Energy, and the Quest for the Sustainable Car* and Paine, Chris, 'Who Killed the Electric Car?', (US: Sony Pictures Classics, 2006).

In this chapter I move away from the fined-grained detail of Chapter 6 and return to the coarser-grained analysis of earlier chapters with the aim of exploring how the shifting contexts of US energy influenced and shaped the development of the SOFC across differing conceptions of these future energy imaginaries. The discussion will consider how SOFC developers looked to modify existing material and market logics to maintain technological legitimacy and sustain the promise of the SOFC in the face of these changing contexts of energy provision and environmental concerns. Further, I also look to explore how the optimism around the future promise of technologies such as the SOFC can have a contradictory effect, simultaneously being seen as central to enabling the future energy transitions required, while at the same time the highly transformative nature of the transition they promise in the near future allowed existing energy conversion regimes to persist for a little bit longer.

Reimagining US SOFC Development

Toward the end of the 1990s the US Department of Energy (DOE) began to realise that the tubular design of Westinghouse (now Siemens Westinghouse after the 1998 acquisition), having now been in development for over twenty years, would struggle to ever reach appropriate cost targets. It was becoming clear to many, including those within the Siemens Westinghouse team, that the large tubular design based on the vapour deposition processes had inherently high costs and were proving difficult to scale up. Further, the arrangements of the tube bundles, as the Westinghouse stacks became known, were resulting in physically larger systems for equivalent power ratings when compared to the more recent designs of thick-film planar cells which were emerging in the second half of the decade. While this was not such an issue for the application in large central power plants initially envisaged in the late 1970s and 1980s, the size of the system was a far more important consideration for distributed generation where smaller more compact units that were required.

While a Westinghouse 100-kilowatt system demonstrated in the Netherlands had been promoted by the company as a success, it could be also argued that rather than demonstrating the prototype of a commercial product it was instead part of a dramaturgy. This represented a carefully controlled demonstration of the capabilities of a technology, often in a judiciously selected and controlled location with careful oversight of the promoting partner and with the demonstration site becoming in effect an “extended laboratory”.[3] The value to developers of such demonstrations in strengthening the legitimacy of the knowledge claims around a technology remains an important part of the developmental process. However, much like Global Thermoelectric had discovered, it was one thing to successfully demonstrate a single SOFC prototype system running directly on natural gas, but something else entirely to move this prototype towards a product that could be mass produced. The accounts within this thesis suggest it was this gap between prototype and product, and the resource and time needed to bridge the gap which was repeatedly underestimated in SOFC development.[4]

The ability to bridge this gap was also not being helped by internal changes within the SOFC group at Siemens Westinghouse. The takeover by Siemens had brought a change in management culture. While at a peer-to-peer level, the Westinghouse team felt it was easy to work with their German counterparts and that there was a mutual respect, new wider management approaches created strains amongst the group. New managers were brought in with a remit to accelerate the commercialisation process, however they had no fuel cell background. In many ways mirroring the tensions experienced within Global Thermoelectric, members of the Westinghouse SOFC team felt the methodologies the new managers tried to employ were unsuitable for a technology at the development stage of the SOFC. While these methods may have been appropriate for implementing incremental changes on an existing commercial product, such as a gas turbine, when applied to the SOFC they resulted in wildly unrealistic targets which some of the team could not buy into and left them feeling professionally uncomfortable.[5] One result of this was a loss of some

[3] The performative aspects of the technical demonstration are a well-documented in the literature of STS and history of technology a classic example is Shapin, Steven and Simon Schaffer, *Leviathan and the Air-Pump : Hobbes, Boyle, and the Experimental Life* First Princeton Classics 2018 edn (Princeton, N.J.: Princeton, N.J. : Princeton University Press, 1985)., however more recent examples include Hilgartner, Stephen, *Science on Stage : Expert Advice as Public Drama*, (Stanford California: Stanford University Press, 2000).and fuel cell specific Eisler, "Getting Power to the People: Technological Dramaturgy and the Quest for the Electrochemical Engine".
[4] For reference to this underestimation see Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*; Wallace, "Fuel Cells: A Challenging History". and from this work Tietz Interview 17 Oct 22
[5] Anonymous Interview 29th Apr 21.

experienced staff, with a number moving to positions in academia, National laboratories or some of the other smaller SOFC companies that had emerged over the second half of the 1990s such as Acumentrics or Global Thermoelectric.[6]

One major figure to leave the team around the turn of the millennium was Subhash Singhal. Singhal had been a driving force in the development of the Westinghouse programme since the mid-1980s and had become one of the most recognisable faces in the international SOFC community. Around the year 2000, Mark Williams, the manager for the DOE SOFC programme, had been talking to Singhal about new ideas he had for the organisation of the US DOE SOFC programme and whether Singhal would like to be a part in co-ordinating this from outside of his current Siemens Westinghouse position. There were some concerns that the DOE had formed a single-programme mentality with the bulk of their funding (around $5 million per year) going to Westinghouse.[7] There were also some underlying and unspoken concerns that Westinghouse had been broken up and sold off and the SOFC programme was now effectively owned by a foreign company. While Siemens had created a US subsidiary in Siemens Westinghouse, the optics of the bulk of US funding going to what was still ostensibly a foreign company was potentially troublesome. Further to this, the emergence of thick-film processing across the 1990s had created a new set of SOFC actors all of whom were looking to gain access to DOE support, including contacting their political representatives about the current DOE single programme approach.[8]

The timing of Williams's offer was fortuitous for Singhal. There were the issues of new cultures at Westinghouse, which were exacerbated by some uncertainty as to where the programme was heading. The SOFC group had secured further funding through the results of the 100kW demonstration, but the group was still located within the remnants of the R&D centre in Pittsburgh with no clear link to a business unit where the activities would finally be located. After the breakup of Westinghouse and with the changes in corporate culture, some felt that it was no longer the company they had been part off for so long. Subhash harboured feelings of this nature and along with other personal changes, family growing up and moving

[6] Ibid.
[7] Interview with Eric Wachsman Conducted by Author 29th April 2024
[8] Singhal Interiew.

away to college, the time felt right for a move. So, he accepted the offer from the DOE and took up a position in the Battelle Pacific Northwest National Laboratory (PNNL) from where he could work with the DOE to help co-ordinate this new ambitious national SOFC programme.[9]

This programme became known as the Solid-State Energy Conversion Alliance (SECA), which aimed to widen the scope of the DOE programme and promote cost reductions and reduced operating temperatures. Commencing in 1999 it was an ambitions $600 million, 10-year programme, involving universities, companies and national laboratories. The programme involved a greater number of participants split into industrial and core technology teams, the latter consisting of the universities and National Laboratories, and aimed to provide the cross cutting fundamental support to overcome the common technical barriers assessed as being faced by all the industrial developers, “the reverse salients.” In order to allow equal access to all of the industrial teams and to encourage collaboration and sharing between the two strands of the programme, the core technology participants were required to grant nonexclusive licences to any inventions arising from the core programme to any of the industrial teams.[10]

For US SOFC actors, SECA was a new concept, with the aim to encourage the industrial teams to work with the core technology programme, sharing information that would lead to identification of the cross-cutting issues which could then be tackled by the core technology participants with results and potential solutions being shared across the industrial teams.[11] It also broke away from very established narratives around large centralised multi-megawatt system fuelled by coal and put the development of small kilowatt level systems based on thick-film technology at the centre of their development plan. From another perspective it could also be contented that the US SOFC programme was actually playing catch up. Other US federal agencies had long established histories with collaborative research consortia in areas such as vehicle development with USCAR, and PNGC, or in

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[9] Ibid..
[10] Bajura, Rita A., 'Memorandum for Ropert S. Kripowicz Acting Assistant Secretary for Fossil Energy : Approval of Exception Circumstance Determination for Inventions Arising under the Solid State Energy Conversion Alliance (Seca) Dated November 28th 2000', (Department of Energy, 2000).
[11] Ibid.

electronics manufacture with SEMATECH.[12] Similarly European and Japanese SOFC efforts had long centred around larger collaborative programmes bringing together academic, national lab and industry partners.

The initial industrial teams were formed from Delphi, General Electric, Acumentrics and Cummings and Siemens Westinghouse. Apart from Siemens Westinghouse these companies had all adopted thick variations of viscous slurry processing to fabricate their SOFC and represented the expanding field of actors enabled by the adoption of thick-film processing. Most were developing planar anode-supported systems, apart from Acumentrics who had opted for a microtubular system reminiscent of that proposed by Kendall. Following several buy outs and take overs of the 1990s the General Electric team were essentially Minh's Allied Signal team, one of the pioneers of the anode-supported concept. As discussed in Chapter six of this thesis, the team from Global Thermoelectric under their new nameplate of Versa Power also became a significant actor in the industrial teams in 2003, with their new owner Fuel Cell Energy being selected as the lead in one of the industrial teams in a subsequent round of SECA funding.[13]

These teams were generally developing smaller systems and fitted well with the SECA aim of using a the "5kW, low cost, high power-density, solid state fuel cell stack" as the core module of the SECA programme.[14] Mark Williams the DOE Fuel Cell Project Manager described this core module as a multi fuel device: "Given a fuel, there will be a fuel cell system that can operate on it." Williams's vision firmly placed the SOFC within the existing hydrocarbon-based fuel infrastructures, with gasoline, diesel, natural and landfill gasses, defence logistical fuels as well as hydrogen all being mentioned. [15]

SECA represented a significant change in approach in SOFC development for the DOE. For over a decade the DOE SOFC programme had been focussed on the Westinghouse tube in conjunction with larger coal-based systems and in that time the world had moved around them. The advent of the thick-film anode-supported cell

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[12] Eisler, *Age of Auto Electric : Environment, Energy, and the Quest for the Sustainable Car* pp. 79-80; Mody, *The Long Arm of Moore's Law: Microelectronics and American Science*, pp. 151-154.
[13] Casaubon, "Message Number 5898".
[14] Williams, Mark C., 'Status and Market Applications for the Solid Oxide Fuel Cell in the U.S. - a New Direction', *ECS Proceedings Volumes,* 2001-16 (2001), p. 5.
[15] Ibid.

and the rapid growth of several new companies with alternate funding mechanisms had revealed that not only had the SOFC development environment changed, but the wider assumptions about energy were also in flux, with deregulated markets changing how energy was traded and supplied. The position of the DOE in shaping research direction around the SOFC, while still powerful, was no longer dominant. To some extent, it could be suggested that the early lead enjoyed by the US and Westinghouse in SOFC development was no longer the case, with both Japan and Europe having significant research and development activities.[16] The establishment of the SECA programme therefore reflected an acknowledgement of the changing contextual landscape around electricity generation and the place of the SOFC within this, with smaller distributed systems running on natural gas becoming much more prominent in the thinking of energy companies and policymakers.

With a programme now focussed on a core module of 5 kilowatts, it may seem incongruous that Siemens Westinghouse was selected as an industrial partner. However, this arguably reflects Siemens Westinghouse's continued position as the most experienced SOFC developer in the US and the ongoing DOE investment already sunk into the Westinghouse programme. While Siemens Westinghouse had entered into an agreement to produce a 5kW version of their tubular system with Canadian company, Fuel Cell Technologies, thereby giving some alignment with the SECA programme and had recently reviewed and questioned the optimal size for an SOFC system, it could also be argued that the company would never really be able to realign their development strategies to focus on a 5kW module as proposed by the architects of the SECA programme. Recent demonstrations had focussed on size ratings around 100 kilowatts and concurrent publications made no mention of SECA. These aspects, along with their involvement in other DOE programmes, such as the

[16] Behling, *Fuel Cells : Current Technology Challenges and Future Research Needs / [Internet Resource]*. Interview, with Robert Stienberger-Wilckens Conducted by Author on 7th Sept 2021

DOE Fossil Energy Vision 21 for large "clean coal" generation, suggested that they still saw larger megawatt scale systems as central to their development ambitions.[17]

The inclusion of Siemens Westinghouse therefore brought forth some of the inconsistencies within the internal logics of the SECA programme and the vision that the DOE were promoting. If the programme was to focus on a core 5kW stack, this was at odds with Siemens Westinghouse who still appeared focussed on larger centralised SOFC systems. Even within the SECA planners themselves, the commitment to the smaller distributed cogeneration approach appeared questionable, with Williams alluding to the possibility of megawatt scale systems by 2015, just five years beyond the remit of SECA.[18] Such comments suggested multiple and potentially conflicting goals in the minds of the planners which muddied targets, planning and ultimately useful progress.

In detailing the rational for the SECA approach Mark Williams looked to digital technologies and computing analogies. He described how the 5kW core module would enable "mass customisation of common modules" and referred to how Dell or Gateway had applied such approaches to bringing down the costs of personal computing.[19] Such analogies were used to construct expectation as to the imminence of SOFC scale up and commercialisation, inviting comparisons to the recent events around the rapid growth of digital industries.

However, this analogy missed a critically important point, that computing systems are based on the movement of electrons, whereas fuel cell systems must also consider mass transport of physical reactants and products in addition to electrons and heat, making for a far trickier system to engineer. As Steven E. Koonin, DOE science undersecretary in the Obama Administration has been attributed as identifying, "it is more difficult to move molecules than bytes".[20] The notion of "mass customisation of common modules" also placed emphasis on the cells and

[17] For reference to review of the size of SOFC systems see Casanova, "A Consortium Approach to Commercialized Westinghouse Solid Oxide Fuel Cell Technology". for reference to 100's kW demonstrations and 5kW prototype with Fuel Cell Technologies see Huang and Singhal, "Cathode-Supported Tubular Solid Oxide Fuel Cell Technology: A Critical Review", pp. 95-96.. For vision 21 involvement see Williams, "A New Direction". and for concurrent publications which make no mention of SECA and continue to discuss larger scale systems see Hassmann, Klaus, 'Sofc Power Plants, the Siemens-Westinghouse Approach', *Fuel Cells,* 1 (2001).
[18] Williams, "A New Direction", p. 3.
[19] Ibid. p. 5.
[20] Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*, p. 7.

stacks, which suggested it was felt by SOFC developers that the answers to all of the SOFCs problems would be found within these components. As such, it ignored or at least downplayed the importance of other components in the system, which Eisler and Wallace have both observed has been a recurring theme in fuel cell development.[21]

Even the very theme of a common core module created inherent contradictions within the heart of the SECA approach. One of the reasons stated for creating the SECA programme was to help augment the development of the multiple emerging US SOFC developers all of whom had a number of different cell and stack approaches.[22] However, the model of a “standard core module” suggests a single “winner” of SOFC design, yet the structure of the licencing agreements for the core technology partners suggested that there would likely be multiple stack designs across the 10 years of the programme and that industrial partners could choose applicable technology solutions in some form of “pick and mix.”[23]

While it was a reasonable argument to propose that many developers would face a communal issue or reverse salient, indeed some of these were identified within the core technology programme, such as issues around gas sealing in the stacks and metal interconnects.[24] It was another proposition entirely to suggest that a single solution would emerge that would satisfy all of the industrial teams. The interface between the different stacks and their wider systems was likely to be very different for each different design, with each being subject to a unique set of technological challenges relating to their specific design. Such issues again highlight the tensions inherent in recent state-sponsored collaborative industrial research where state funding was often directed towards the shared interests of solutions to common problems, which was often in opposition to the competitive and commercial imperatives of market-oriented R&D where companies looked to differentiate

[21] Eisler, ""A Modern 'Philosopher's Stone'": Techno-Analogy and the Bacon Cell", p. 350; Wallace, "Fuel Cells: A Challenging History", p. 91.
[22] Williams, "A New Direction", p. 3.
[23] Bajura, "Memorandum for Ropert S. Kripowicz Acting Assistant Secretary for Fossil Energy : Approval of Exception Circumstance Determination for Inventions Arising under the Solid State Energy Conversion Alliance (Seca) Dated November 28th 2000", pp. 3-4., in a similar vein Williams, "A New Direction", p. 5. also suggests multiple times will commercialise the SOFC by 2010.
[24] Williams, Mark C., Joseph P. Strakey, and Wayne A. Surdoval, 'The U.S. Department of Energy, Office of Fossil Energy Stationary Fuel Cell Program', *Journal of Power Sources,* 143 (2005), p. 194.

themselves from rivals though promoting the varying affordances of their different designs.

Contradictions and potential confusion over goals aside, the SECA programme's ambitious funding goal of around $46 million per year took several years to ramp up with only $2.5 million and $5 million being allocated to the programme in 2000 and 2001 respectively, indicating a rather slow start to the programme. This jumped to up to $33 million and beyond in 2003 as both the initial set of industrial teams initiated development activities and the number of industrial teams was expanded to six.[25] While the stated aim of the programme was to look at the smaller distributed power market as the most likely immediate avenue for SOFC commercialisation, the promotion of the fuel-flexible SOFC and its framing as a bridge between existing carbon-based and future hydrogen energy economies had resulted in competing demands for where the SOFC should or could fit into current and imagined energy systems.[26] Each of these demands placed their own specific needs onto the SOFC design, often requiring modification to cells, stacks or systems to optimise for the different roles. This in turn would ultimately lead to unfocussed and inconsistent technological objectives. These multiple demands would be further complicated by the announcement of the hydrogen and fuel cells initiative by President George W. Bush in his 2003 state of the union address.[27]

Hitched to Hydrogen

The Bush initiative placed hydrogen at the centre of US energy and transportation policy, a move which would have implications for the SECA programme and US SOFC development. Transportation has long been a central driver in US energy policy, this can be seen in responses to the 1970s energy crises where although the crises were in part due to structural deficiencies in the wider US energy supply system, much of the cultural and social imagery revolved around the price and

[25] Peterson, David and Rick Farmer, 'Historical Fuel Cell and Hydrogen Budgets', (US Department of Energy, 2017), (p. 3).
[26] US Dept of Energy, 'Solid State Energy Conversion Alliance Seca Workshop Proceedings', (Baltimore Maryland: US Department of Energy, 2000).
[27] Bush, "2003 State of the Union Address".

availability of gasoline at the pumps.[28] Similarly, the push to reduce pollution in the late 1980s and early 1990s emerged in large part due to the issues of smog around Californian cities, such as Los Angeles, which was seen as an increasing issue across the 1950s and 1960s. This in turn, had led to the formation of organisations such as the Californian Air Resources Board (CARB) in the early 1970s, with the aim of cleaning up the air around Californian cities.[29] It was these efforts which lead to the state passing mandates on reductions of tailpipe emissions and quotas on zero emission vehicles. These led directly to the trials and tribulations of battery electric vehicle development in the 1990s and influenced federal government environmental policy through programmes such as Partnership for a New Generation of Vehicles (PNGV).[30]

The US's long dependence on the automobile had led to gasoline having one of the highest levels of consumption of all energy sources in the US. It surpassed coal in 1949 at 12 quadrillion BTUs (British Thermal Units) peaking at just over 40 quadrillion BTU in 2005. This was almost double the consumption of coal and natural gas in that same year, both of which had a consumption level of around 22 quadrillion BTU.[31] Over the years the level of petroleum consumed as motor gasoline for transportation has varied between 40% to 50% of US primary energy sources, which for 2005 equated to just over nine million barrels per day.[32] Further with the decline in US manufacturing, since 2000 transportation had also overtaken industrial sources as the largest emitter of carbon dioxide.[33]

It therefore follows why some have described US policymakers as taking a "tail pipe" path to energy policy and reducing emissions as opposed to the approaches in Europe which centred more on an "electrical and renewables" path to reduction of emissions.[34] Such claims can also be warranted by the significant effort

[28] Kleinfield, N.R., 'American Way of Life Altered by Fuel Crisis', *The New York Times*, (1983); Badger, Emily and Eve Washington, 'Why the Price of Gas Has Such Power over Us', *The New York Times*, (2022).
[29] Eisler, *Age of Auto Electric : Environment, Energy, and the Quest for the Sustainable Car* p. 14.
[30] Ibid.; Eisler, "Public Policy, Industrial Innovation, and the Zero-Emission Vehicle".
[31] US Energy Information Administration, 'History of Energy Consumption in the United States, 1775–2009', 2024 (2011) <https://www.eia.gov/todayinenergy/detail.php?id=10#>.
[32] US Energy Information Administration, 'Annual Energy Review', (Washington DC: US Energy Information Administration,, 2011).
[33] US Energy Information Administration, 'U.S. Energy-Related Carbon Dioxide Emissions, 2023 - Figure 8', (2021) <https://www.eia.gov/environment/emissions/carbon/archive/2021/>.
[34] Interview with Phil Doran, Conducted by Author 27th April 2022.

of President Carter to set up development of synthetic liquid fuels in the late 1970s as a potential route to reducing the US dependence on foreign oil and shielding it from further shocks as had been experienced across that decade. Similarly, just over twenty years later in 2003, President George W. Bush also looked to the automotive sector as the focus of his ambitious energy policies based around hydrogen.

In the early 2000s ongoing tensions in the Gulf region of the Middle East were heightened by the September 2001 terrorist attacks, again both brought the US dependence on foreign oil and the tenuous supply chains into sharp relief. In 2001 total oil product imports were as high as at any time in history at over 10 million barrels per day and were still increasing, and of this around 20% were from counties in the Gulf region.[35] Therefore, with rhetoric mirroring the energy cries of the 1970s, President Bush positioned his hydrogen-fuel initiative in terms of energy independence for the country.[36] Unlike the 1970s however, by the early 2000s the detrimental impact of carbon dioxide emissions on the climate had also come to the fore and in 1997 many nations including the US signed the United Nations Kyoto Protocol requiring them to reduce their greenhouse gas emissions. Although signed by the US it was never ratified by the Senate and in 2001 President Bush announced the US withdrawal from the agreement citing that it would harm the US economy and put it at a disadvantage compared to other highly polluting nations such as China and India.[37]

Withdrawing from Kyoto was diplomatically problematic as it put both the legitimacy and effectiveness of the agreement into question. It also presented the US, and the Bush Administration in particular, in a poor light with regard to its commitment to environmental policies to help mitigate the emerging concerns around climate change. Although President Bush later reiterated in a June 2001 press announcement that his opposition to the protocol was not down to abdication of responsibilities around climate change, rather due to what he saw were structural shortcomings in how the protocol was constructed. He felt the treaty disadvantaged the US while doing little to address carbon dioxide emissions from countries such as India and China. President Bush stressed that he preferred technical solutions to

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[35] US Energy Information Administration, "2011 Annual Energy Review", pp. 126-127.
[36] Bush, "2003 State of the Union Address".
[37] Borger, Julian, 'Bush Kills Global Warming Treaty', *The Guardian*, (2001).

climate change, developing new technologies to prevent emissions in the first place.[38] It was against these two contexts that hydrogen fuel initiative was created, not only would it wean the US away from its dependence on foreign oil, it would also demonstrate US scientific and technological leadership in the creation of environmentally benign, low emission energy systems, mitigating diplomatic fallout from the Kyoto withdrawal.

The 2003 hydrogen fuel initiative was a $1.2 billion programme with the aim of augmenting the 2002 FreedomCAR programme to produce cost competitive hydrogen fuel cell vehicles by 2010, with a total government spend which was planned to be in the region of $1.7 billion by 2008. While a great deal of the fuel cell effort within President Bush's hydrogen plans would be focussed on low temperature polymer exchange membrane fuel cells (PEM) for drive units within vehicles, $720 million of the hydrogen fuel initiative budget would be for the development of hydrogen infrastructure, production and storage, which is where the SECA programme would end up being situated.[39] The hydrogen programmes were bold initiatives, however such were the magnitude of the issues around production, storage and distribution of hydrogen that not everybody was convinced what could realistically be achieved with the money and time allocated, with many suggesting it would take far longer and cost far more.[40]

Production and supply of hydrogen remained one of the biggest obstacles to President Bush's ambitions of a fleet of hydrogen cars. Unlike oil, hydrogen does not occur in its molecular form naturally on Earth, it must be manufactured, before being distributed and consumed by combining with oxygen to release energy carried within its chemical bonds. It is manufactured from primary energy sources such as carbonaceous fuels or using electricity from renewable or nuclear generation and is therefore considered an energy vector, a carrier of that energy from point of manufacture to point of consumption. In this respect it can be considered more like electricity rather than coal or oil and it is the efficiencies, or lack of, of the various conversion processes during its manufacture that detractors of hydrogen often point

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[38] Bush, George W., 'President Bush Discusses Global Climate Change', (2001) <https://georgewbush-whitehouse.archives.gov/news/releases/2001/06/20010611-2.html>.
[39] Bush Whitehouse Press Release, 'Fact Sheet: Hydrogen Fuel: A Clean and Secure Energy Future ', (2003) <https://georgewbush-whitehouse.archives.gov/news/releases/2003/02/20030206-2.html>.
[40] 'Myopic Hydrogen Vision', *Nature Materials*, 2 (2003).

to, especially when the primary energy source is based on a fossil fuel. Therefore, a significant aspect of President Bush's hydrogen fuel initiative was to address such issues, with the FutureGen project aiming to develop large scale integrated production of hydrogen and electricity from coal.[41]

In the early 2000s coal was still a significant source of primary energy in the US, generating around 2000 gigawatt hours of electricity, roughly 50% of the country's total generation capacity and the consumption of coal was still growing in terms of tonnages used and electrical output generated, even though its share of the generation mix was beginning to reduce.[42] With a significant thrust of the hydrogen programmes being to reduce dependence on foreign energy sources, from the point of view of the US government and policymakers it made sense to look at coal as the feedstock for hydrogen production. It was already the majority source of energy for electricity production, the country had vast supplies of it, and the product of gasification contained around 50% hydrogen. So, in a similar manner to the 1970s, the gasification of coal again became the great hope of energy independence. This time round it was not using coal to make synthetic gasoline for existing vehicle fleets, but to manufacture hydrogen, which would allow for a paradigmatic shift in vehicle energetics and a future vision of pollution free electromobility.

As part of its efforts to reduce emissions from coal fire power plants the DOE had proposed "Vision21" a wide ranging programme including developing an integrated gasification coal combined cycle (IGCC) and fuel cells with the aim of substantially reducing greenhouse gas emissions from the electricity generation sector, but specifically coal.[43] The Vision 21 programme became the blueprint for the FutureGen programme with the latter adding hydrogen gas production in support of president Bush's hydrogen transport initiatives to the aims as well as reduced emissions electricity generation. These were going to be large installations with the

[41] Giove, Joseph III, 'Futuregen: The Energy Plant of the Future', in *DOE Hydrogen Program Merit Review and Peer Evaluation Meeting,* (Department of Energy, 2006).
[42] US Energy Information Administration, 'Natural Gas Expected to Surpass Coal in Mix of Fuel Used for U.S. Power Generation in 2016', *Today in Energy,* 2024 (2016) <https://www.eia.gov/todayinenergy/detail.php?id=25392>; US Energy Information Administration, 'U.S. Coal-Fired Electricity Generation in 2019 Falls to 42-Year Low', *Today in Energy,* 2024 (2020) <https://www.eia.gov/todayinenergy/detail.php?id=43675>.
[43] Department of Energy, 'Vision 21 Program Plan: Clean Energy Plants for the 21st Century', (1999); Williams, "A New Direction", p. 6.

initial prototype demonstrations proposed at 275 megawatts in scale.[44] Proposed arrangements for FutureGen systems show hydrogen would be separated from the gasified coal for use as transportation fuel. The SOFC would utilise some of the less pure hydrogen from the tail gas exhaust of these gas conversion and separation processes directly to generate electricity alongside gas turbines.[45] These turbines would integrate with the SOFC both to pressurise the system and to utilise the hot gasses from the SOFC exhaust, both of which had been shown to improve system efficiencies.[46] In order to properly integrate all of these different systems they would need to be appropriately matched with respect to size. This drew SOFC development back to a need for large systems of many tens or even hundreds of megawatts and appeared in direct contradiction to the initial objectives of SECA which had identified small 5kW systems as potentially being the fastest route to commercialising the SOFC with larger system only appearing later.[47]

As well as issues around size, the FutureGen design also planned for the SOFC within the system to be running on hydrogen. While this was not an issue for the SOFC from a technological standpoint, it created issues around the broader perception of the SOFC within wider energy infrastructures. The newfound presidential interest in fuel cells and hydrogen was creating far more general interest in these technologies and many were not only beginning to more strongly associate the fuel cell with hydrogen but also to conflate them into a single entity “the hydrogen fuel cell”.[48] With this focus on hydrogen, the prime attribute of the SOFC, its promise to run on multiple hydrocarbon-based fuels and its potential to exist within current hydrocarbon-based fuel infrastructures, became somewhat lost on those outside of the immediate development of the device. It was therefore to some

[44] Giove, "Futuregen: The Energy Plant of the Future".
[45] Wachsman, Eric D. and Mark C. Williams, 'Hydrogen Production from Fossil Fuels with High Temperature Ion Conducting Ceramics', *The Electrochemical Society Interface,* 13 (2004), p. 36.
[46] Williams, Strakey, and Surdoval, "The U.S. Department of Energy, Office of Fossil Energy Stationary Fuel Cell Program", p. 194; Gardner, et al., "Sofc Technology Development at Rolls-Royce", pp. 128-129.
[47] Williams, "A New Direction".
[48] This strong association between hydrogen and fuel cells, and the efforts of developers to break this through the idea of the fuel cells as the universal energy convertor forms a major theme in Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*.

extent unavoidable that the multifuel SOFC would also get drawn into this hydrogen nexus and become just another “hydrogen fuel cell”.[49]

The Shifting Sands Around SECA

By the end of 2003, with the addition of the Fuel Cell Energy team containing Versa Power, the former Global Thermoelectric, the SECA programme now had a compliment of six industrial teams. All of whom were working towards meeting the first of the three phased set of targets, with some form of the 5kW core stack outlined by Williams. Many of the early reports coming from the DOE management teams suggested good progress was made towards the early phase one performance targets of the programme and those involved felt the programme was running well.[50] To a large extend it could be suggested that this was in part because a five kilowatt stack module matched what many of the industrial teams had been independently developing in any case, with the possible exception of Siemens Westinghouse, and as such they were in a good position to leverage knowledge and learning gained prior to their being part of the SECA programme. Indeed, as was referred to earlier one of the key functions of the SECA programme was to help support the companies developing smaller systems who had been somewhat marginalised by previous DOE focus on large, centralised power generation facilities.

While even the earlier SECA outlines had contained some reference to larger megawatt scale SOFC systems, the way these had been presented suggested that the larger systems were someway off in the future, something that would come about after the commercial introduction of smaller systems. With the inclusion of the SECA programme into the presidential initiative to develop hydrogen delivery systems as part of large coal fuelled infrastructure however, this narrative changed and the larger systems were again part of the wider DOE SOFC agenda, with some

[49] This conflation of high temperature fuel cells with hydrogen continues to the present. In a recent, Guardian “Politics Live” entry by Andrew Sparrow on 13th March 2023 “ Ceres Power of the UK is described as developing “hydrogen fuel cells”, however their SOFC product has always been aimed squarely at home cogeneration market using natural gas as a fuel, and so demonstrates the difficulty of wider reporting to separate the device from the fuel. Guardian Politics Live entry available at Sparrow, Andrew, 'Politics Live', *Guardian*, (2023).
[50] Williams, Strakey, and Surdoval, "The U.S. Department of Energy, Office of Fossil Energy Stationary Fuel Cell Program", pp. 193-194; Wachsman Interview

seeing SECA's role as developing these larger systems in support of the wider hydrogen goals .[51] In order to maintain the validity of the initial visions of the SECA programme within this changing context, SECA programme managers still promoted the small distributed power systems based around the 5kW core module as the most likely route for initial SOFC commercialisation. Although with the need to now also be supporting the FutureGen project they also began to discuss "simultaneous" aggregation and scale up to larger systems with SECA designs being applicable to these larger systems.[52]

In making this claim the programme managers drew on assumptions of the scalability and flexibility of the fuel cell. In conventional thermally-based generation of electricity there are a number of energy conversion steps, from heat to kinetic to electrical, each of which contributes efficiency losses. One way in which these losses could be mitigated was through economies of scale, with losses being easier to manage in larger, interconnected generating systems and was one reason for the establishment of large, centralised generation facilities with grid distribution across regions and nations.[53] In a fuel cell, however, with its direct conversion of chemical to electrical energy these losses are minimised with the result that both large and small systems can be highly efficient. This has led to the idea of fuel cells being highly scalable, that small scale and large-scale systems are both viable with respect to efficient electricity generation. However, this is not the same as saying all sizes of systems are the same or that a small system directly relates to a large system. Both Eisler and Wallace emphasised that the fuel cell stack is just one part of a wider, more complex system, a factor that is often missed, as thinking around the device often privileges the cell and stack.[54] The scalability attributed to fuel cells relates to the electrochemical reactions within the cells and does not consider these wider ancillary components that must be included within a system, many of which may not scale in line with the electrochemical components.[55] Therefore, it does not

[51] Peterson and Farmer, "Historical Fuel Cell and Hydrogen Budgets", p. 1.
[52] Williams, Strakey, and Surdoval, "The U.S. Department of Energy, Office of Fossil Energy Stationary Fuel Cell Program", p. 195.
[53] Hughes, *Networks of Power : Electrification in Western Society, 1880- 1930*, pp. 370-371.
[54] Eisler, ""A Modern 'Philosopher's Stone'": Techno-Analogy and the Bacon Cell", p. 350; Wallace, "Fuel Cells: A Challenging History", p. 91.
[55] Singhal Interiew.

necessarily follow that small and large systems can be related and that one can be "aggregated" to the other, especially between 5-10 kilowatts and multi megawatts.

The limitation of such notions of scalability and aggregation were shown later with companies such as Versa power being awarded SECA funding to develop larger stacks with power outputs which would better integrate with the rekindled vision of multimegawatt SOFC systems as part of the FutureGen programme. This required development of stack blocks of the order of tens and even hundreds of kilowatts, orders of magnitude larger than the original SECA vision of the 5kW core module.[56] The development of these larger stacks resulted in multiple targets which proved to dilute efforts of companies such as Versa Power. It must be remembered that the stack technology of Versa had come from the efforts of Global Thermoelectric where the whole SOFC design ethos had centred around the commercialisation of 1-5kW SOFC systems for either remote power or domestic cogeneration. While this was a perfect match for the early central aim of SECA in using the 5kW module as a route to initial commercialisation, the increasing prominence of megawatt-scale ambitions to support FutureGen demanded significant changes in stack and system design.

For Versa power this meant adjusting processing methods to produce larger cells and stacks, first towards sizes around 40kW but with ambitions towards 250kW as the modular unit that would scale up towards the megawatt facilities demanded by FutureGen.[57] While of course having this range of stack sizes potentially opened up multiple markets for the company, it also demanded working on multiple design of system simultaneously. As was highlighted previously, the supporting elements around a system did not necessarily scale well and needed to be tailored specifically for the design at hand. In a company whose work force had been drastically reduced over the preceding years and was now sitting at around 30-40 core staff, this spread effort across multiple designs limiting the attention given to each. It also somewhat contradicted the philosophy that Robert Stokes then President and CEO of Versa power was advocating when discussing the many potential application and market options for the SOFC "choose one and focus".[58]

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[56] McConnell, Vicki P., 'Versa Power's Sofc Could Scale to Mw for Seca, and Work in Transport Hybrids', *Fuel cells bulletin,* 2007 (2007).
[57] Stokes, Robert, 'Versa Power: Solid Oxide Fuel Cell Applications', in *Hydrogen Technical Advisory Committee,* (Arlington, Virginia, 2011), p. 32.
[58] Ibid. p. 5.

The move to meeting the multiple goals of government funded projects also underlined the changes within Versa Power. In the late 1990s and early 2000s it had been a company with a focussed aim of commercialising a product for market. Now it was essentially a contract research company whose existence was predicated on meeting project deliverables with the focus on commercialisation being lost. This was summed up by one employee who said,

> When you get into funded projects, say from government agencies, they become project orientated in the finite term. The goals of the project are met, tick those boxes, but you're not necessarily commercialising the technology. You're not taking it all the way.[59]

This suggested a frustration that government projects were not leading to commercialisation and similar frustrations were voiced by an ex-employee who suggested that in some ways the company had lost its drive and focus and that reliance on government funding was becoming a "crutch".[60] Another issue facing both industrial and core technology teams within the SECA programmes was the issue that the short-term nature of the projects being issued by the DOE. The negative impact of these short programmes within the core technology teams was also suggested by Behling, where she contended that they were focussed on shorter term problem solving rather than gaining more fundamental understanding over the longer term.[61] The short duration of projects was also seen as an issue in the industrial teams with one anonymous interviewee remarking on the issues of working project to project,

> as time has gone on the project term has gotten shorter and shorter… in a durability project of several thousands of hours this can leave little room for actual development.[62]

The changing goals of SECA away from the focussed development of the 5kW core module was further highlighted in 2008 with Rolls-Royce Cell Systems (RRFCS) becoming a new member of the industrial teams. Although originating in the UK, the company had bought the fuel cell company SOFCo from McDermott and

[59] Anonymous Interview Conducted by Author on 27th June 2018.
[60] Anonymous Interview Conducted by Author on 29th June 2018..
[61] Behling, *Fuel Cells : Current Technology Challenges and Future Research Needs / [Internet Resource]*, p. 240.
[62] Anonymous 27th June 2018..

repositioned RRFCS as a US concern. This move allowed the company to qualify for SECA funding and also to access the emerging and potentially lucrative US distributed power generation market, the needs of which some in RRFCS felt was a good match for the RRFCS technical offering.[63] The Rolls-Royce design was based around basic modules of 250kW in size, these being pressurised and linked together to form systems of the order of one megawatt or larger in conjunction with small gas turbine.[64] Unlike Siemens-Westinghouse with their 5kW venture with Canadian company Fuel Cell Technologies, Roll-Royce had no pretence of a small system in the 5kW range and was solely focussed on larger scale pressurised systems, so underlining the shift of SECA away from the rationale around which it was originally conceived.

This is not to suggest that smaller systems were abandoned completely. Delphi were still interested in the 1-10 kW size range for their vehicular auxiliary power unit (APU) designs, especially larger trucks, while other companies such as Acumentrics and Versa still maintained interest in smaller combined heat and power systems, the DOE also continued to use testing and results from these smaller units as evidence of progress towards larger goals. [65] Wider DOE presentations suggested however, that the SOFC and the SECA programme had ultimately become a technology subset within the much larger and encompassing FutureGen programme.[66] Some saw this as a result of the positioning of SOFC activities within the DOE Office of Fossil Fuels, where a strong orthodoxy around large, centralised generation facilities running on coal persisted.[67] While this positioning may have helped legitimatise the place of the SOFC within this vision, it also created issues for

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[63] Anonymous Interview Conducted by Author on 28th June 2018.
[64] Agnew, Gerry, et al., 'The Design and Intergration of the Rolls-Royce Fuel Cell Systems 1mw Sofc', in *ASME Turbo Expo 2005: Power for Land, Sea, and Air* (Reno, Nevada: ASME, 2005).
[65] Williams, Mark, et al., 'Solid Oxide Fuel Cell Technology Development in the U.S', *Solid State Ionics,* 177 (2006); Surdoval, Wayne A., 'Doe and Seca and Futuregen Programs: Progress and Plans', in *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century,* (IEEE, 2008).
[66] Such examples of the perception and positioning of SECA within FutureGen can be seen in presentations such as Zitney, Stephen E., 'Futuregen: Stepping-Stone to Sustainable Fossil-Fuel Power Generation', in *AIChE 2006 Annual Meeting,* (San Francisco CA, 2006); Strakey, Joseph P., 'Seca, Coal and Futuregen', in *8th Annual SECA Workshop,* (San Antonio, Texas, 2007). and Surdoval, "Doe and Seca and Futuregen Programs: Progress and Plans".
[67] Wachsman Interview

the identity of the SOFC as a fuel flexible energy conversion technology on its own right.

The notion of the 5kW core unit was seemingly being lost, along with the ideas that small combined heat and power units of this size had been seen as potentially important market entry products, something that was not being lost in other parts of the world such as Europe and Japan.[68] The SOFC had also become linked to the hydrogen production aspects of the FutureGen programme, utilising the off gases from the hydrogen production and purification systems, again reinforcing the wider perception of the "hydrogen fuel cell".[69] Further, the SOFC was often seen as a future technology to be incorporated into later iterations of the programme with initial demonstrations relying mainly on integrated gasification combined cycle (IGCC) systems utilising gas turbines and not relying on fuel cells. Together these perceptions of the SOFC created issues when the FutureGen project itself began to face problems. As with many programmes as large and ambitious as FutureGen delays and cost overruns were inevitable and put pressure on budgets and timelines.

The Axe Falls

In late 2007 towards the end of the Bush presidency a competition to host the first demonstration of a FutureGen system was held between two sites in Texas and one in Illinois, with the Illinois location announced as the winner in December 2007. In January 2008 the whole FutureGen project was abruptly cancelled with the Bush administration citing rising costs and disagreements with the level of industry cost sharing. However, the rapidity of the change of heart from the administration had a number of people wondering about the rationale for such a change. Some suggested politics was playing a significant role and pointed to the fact that the two potential sites in the president's home state had lost out had influenced decision making.[70] The

[68] Suzuki, Minoru, et al., 'Development of Sofc Residential Cogeneration System at Osaka Gas and Kyocera', *ECS Transactions,* 7 (2007); Shimano, Jun, et al., 'Development Status of a Planer Type of 1 Kw Class Sofc System', *ECS Transactions,* 7 (2007).

[69] Wachsman and Williams, "Hydrogen Production from Fossil Fuels with High Temperature Ion Conducting Ceramics".

[70] Goldston, David, 'Demonstrably Wrong: Public-Private Demonstration Projects Are a Good Way to Test Technology in the Field. But the Driving Force Is Often More Political Than Scientific', *Nature (London),* 453 (2008).

case was referred the Government Accountability Office, whose report in March 2009 revealed inaccurate cost estimations from the DOE leading to a $500 million overestimate in costs.[71]

During the course of the Accountability Office investigation there was also a change in administration with Democratic President Barak Obama taking over from the previous Republican administration of Bush. While the Obama administration looked more favourably on many climate issues, it was not a positive development for SOFC developers. President Obama's new Energy Secretary, physicist Steven Chu was not, at the time, a fan of hydrogen. He felt that there were four major issues to be solved within the technology: better production, better storage, better distribution and better fuel cells. Together, he called these the "four miracles" and that they formed significant barriers to the realisation of hydrogen transport systems in the short term. Chu said, "if you need four miracles, that's unlikely: saints only needed three".[72] One of his first acts as Energy Secretary was therefore to drastically cut the funding to hydrogen projects. Chu reasoned that hydrogen was just too far away to make sense and with the economic pressures of the recent 2008 financial crash it made more sense to look at nearer term options. For those in search of an environmentally friendly non-polluting vehicle, this meant a return to battery and hybrid options that automakers had rejected in the late 1990s.[73]

With FutureGen already facing being cut from the Bush administration and the hydrogen production aspects of the programme already being downplayed in the proposed early demonstrations, FutureGen seemed a straightforward cut. When entering office in 2009 President Obama was portrayed as positively predisposed to the FutureGen demonstration and the notion of "clean coal".[74] From the president's perspective this was in part due to his previous opposition to the Bush cut of the Illinois demonstration from when he recently served as an Illinois senator. It therefore looked highly likely that some form of FutureGen would be reprieved and

[71] 'Maths Mistake Blamed for Killing Off 'Clean Coal' Plant', *Nature,* 458 (2009).
[72] Bullis, Kevin, 'Q & A: Steven Chu', in *MIT Technology Review,* (Cambridge Mass, 2009).
[73] Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*, pp. 181-183; Eisler, *Age of Auto Electric : Environment, Energy, and the Quest for the Sustainable Car*
[74] This position would change over the course of his presidency with many in the coal lobby later accusing him of waging a "war on coal", Revesz, Richard and Jack Lienke, 'How Obama Went from Coal's Top Cheerleader to Its No. 1 Enemy', *Grist,* (2006) <https://grist.org/climate-energy/how-obama-went-from-coals-top-cheerleader-to-its-no-1-enemy/>.

the programme would not be cut completely. This may have sounded positive for the SECA programme as it had become more connected with FutureGen over these preceding years, however it was seen as part of the hydrogen generation portion of this programme. Along with wider perceptions of “hydrogen fuel cells” as a single entity and with hydrogen and fuel cell cuts being enacted elsewhere in the DOE, the hydrogen infrastructure underpinned by the original FutureGen programme was no longer required in the short to medium term so the hydrogen production aspects of FutureGen were now seen as a superfluous add on.

The Administration therefore “zeroed” the SECA budget and allocated no money to the programme, effectively shutting it down. It was therefore an ironic twist of fate that saw some of the hydrogen dependant, low temperature fuel cell programmes of the Office of Energy Efficiency and Renewable Energy (EERE) being repackaged and maintained (albeit at a much lower level) as long term strategic research ambitions while development in the SOFC, probably the most fuel flexible type of fuel cell, with the least need of a supporting hydrogen infrastructure, being the one type completely cancelled.

SOFC Redux

The cancellation of the SECA programme sent shockwaves not only around the US SOFC community but also resulted in wide surprise in other parts of the world such as Europe and Japan where fuel cell and SOFC development work was still being undertaken as part of large co-ordinated programmes with significant government contributions. In Japan a deployment-led approach known as “Ene-farm” was underway to bring down costs in small, combined heat and power units of around one to five kilowatts.[75] In Europe a large integrated project known as “REAL-SOFC” had been funded by the European Commission bringing together most of the significant SOFC actors in Europe to improve robustness and durability in SOFC, along with various follow on and parallel programs and collaborative partnerships

[75] Suzuki, et al., "Development of Sofc Residential Cogeneration System at Osaka Gas and Kyocera"; Kadowaki, Masataka, 'Current Status of National Sofc Projects in Japan', *ECS Transactions,* 68 (2015).

which built from this.[76] This continued international support for SOFC and the potential impact on US positioning and competitiveness in this field was emphasised by Prof. Eric Wachsman in his 2012 criticism of the DOE decision to cancel SECA.[77] Wachsman, a professor of materials science focussed on new materials development for SOFC, was a senior figure in the SOFC field. He had been a US proponent of the materials logics around using higher conducting electrolyte materials to lower SOFC operating temperatures in the 1990s.[78] In the 2000s he remained a prominent figure in the SECA core programme, not only continuing fundamental materials development for lower temperature operation but also trying to commercialise smaller systems based around these.[79]

A significant part of Wachsman's defence of SECA revolved around mapping the various aspects of SOFC characteristics and performance to each of the DOE's six key strategies which had arisen from the "Quaternary Energy Review", a major strategic policy document whose aim was to guide DOE activities over the coming five years.[80] In this way, he aimed to show the utility of the SOFC across the range of DOE priorities and the short-sightedness of the Department of Energy in cancelling the SECA programme.[81] Wachsman argued that the DOE was only seeing the fuel cell within the contexts of hydrogen economies and transportation. This narrowly focussed view of the fuel cell and its place can be seen in contemporary presentations from the DOE on the future development of fuel cell technologies where the SOFC get scant if any mention and the vast majority of the narrative revolves around low temperature fuel cells for transportation applications.[82]

Wachsman sought to re-emphasis the link of the SOFC and its applicability in existing hydrocarbon energy frameworks pointing to the fact that it was a potential bridging technology between existing and future energy frameworks. Within his

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[76] Steinberger-Wilckens, R., et al., 'Real-Sofc - a Joint European Effort to Improve Sofc Durability', (2009), pp. 43-56.
[77] Wachsman, Marlowe, and Lee, "Role of Solid Oxide Fuel Cells in a Balanced Energy Strategy".
[78] Wachsman Interview
[79] Ibid. Overly, Steven, 'At Redox Power Systems, the Future of Electricity Lies in Fuel Cells', *The Washington Post,* (2013).
[80] Department of Energy, 'Report on the First Quadrennial Technology Review', (2011).
[81] Wachsman Interview
[82] Satyapal, Sunita, 'Overview of Hydrogen and Fuel Cell Budget', in *Stakeholders Webinar - Budget Briefing,* (Department of Energy, 2011); Satyapal, Sunita, 'Hydrogen and Fuel Cell Program Overview', in *2012 Annual Merit and Peer Evaluation,* (Department of Energy, 2012).

petitioning Wachsman acknowledged the need for further cost reductions, and while recognising the role of increased production and deployment in achieving this, a significant part of his outline for future development still focussed on the need for new materials to deliver temperature reductions. While it could be argued that this simply reflected his own position within the SOFC community and his research interests in low temperature electrolytes, it also echoed a wider belief across many of the SOFC community that solutions to problems would be attained through the development of new materials, which continued to position and promote promissory materials in the cell and stack as the route to solutions in the design and development of the SOFC.[83]

The petitioning of Wachsman and others from the SECA programme to decision makers outwith the Obama administration paid off. Congress overrode the administrations initial zero budget and awarded the SECA programme $25 million for the following fiscal year, a level of funding which was maintained for the majority of the next decade.[84] Although still some way short of the roughly $50 million of recent preceding years, it was in some way proportional to the roughly 50% funding cuts seen by the EERE hydrogen and fuel cell programme.[85] This funding at least allowed DOE-sponsored SOFC funding to continue. However, the focus began to shift over the coming years towards natural gas fuelled distributed generation systems with electrical outputs of the order of several 10's to a few 100's kilowatts, arguably a return towards the original thinking around the SECA

[83] This focus on the promise of materials to deliver solutions is not only part of Wachman's paper but can be seen across many SOFC reviews, where development of materials and processing of materials within the cells and stacks remained the main focus, such as Will, J., et al., 'Fabrication of Thin Electrolytes for Second-Generation Solid Oxide Fuel Cells', *Solid State Ionics*, 131 (2000); Steele and Heinzel, "Materials for Fuel-Cell Technologies"; Brandon and Skinner, "Recent Advances in Materials for Fuel Cells"; Atkinson, et al., "Advanced Anodes for High-Temperature Fuel Cells".

[84] Vora, Shailesh D, Gary Jesionowski, and Mark Christopher Williams, 'Progress in the U.S. Department of Energy Office of Fossil Energy's Solid Oxide Fuel Cell Program', *ECS Transactions*, 96 (2020), p. 17; Peterson and Farmer, "Historical Fuel Cell and Hydrogen Budgets", p. 3.

[85] Peterson and Farmer, "Historical Fuel Cell and Hydrogen Budgets", p. 3.

programme. While larger multi-megawatt scale coal gas fuelled systems were still referred to, these were pushed even further into the future.[86]

By 2014, two industrial teams were gaining the bulk of the DOE SOFC funding at around $7.5 million each, these were Fuel Cell Energy who had focussed on a 50kW SOFC running at atmospheric pressure and LG Fuel Cell Systems (formally Rolls Royce Fuel Cell Systems) who remained focussed on developing a pressurised 200kW system.[87] The Fuel cell energy team were the former Versa Power who had been brought back within the full control of the Fuel Cell Energy parent company through a buyout of the various other partners which had formed the Versa Power consortium. While Fuel Cell Energy were still focussed on scale up and commercialisation of larger molten carbonate fuel cell systems, the company had also come to recognise that the SOFC provided several future development opportunities that were not applicable to the molten carbonate systems. These centred around mid-scale industrial power opportunities and longer-term ideas around high temperature electrolysis which also began to emerge around 2008. These mid-scale electrical outputs around the low 100s of kilowatts were believed to potentially provide a better synergy to Fuel Cell Energy's existing larger molten carbonate developments than did the initial 1-5kW residential combined heat and power units that had been the focus of Global Thermoelectric during Fuel Cell Energy's initial buy out, and therefore provided a stronger logic across the Fuel Cell Energy company portfolio.[88]

The revised thinking around the DOE approaches to SOFC development over the decade since 2008 also reflected the changing energy contexts in the US over this time. The opening up of large fields of unconventional natural gas by hydraulic fracturing (fracking) had resulted in natural gas becoming second only to petroleum

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[86] This development in DOE approach to SOFC research can be discerned from DOE programme updates such as Vora, Shailesh D, 'Seca Program Overview and Status', *ECS Transactions,* 57 (2013); White, Briggs M., Wayne L. Lundberg, and Joseph F. Pierre, 'Accomplishments, Status, and Road Map for the Us Department of Energy's Fossil Energy Sofc Program', *ECS Transactions*, 68 (2015); Vora, Shailesh D, Wayne L. Lundberg, and Joseph F. Pierre, 'Overview of U.S. Department of Energy Office of Fossil Energy's Solid Oxide Fuel Cell Program', *ECS Transactions,* 78 (2017); Vora, Jesionowski, and Williams, "Progress in the U.S. Department of Energy Office of Fossil Energy's Solid Oxide Fuel Cell Program".
[87] Vora, Shailesh D, 'Office of Fossil Energy's Solid Oxide Fuel Cell Program Overview', in *15th Annual SECA Workshop,* (Pittsburgh, PA: Department of Energy, 2014), p. 19 (p. 19).
[88] Pastula Interview 5 Apr 22; Anonymous Interview 29th Apr 21

as the most consumed primary energy resource in the US. Natural gas consumption had overtaken coal in 2006, after which coal consumption maintained a steady decline in consumption dropping from a peak of around 22 quadrillion BTU in 2006 down to 10 quadrillion BTU by 2020. At the same time use of natural gas increased dramatically, almost matching Petroleum by 2020 at 32 quadrillion BTU by 2020.[89] The increased availability of natural gas opened up the electricity generation market for smaller generation facilities based on gas turbines. It could be suggested that this led to a similar effect to that witnessed almost two decades earlier in the UK when the North Sea gas fields opened up with what was known as the "dash for gas", where the newly-available gas facilitated a proliferation of gas turbine generation facilities which were generally smaller and less polluting than large coal fired systems.[90]

Gas turbine systems were also far cheaper to build and could also be commissioned far quicker than the larger coal-fired central facilities. These factors allowed smaller electrical generation companies to enter the field and to begin to challenge the dominance of the large centrally run coal fired systems. Further, with increasing environmental regulations and President Obama signing up to the 2015 Paris Accords the contradictions of "clean coal" were becoming ever more apparent. Although natural gas is still a fossil fuel, its combustion was far less polluting than coal, emitting not only fewer noxious gases and particulates, but also less carbon dioxide per kilowatt than coal, this led to some to try to claim natural gas was a "green energy source".[91] In the neoliberal deregulated energy markets such factors reinforced one another to overtake the more deterministic, "quasi-planning" which could be argued that earlier DOE thinking had represented.[92]

An example of such quasi-planning, was, as Wachsman described it, the "stove-piping" of the SOFC into the DOE Office of Fossil Fuels. This tied SOFC

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[89] US Energy Information Administration, 'Total Energy: Primary Energy Consumption by Source', 2024 <https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T01.03#/?f=A>.

[90] Winskel, "When Systems Are Overthrown: The 'Dash for Gas' in the British Electricity Supply Industry".

[91] Harvey, Fiona, 'Fossil Fuel Firms Use 'Biased' Study in Massive Gas Lobbying Push', *The Guardian,* (2011).

[92] Eisler ascribes the term "quasi-planning" as representing the mixture of scientific and political and administrative imperatives which underpinned US national level-policy making, which when working across agencies could lead to uncoordinated or contradictory outcomes. Eisler, *Age of Auto Electric : Environment, Energy, and the Quest for the Sustainable Car* p. 8.

funding to the needs of the coal programme and compelled SOFC developers to think of their technology with respect to integration with designs of large coal generation. This made it difficult for SOFC developers to follow and take advantage of emerging trends such as the rise of smaller distributed natural gas fuelled generation.[93] It could be argued that such thinking was evident in the late 1980s early 1990s where the DOE focused on larger Westinghouse systems and missed the opportunity to support developers of smaller thick-film based stacks. Again, in the 2000s the initial modular opportunities of smaller systems based on the 5kW core stack had been pushed into the background to meet the coal industries desire for megawatt scale systems the tie to which ultimately led to the cancellation of the SECA programme. One developer which did side-step the DOE strictures and control was Bloom Energy, an SOFC company who had raised significant funding the private venture capital, so minimising the need to engage with the DOE, and between 2010 and 2020 would deploy more SOFC capacity than any company in the US.

In the early 2000s a small research group headed by KR Sridhar at the University of Arizona had a small solid oxide electrolyser flight tested and ready to go to Mars. The aim was to demonstrate the electrolytic decomposition of carbon dioxide, the major constituent of the Martian atmosphere, into oxygen and carbon monoxide. These gases would be used to sustain personnel on missions to Mars and provide the constituents for fuel for the return journey.[94] At the same some mission planning difficulties in the NASA Mars programme led to the mission slated for the University of Arizona experiment to be cancelled.

With no prospect of a new mission for the technology, KR Sridhar and a few members of his research team looked to terrestrial applications and formed a small university spin out called Ion America. They managed to interest a number of influential venture capital funders and in 2003 moved the venture to Silicon Valley California and raised significant funding.[95] So successful was this funding drive that

[93] Wachsman Interview
[94] Sridhar, K. R. and B. T. Vaniman, 'Oxygen Production on Mars Using Solid Oxide Electrolysis', *Solid state ionics,* 93 (1997); Gottmann, Matthias and K. R. Sridhar, 'Thermal Package of the Oxygen Generator Subsystem on the Next Mars Lander', *SAE transactions,* 109 (2000).
[95] Anonymous Interview 29th Apr 21 As part of this initial expansion I would join Ion America while it was still a smaller start up to work on cell development between January 2004 and December 2005. As the company began to move beyond its initial startup roots towards a larger corporate entity, I left to move to a UK academic research post in SOFC materials development.

between 2000 and 2011 the funding for this single company was said to have equalled the entire SECA budget.[96] Over the coming years, they would progressively develop their technology, based on an electrolyte supported thick-film arrangement.[97] While earlier ideas still looked to combine elements of electrolysis through reversible SOFCs where a single device could be run as either a fuel cell or electrolyser in a regenerative system, the company quickly established that small industrial distributed power generation would be the key market sector they would pursue.[98]

In 2006, Ion America remarketed itself as Bloom Energy and initiated a rapid scale up and deployment programme. By 2017, the company had installed 297 megawatts of SOFC systems at a number of high-profile blue-chip companies such as Google, Walmart, and Coca Cola, amongst others.[99] Although the company maintained a programme of research, they stated their main driver for cost reduction was through manufacturing improvements and materials costs through improved efficiencies.[100] The company stated the importance of creating a "statistically meaningful field installed base" from which to derive real world learning to drive innovation.[101] To this end, in addition to a base of highly knowledgeable SOFC staff, the company also looked to hire engineers from industries with backgrounds in cost reduction through high throughput, automation and quality control, such as the automotive industry.[102]

The value Bloom placed on the learning and knowledge that would come from deployment and use at customer sites echoed the rationale between the Japanese Ene-farm programme and the similar European Ene-field and later Callux programmes. In both the Japanese and European cases, the programme aims were the deployment of small 1-5kW scale domestic combined heat and power units

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[96] Wachsman, Marlowe, and Lee, "Role of Solid Oxide Fuel Cells in a Balanced Energy Strategy", p. 5501.
[97] Ibid.
[98] Reference to Blooms early reversible SOFC development while still known as Ion America can be seen here Hickey, Darren, 'Optimization and Demonstration of a Solid Oxide Regenerative Fuel Cell System', *ECS Proceedings Volumes*, 2005-07 (2005).
[99] Bloom Energy, 'Form S-1 Registration Statement', ed. by Securities and Exchange Commission (Washington, D.C, 2018), (pp. 141-143); Bloom Energy, 'Bloom Energy Case Studies', 2024 (2024) <https://www.bloomenergy.com/customers/>.
[100] Bloom Energy, "Form S-1 Registration Statement", p. 148.
[101] Ibid. p. 58.
[102] Ibid. p. 153.

numbering in the thousands. [103] The choice of small domestic units around 1-5kW in Japan and Europe versus the move to larger industrial scale units of several 100kW or larger in the US by both Bloom and Fuel Cell Energy reflected the different energy contexts that were operating in the various countries and how that affected decision making processes of local developers. What Lécuyer and Brock would describe as the application of “market logics” in shaping, designing and building a product to meet the perceived needs of the targeted market.[104]

One significant contextual difference between the US energy market and those of Japan and Europe was the relative costs of natural gas and electricity, also known as the “spark gap”.[105] In Japan and Europe the cost of electricity from the grid was higher than the retail cost of gas therefore there was a business case for the local generation of electricity from gas and the highly efficient, quiet, low emission operation of the SOFC offered a technology that could potentially deliver this local generation directly to the consumer, hence the popularity of domestically-sized SOFC units in these regions. Small-scale local generation of electricity was given a further incentivisation by the Fukushima nuclear disaster in Japan, which had a massive impact on the policies around the provision of electricity in that country. Wider influences of Fukushima were also evident around the world, such as nuclear power falling out of favour in several European countries such as Germany.[106]

In the US however, the price differential between electricity and gas was far lower, reducing the incentive for local generation at the consumer level. The local energy contexts in the US which arguably favoured the fuel cell were the instabilities in the electrical grid. These instabilities arose from the physical vulnerability of such

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[103] For information on Japanese and European deployment programmes see Kadowaki, "Current Status of National Sofc Projects in Japan". and Atanasiu, Mirela, 'The Status of Sofc R&D in the Fuel Cell and Hydrogen Joint Undertaking Program', *ECS Transactions*, 68 (2015). respectively.

[104] Lécuyer and Ueyama, "The Logics of Materials Innovation: The Case of Gallium Nitride and Blue Light Emitting Diodes"; Lécuyer and Brock, *Makers of the Microchip*.

[105] Hawkes, A.D., D.J.L. Brett, and N.P. Brandon, 'Role of Fuel Cell Based Micro-Cogeneration in Low Carbon Heating', *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 225 (2011).

[106] Hayashi, Masatsugu and Larry Hughes, 'The Fukushima Nuclear Accident and Its Effect on Global Energy Security', *Energy Policy*, 59 (2013); Paillere, Henri and Jeffrey Donovan, 'Nuclear Power 10 Years after Fukushima: The Long Road Back', *IAEA News*, (2021) <https://www.iaea.org/newscenter/news/nuclear-power-10-years-after-fukushima-the-long-road-back> [accessed 30th April 2024]; Hermwille, Lukas, 'The Role of Narratives in Socio-Technical Transitions—Fukushima and the Energy Regimes of Japan, Germany, and the United Kingdom', *Energy Research & Social Science*, 11 (2016).

an extended system to bad weather, such as the East Coast blackouts of 2003 or through systematic instabilities caused by failures in the market mechanisms put in place to attempt to construct a more open and deregulated energy market in the 1990s, manipulation of which led to energy shortages in California across the early 2000s.[107]

At a domestic level such instabilities could be dealt with through small generators sets running on gasoline or diesel, both cheap and generally easily available. At an industrial level, it was not so straightforward. The larger generators required for uninterrupted power at a commercial building such as a data centre incurred considerable costs with regards to maintenance and upkeep, however the costs of losing power were also considerable, with estimated losses running into millions of dollars for outages lasting even just for a few minutes.[108] In the new millennium of globally-connected commerce maintaining power and connection was everything. It was this market that Bloom looked to tap into, where the value of the electricity was imbued with more than just the market price per kilowatt, it also carried an insurance value which favoured the SOFC. Bloom was not alone in such thinking. The instabilities of the US electrical grid had for many years been a strong motivating factor for other developers of industrial-sized (hundreds of kilowatts) SOFC systems such as Rolls-Royce when looking to identify potential market sectors which matched their technology.[109]

The Bloom Energy systems utilised either natural gas, or in some cases biogas from decomposition of landfill waste, both of which attracted significant government subsidy to encourage the use of "green" energy sources, such as the Californian Self Generation Incentive Program (SGIP).[110] These subsidies

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[107] Sweet, Bill, 'The Blackout of 2003', *IEEE Spectrum,* (2003) <https://spectrum.ieee.org/the-blackout-of-2003> [accessed 30th April 2024]; Wald, Matthew L., 'The Blackout That Exposed the Flaws in the Grid', *The New York Times,* (2013); Broder, John M., 'California Power Failures Linked to Energy Companies', *The New York Time* (2002); Borger, Julian, 'Tapes Reveal Enron's Secret Role in California's Power Blackouts', *The Guardian,* (2005).

[108] Clay, Kelly, 'Amazon.Com Goes Down, Loses $66,240 Per Minute', in *Forbes,* (New Jersey, 2013).

[109] Anonymous Interview 28th June 2018.

[110] Bloom Energy, "Form S-1 Registration Statement", p. 23; Wesoff, Eric, 'Bloom Energy Plays the Subsidy Game Like a Pro', *Other Energy,* 2024 (2011) <https://www.greentechmedia.com/articles/read/bloom-energy-plays-the-sgip-subsidy-like-a-pro>; Kanellos, Michael and Eric Wesoff, 'Do Bloom Fuel Cells Really Get $8.25 a Watt in Subsidies?', *Batteries Storage and Fuel Cells,* 2024 (2011) <https://www.greentechmedia.com/articles/read/do-fuel-cells-really-get-8-25-a-watt-in-subsidies>.

substantially reduced the costs of ownership of an SOFC system making them more attractive for potential customers. Qualification for such environmentally based subsidies also allowed customers to present progressive green identities to customers as they could point to their adoption of low emission electricity generation. Despite its commitment to deploying multiple systems in real world applications, it is still not clear whether this was a path to cost reduction. The centrality of the subsidies to the business model proved divisive, with some asking questions around its longer-term viability and raised questions around the potential for greenwashing.[111] There had also been some implied technical criticism to the effect that Bloom's electrolyte-supported approach represented earlier technological embodiments and as such would never reach the required cost targets for a commercially viable system.[112]

Bloom's approach mirrored the approaches of the Japanese and European Ene-farm and Ene-field programme and suggested an alternative view to SOFC development. One which looked to increased production numbers and mass deployment as a means of cost reduction. It was of course recognised that there was a minimum degree of performance that was required to produce a viable SOFC system, but once this had been surpassed then further cost reductions could be won through design for manufacture and improvements in processing such as automation, better production yields and reduced waste. At the same time, others were advocating continued development of new materials as the main route to cost reduction or suggesting that a commercially viable system could not be realised and deployed before gaining a far greater level of fundamental understanding.[113] This highlighted a number of the significant questions facing SOFC developers: where did this this minimum degree of performance lie? Had it yet been reached? And, how did this affect the balance between fundamental research and product development? At what

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[111] Nguyen, Vicky, Liz Wagner, and Mark Villarreal, 'Incentive Money for Bloom Energy and Other Fuel Cell Makers May End ', *Energy,* 2024 (2016) <https://www.nbcbayarea.com/news/local/state-regulators-consider-decision-to-end-big-benefits-for-fuel-cells/1995638/>; Nguyen, Vicky, Liz Wagner, and Mark Villarreal, 'Is Bloom Energy Greenwashing the Public?', *Santa Clara County,* (2014) <https://www.nbcbayarea.com/news/local/is-bloom-energy-greenwashing-the-public/1981688/>.
[112] Wachsman, Marlowe, and Lee, "Role of Solid Oxide Fuel Cells in a Balanced Energy Strategy", p.5501.
[113] Ibid.; Behling, N., 'Making Fuel Cells Work', *Issues in Science and Technology,* 29 (2013).

point is attention better paid to manufacturing, production and deployment to reduce costs?

Such questions are not unique to the SOFC and can be seen across many different types of technological development. Similar debates having been seen to take place in the development of batteries for electric vehicles in the 1990s, where questions around whether cost reductions would result from manufacture at scale or further research and development were also posed.[114] The frequency of these debates reveals the dialogue that takes place between the research laboratory and the manufacturing facility and that the notions of pseudo-linearity that may exist in the minds of project-managers and policymakers do not reflect actual technology development practices.[115]

Historian Cyrus Mody attempts to capture this dialogue between the laboratory and the shopfloor in his proposed “zig-zag” model of innovation.[116] Here, Mody suggests that knowledge and information is free to move in multiple directions around a knowledge community and that insights from application are as likely to inform fundamental research as the other way around. This shows how moving to mass production can potentially lead to cost reduction by revealing problems or asking questions which would never arise from fundamental studies alone. David Edgerton captures this ability of technological application to inform research through one of his ten “eclectic theses” with the suggestion that “invention and innovation rarely lead to use, but use often leads to invention and innovation.”[117]

Some studies have attempted to investigate any effects of increasing production volumes in reducing costs by exploring if they could observe “experience curve” behaviour through studying the costs of the various fuel cell types which had

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[114] Eisler, *Age of Auto Electric : Environment, Energy, and the Quest for the Sustainable Car* pp. 91-93.
[115] Historian David Edgerton reflected on this disconnect between ideas of practice and actual practice in Edgerton, "‘The Linear Model’ Did Not Exist: Reflections on the History and Historiography of Science and Research in Industry in the Twentieth Century".. However, while looking to portray the “linear model” as a construct of historians he gave minimal attention to the presence of such heuristics in the minds and workings of project managers and policymakers, where systems such as “technology readiness levels” (TLRs) are commonly employed and are based on a certain level of linear progression for example see Mankins, "Technology Readiness Assessments: A Retrospective".
[116] Mody, *The Long Arm of Moore's Law: Microelectronics and American Science*, pp. 54-56.
[117] Edgerton, David, 'From Innovation to Use: Ten Eclectic Theses on the Historiography of Technology', *History and Technology*, 16 (1999), p. 123.

been subjected to increased deployment over the preceding years.[118] These studies revealed that while the Japanese PEM stacks of the Ene-farm programme did show evidence of following experience curves and exhibited learning rates, the same was not evidenced for either the larger stationary SOFC or molten carbonate fuel cell systems in the US.[119] The authors of this report suggested that the inability to distinguish a learning rate for the SOFC systems may have been due to the fact that the cost of the SOFC system was lost within wider pricings of an installation which included costs outside the immediate SOFC system such as groundworks, permits and other costs which could vary widely between individual installations and did not necessarily reflect the cost of the stack.

The apparent lack of cost reductions for stack production or that profitability still appeared to be some way off for many companies, along with the fact that the level of SOFC finding from the DOE was well below previous levels, led to a flattening of US SOFC research across the second decade of the twenty first century.[120] While some developers such as LG Fuel Cell Systems pulled out of SOFC technology, others such as Bloom and Fuel Cell Energy remained committed to the technology, with the former going public in 2018 and the latter, after a change of senior management, raising considerable capital around the same time.[121]

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[118] Experience curves are the relationship between the reduction of cost of an artifact and the increase in its production capacity. This can be expressed as a "learning rate", the percentage drop in price for each doubling of production capacity. However, their applicability in representing cost reductions earlier stage products which are just emerging from the research phase is not straightforward, as cost of manufacture and price of the artifact (where the latter is often taken as the indicator of the former) do not track one another as they would do in a more mature product established in the market Neij, Lena, 'Cost Development of Future Technologies for Power Generation—a Study Based on Experience Curves and Complementary Bottom-up Assessments', *Energy Policy,* 36 (2008); Junginger, M., et al., 'The Experience Curve Approach: History, Methodological Aspects and Applications', in *Technological Learning in the Energy Secor: Lessons for Policy, Industry and Science,* ed M. Junginger, W. van Sark, and W. Faaij (Cheltenham: Edward Elgar, 2010), pp. 9-17; Junginger, M., et al., 'Putting Experience Curves into Context: Links to and between Technology Development, Market Diffusion , Learning Mechanisms and Systems Innovation Theory ', in *Technological Learning in the Energy Secor: Lessons for Policy, Industry and Science,* ed M. Junginger, W. van Sark, and W. Faaij (Cheltenham: Edward Elgar, 2010), pp. 36-47.

[119] Wei, Max, Sarah Josephine Smith, and Michael D. Sohn, 'Non-Constant Learning Rates in Retrospective Experience Curve Analyses and Their Correlation to Deployment Programs', *Energy Policy,* 107 (2017); Wei, Max, Sarah J. Smith, and Michael D. Sohn, 'Experience Curve Development and Cost Reduction Disaggregation for Fuel Cell Markets in Japan and the Us', *Applied Energy,* 191 (2017).

[120] Peterson and Farmer, "Historical Fuel Cell and Hydrogen Budgets"; Wachsman Interview

[121] Bloom Energy, "Form S-1 Registration Statement"; Wood Interview 28 Nov 22

SOFC technology remained centred around of ideas of clean electricity generation at multiple scales from multiple fuels, still a grand aspiration for technology developers and policymakers alike. Even with its unresolved issues, the SOFC endured as a perfect vehicle upon which narratives around these aspirations could be constructed, supporting the status quo of "efficient" hydrocarbons, while simultaneously enabling imaginaries of near future frameworks of low carbon energy, such as the current reimagining of the SOFC within renewable energy systems.[122] This reimagining would take SOFC technology back towards the idea of a universal energy convertor, a "reversable cell", which had formed the original concepts for the technology envisaged by Francis Bacon sixty or seventy years before.[123]

Back to the Future

In parallel to the increase in natural gas utilisation in the US, renewable energy was also seeing a large growth across the first two decades of the twenty first century. In 2022 primary energy consumption from renewables had risen to 13% of the US total, this had doubled from a consumption level of 6.2% in the year 2000.[124] A similar increase was seen in Europe with energy consumption from renewables rising from 7.7% to 15% over the same period, however overall levels of renewable energy consumption in Europe were more than double that of the US in 2000. The increased penetration of renewables into the US energy mix over the following 20 years would reduce that deficit but by 2021 Europe was still consuming around 30% more energy from renewables than the US.[125] The higher utilisation of renewables in Europe reflected the differing energy contexts between the two regions, especially with respect to how governments and associated institutions had engaged with the challenges which were emerging due to the increased awareness of the influence of fossil fuels on climate change. While these rises were where nowhere near the levels

[122] Lemmon, John, 'Reimagine Fuel Cells', *Nature*, 525 (2015).
[123] Eisler, ""A Modern 'Philosopher's Stone'": Techno-Analogy and the Bacon Cell", pp. 349-350.
[124] US Energy Information Administration, "Total Energy: Primary Energy Consumption by Source".
[125] Ritchie and Roser, "Energy".

of natural gas, they still reflected a significant increase in renewable generation capacity and caught the attention of both policymakers and SOFC actors.

One aspect of the increased deployment of renewable energy was reduction in the costs of the various technologies used, in particular the two most widespread, wind and solar. Following the commitments agreed to in both Kyoto and later Paris, many governments encouraged renewable energy technologies through financial incentives such as "feed in tariffs", paying advantageous rates for small renewable energy producers to sell their electricity to the grid, or similar incentives, all of which looked to increase the return on investment in the new technologies. These measures had the desired effect, increasing the uptake of both solar and wind technologies, so reducing costs as increased production led to learning curve behaviour. Indeed, it was such "green" incentivisation that Bloom Energy had taken advantage of with their industrial scale distributed energy SOFC systems, when in the US some states defined natural gas a "green fuel" eligible for such schemes.

These cost reductions began to make renewables cost competitive with oil and gas combustion for generating electricity. In recent cases, especially with the volatility of natural gas prices due to geopolitical instabilities, renewables have proved to be the cheapest form of electricity production for many western nations and as was the case in the 1970s renewables have been framed within the context of national energy security and minimising exposure to geopolitical energy shocks.[126] No longer was renewable energy seen as the technology of "kooks" or dreamers imagining future energy utopias, renewable energy was beginning to have a measurable impact on the behaviour of the electricity grid. This shifted the thinking of power engineers and utilities managers towards the increased need for energy storage. [127] This increased awareness of the need for storage again gave the SOFC

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[126] Roser, M., 'Why Did Renewables Become So Cheap So Fast?', 2024 (2020) <https://ourworldindata.org/cheap-renewables-growth>; Ambrose, Jillian, 'Most New Wind and Solar Projects Will Be Cheaper Than Coal, Report Finds', *The Guardian,* (2021).

[127] Barton, J.P. and D.G. Infield, 'Energy Storage and Its Use with Intermittent Renewable Energy', *IEEE Transactions on Energy Conversion,* 19 (2004); Suberu, Mohammed Yekini, Mohd Wazir Mustafa, and Nouruddeen Bashir, 'Energy Storage Systems for Renewable Energy Power Sector Integration and Mitigation of Intermittency', *Renewable & sustainable energy reviews,* 35 (2014); Denholm, P., et al., 'Role of Energy Storage with Renewable Electricity Generation', (Office of Scientific and Technical Information (OSTI), 2010).

actors an opportunity to once more reframe their devices, this time as a promissory means of providing energy storage.

Throughout the development and deployment of ever-increasing levels of electricity generation, the grid has always been regarded as instantaneous, we generate, we use, with little thought or regard of the in-between. Outside of specific applications of batteries to power miniature, mobile or remote devices the relationship between populations and electricity has become one of instant availability, flick the switch and it is there. The increased adoption of renewable energy had begun to challenge this assumption and the need for increased levels of storing energy at grid level was beginning to become apparent. Energy storage at grid level to even out peak demand was not in itself a new concept. Pumped storage, where water was pumped into a high reservoir during times of low demand and excess electricity on the grid, to later be released to flow back down to the lower level through generating turbines had been in use since the 1930s. Although suitable sites for pumped storage were geographically limited, requiring the correct topography between the lower and upper levels. This limited pumped storage to larger systems, able to supply gigawatt levels of stored energy, evening out peaks and troughs of supply and demand across the grid. As renewable generation became an increasing part of the energy mix it was beginning to become apparent that large, pumped storage would not meet the requirements to overcome the intermittency of renewables.

One important aspect of renewable generation was its siting to take best advantage of the appropriate climatic conditions. For example, wind, which was rapidly becoming the most widely deployed form of renewable generation, often required positioning wind turbines in high or exposed locations maximising exposure to the prevailing winds. Such locations were often remote, removed from centres of population and likely to be at the outer edges of the grid where connections were at their weakest and least robust.[128] In these situations, one of the main issues around renewable generation was one of grid capacity during times of high levels of renewable generation. As the level of renewable generation increased it was

[128] Popovich, Nadja and Brad Plumer, 'Why the U.S. Electric Grid Isn't Ready for the Energy Transition', *The New York Times,* (2023).

becoming more common for the amount of electricity generated to exceed the capacity of the local grid which connected the generating technologies.[129] This meant that capturing this excess energy through pumped storage was of limited utility as the grid infrastructure was insufficient to feed this electricity to the central storage sites. This situation of "grid constraint" often led to renewable generation capacity being turned off when high levels of such generation was possible to prevent the grid becoming overloaded. The ability of renewables such as wind turbines to be easily "turned off" meant that generating capacity such as wind often bore the brunt of these constraint measures while more conventional thermally based generation remained on.[130]

What was needed to better integrate the increasing levels of renewables and overcome issues of intermittency and constraint was some form of local energy storage solution. Such storage being local to the point of generation would allow any excess electrical energy to be stored in another form, such as chemical energy, which could be stored until such time as it was required when it could then be converted back to electrical energy. Many SOFC and other fuel cell actors would begin to advocate that this perfectly described a fuel cell-electrolyser type device.

While interest in framing the SOFC technology as a solid oxide electrolysis cell (SOEC) began to gain more significant momentum across the later years of the first decade of the 2000s such ideas were not new. In the 1960s, early ideas for solid oxide cells at General Electric focussed on electrolysis.[131] In the 1990s, some researchers studying SOECs using the increased performance planar thick-film designs found the need to dissipate increased levels of oxygen production at the air electrode which led to a significant microstructural development, the "composite cathode" where electrolyte and electrode powders were mixed to increase the surface

[129] Mooney, Attracta, 'Gridlock: How a Lack of Power Lines Will Delay the Age of Renewables', *Financial Times*, (2023).
[130] Agbonaye, Osaru, et al., 'Value of Demand Flexibility for Managing Wind Energy Constraint and Curtailment', *Renewable Energy,* 190 (2022).
[131] Spacil and Tedmon, "Electrochemical Dissociation of Water Vapor in Solid Oxide Electrolyte Cells"; Spacil, 3,635,812.

area for the electrochemical reactions which when applied to fuel cells also facilitated further performance increases.[132]

Further back and outwith solid oxide technology, alkaline electrolysis cells had formed the backbone of the burgeoning European industry in electrochemical synthesis in the first half of the twentieth century with significant centres of development in Germany, Switzerland and Norway. In Norway, the wide availability of hydroelectricity resulted in electrochemistry becoming the favoured mechanism for the manufacture of a wide range of chemicals from fertilisers to explosives. By 1928 the Norsk Hydro plant in Rjuken was mass producing hydrogen for ammonia production with large banks of alkaline electrolysers with an installed capacity of 165 megawatt, illustrating the technology at scale.[133] It was only with the emergence of oil derived chemicals across the second half of the twentieth century that saw electrochemical and associated synthesis routes dropping out of favour and to a certain extent side-lined.

When Francis Bacon first started developing the device that would eventually emerge as the alkaline fuel cell (AFC), he initially imagined an electrochemical energy converter. A device that would rapidly and efficiently convert electrical energy to chemical energy and then just as efficiently and rapidly covert the chemical energy back to electrical energy. The basis of what would now be termed a reversable or regenerative fuel cell.[134] Bacon was influenced by the prominence of electrochemical synthesis across Europe , such as the electrolyser development in Germany in the 1930s, when he first started to conceive his system, however by the time he was trying to gain support for further development in the early postwar years of the late 1940s and early 1950s the contexts of both energy and chemical synthesis were changing with the increasing dominance of oil and increasing needs for electricity generation.

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[132] Yamashita, Akihiro, Hiroshi Tsukuda, and Tsutomu Hashimoto, 'Anodic and Cathodic Electrode Reaction at La1-xSrxMnO3', in *First European Solid Oxide Fuel Cell Forum,* ed. by Ulf G. Bossel (Lucerne: European Fuel Cell Forum, 1994), pp. 661-669.
[133] Tom Smolinka, et al., 'The History of Water Electrolysis from Its Beginnings to the Present', in *Electrochemical Power Sources: Fundamentals, Systems, and Applications,* ed Tom Smolinka and Jurgen Garche (Amsterdam: Elsevier, 2021), pp. 83-164 (p. 109).
[134] Bacon, "The Fuel Cell: Some Thoughts and Recollections", p. 15C; Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*, p. 18.

Policymakers and funding agencies were not interested in Bacon's energy convertor, what they wanted were means to generate electricity to feed the growing demand for electricity.[135] This pushed Bacon towards the fuel cell side of his device, ultimately arriving at the alkaline fuel cell which NASA used to open up the way to the moon with the Gemini and Apollo missions of the 1960s and 1970s, with a later version also used in the Space Shuttle.[136] This emphasis towards the fuel cell was evidenced in the solid oxide field insofar as General Electric did not pursue its electrolyser concepts into the 1970s while Westinghouse, focussed on the fuel cell aspects of the device, gained repeated funding from government agencies such as the Office of Coal Research, ERDA and eventually DOE.[137]

Therefore, the increased interest in reversable fuel cells and electrolysis for energy storage in the second decade of the twenty first century has a strong resonance with Bacon's earliest conceptions for his device. SOFC developers began to reframe their devices as energy convertors rather than just electrical generators. The increasing realisation of policymakers that there was an important need for more energy storage also provided funding for the investigation and development of such devices. This in turn legitimised the potential place of SOECs and began to stimulate interest of industrial SOFC developers.[138] Across the 2010s, many companies began electrolyser development programmes repositioning potential products within the energy storage regime.[139] Again, developers of solid oxide systems are promoting the advantages of the high temperature operation of such systems. Not only are these advantages being promoted with respect to the higher efficiencies due to the reduced electrical demand required for high temperature electrolysis but also the potential for electrolysis of other gases such as carbon dioxide.[140] This also positions the device within the future imaginaries of carbon capture and utilisation systems which are

[135] Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*, p. 24.
[136] Burke, Kenneth A., 'Fuel Cells for Space Science Applications', in *First International Energy Conversion Engineering Conference,* (Portsmouth, Virginia,, 2003).
[137] These events have been discussed from the perspective of the fuel cell development in Chapter 3 of this thesis.
[138] Minh, Mizusaki, and Singhal, "Advances in Solid Oxide Fuel Cells: Review of Progress through Three Decades of the International Symposia on Solid Oxide Fuel Cells", p. 71.
[139] Anonymous Interview 29th Apr 21; Bloom Energy, 'The World's Largest and Most Efficient Solid Oxide Electrolyzer', 2024 (2024) <https://www.bloomenergy.com/bloomelectrolyzer/>.
[140] Hauch, Anne, et al., 'Highly Efficient High Temperature Electrolysis', *Journal of Materials Chemistry,* 18 (2008); Ebbesen, Sune Dalgaard and Mogens Mogensen, 'Electrolysis of Carbon Dioxide in Solid Oxide Electrolysis Cells', *Journal of Power Sources,* 193 (2009).

forming an increasingly prominent role in the minds of policymakers looking to mitigate carbon emissions while remaining wedded to existing energy cultures.

While the link to hydrogen as the chemical storage medium potentially places the SOEC back into the realms of hydrogen economy imaginaries, an important difference in this current vision is that the hydrogen produced is only required to be stored locally as an energy buffer. The main energy vector remains electricity. This more discrete, distributed and static notion of the place of hydrogen negates the need for an integrated national level hydrogen distribution system that was demanded by notions of hydrogen-based transportation systems, so avoiding three of the "four miracles" required by Steven Chu.

This synergy with the needs of the ever-increasing renewable energy sector began to create renewed excitement in solid oxide cells and systems. While not at the height of the hype of the late 1990s, by the late 2010s this latest framing of the SOFC was building expectation around its potential role in an electricity imaginary based around distributed renewables and attracting renewed investment.[141] No longer would the SOFC have to compete with combustion-based technology with respect to costs of electrical output. Its unique attributes of reversibility are now promoted as a means to plug gaps overcome worries of renewable intermittency, thereby potentially forming an integral part of the renewable energy solution.

It is an interesting turn that Francis Bacon, first conceived his device as just such an energy converter but in the energy context of the immediate postwar years, with seeming unlimited hydrocarbon resources and the promise of nuclear power on the horizon nobody had any call for conversion and storage. What the policymakers were interested in was electricity generation. This resulted in 60 years of fuel cell developers chasing the tail of combustion-based technologies.

But will electrolysis within renewable energy frameworks be the killer application that the solid oxide cell has been looking for, the problem for which the solution has long been in search of? Again, initial laboratory results and demonstrations have been encouraging, time will tell, maybe in five years.

[141] Anonymous Interview 29th Apr 21; Wood Interview 28 Nov 22; Pastula Interview 5 Apr 22

Chapter 8: Summary and Conclusions

This thesis started from the question, if the solid oxide fuel cell has always been five years away, then what has sustained interest in a technology where concerted development efforts now span over six decades, yet the elusive commercial product still remains five years away? To begin to address this question, I turned to the premise put forward by Harold Wallace in his 2019 review of general fuel cell history *Fuel Cells: a Challenging History*, suggesting to us that we "look for changes in the larger societal contexts within which technologies exist, especially economic and political changes, while remembering that human nature tends towards persistence."[1] He further suggested that in cases such as fuel cells where at a superficial level history may seem to repeat itself that "Understanding context helps explain historical differences. Understanding people helps explain historical similarities."[2] These statements implied a number of further questions: who were these tenacious people who persisted with the development of the solid oxide fuel cell and how did their actions, practices and worldviews shape the development of the SOFC? Secondly, what were the wider contexts that changed around these SOFC developers and how did these changes influence and reshape how they saw their device and its place in the energy landscape?

Through my analysis of the various actors with interests in the SOFC, it quickly became evident that the main architects of the SOFC are the materials scientists and engineers who not only made the device itself but also invented the materials from which it was assembled. It was through the affordances of these materials and the devices they suggested, linked to wider social visions and imaginaries of future energy utopias, that the promises and expectation around the SOFC were constructed. Through these promissory materials and processes, a view became established that any current set of issues associated with the SOFC would be overcome either by inserting a new material or novel process, both of which could allow the SOFC to be considered for a different set of applications. Thereby the

[1] Wallace, "Fuel Cells: A Challenging History", p. 94.
[2] Ibid.

promise of a new material or manufacturing process would be the spur for continued funding to overcome an existing technical barrier or to reframe the SOFC towards a new application. A research group would promote a novel material, a new way of using an existing material, a new SOFC design or a new manufacturing process, any of which they promised would overcome the problems experienced by earlier attempts to commercialise the SOFC. They would convince sponsors and funders through encouraging laboratory or early stack results that this time it would solve the problems, that this time it would work and in a few years a product would be released to the market. It was through this tenacity of the researchers continually developing new materials or processes that the idea could be kept alive, as repeatedly, when one group did not deliver against the promise it was not long before another group emerged offering a new set of promises.

The power and primacy given to the materials of the cell and stack were not unique to the solid oxide fuel cell. While materials had always been central to many engineering and technological advances from bridges to steam trains, it was only after the second world war that they gained their promissory potency. New methods of analysis allowed scientists to understand materials at the molecular and atomic level facilitating their manipulation to enhance or lessen particular properties or attributes, leading to what Bernadette Bensaude Vincent described as “materials by design”.[3] Such were the affordances offered by these “bespoke” materials that they underpinned many advances across electronics and aerospace leading William O Baker (vice president and later president of Bell Labs) to declare the postwar years as “the materials age.”[4] The centrality of materials to government thinking was further heightened by the events of the Cold War compelling the development of evermore potent weaponry, more advanced defence structures and initiating the “space race”.[5] This placed materials close to the centre of ideas around national security and

[3] Bensaude-Vincent, "Das Konzept Von Werkstoffen in Historischer Perspektive".
[4] Baker, "The National Role of Materials Research and Development, Address Delivered at the Materials Science Luncheon, Astm Materials Science Division Symposia [1961]".
[5] Leslie, *The Cold War and American Science : The Military-Industrial-Academic Complex at Mit and Stanford*.

policymaking, resulting in new institutions focussed on the power of new materials to deliver solutions against whatever policy imperatives existed at a given time.[6]

While it was these notions of the power of materials to address a multitude of policy concerns on which the idea and promise around the SOFC was constructed, realising this device has not been a straightforward task. SOFCs operating at the limits of the materials from which they were constructed, allied with ever changing policy drivers, placed many challenges on the practices of the scientists and engineers. To explore how the affordances of their materials influenced these practices and shaped approaches to solutions I drew on the analytical framework of "contextual logics" described by Christophe Lécuyer and David Brock, three of which are based around materials, markets and competition.[7] Of these I focussed on the "materials logics" which provided a lens through which to view how technical actors understood the affordances of their materials and how this shaped their decision making and formed their research agendas.

Using "material logics" as a framework allowed the roles of the materials to be discussed in such a way that it did not give agency to the materials themselves. Rather it stressed the importance of material affordances in shaping the agency of the materials scientists and engineers who had to work within their understanding of the boundaries of the chemical and physical world. I contend that the "logics" framework allowed some scope to consider the SOFC through the challenges faced by the scientists and engineers in building a device with demanding operating conditions, with design constrained by the limits and capabilities of existing materials as they understood them at that particular time. Utilising this framework highlighted how much of the practice employed by the scientists and engineers revolved around innovative and creative developments, either in invention of new materials or application of new processes, both of which intended to develop new knowledges to expand material affordances which in turn opened up new decision-

[6] Baker, "The National Role of Materials Research and Development, Address Delivered at the Materials Science Luncheon, Astm Materials Science Division Symposia [1961]"; Baker, "Using Materials Science"; Psaras, Peter A. and H. Dale Langford, *Advancing Materials Research / [Internet Resource]*, (Washington, D.C.: National Academy Press, 1987).
[7] Lécuyer and Ueyama, "The Logics of Materials Innovation: The Case of Gallium Nitride and Blue Light Emitting Diodes"; Lécuyer and Brock, *Makers of the Microchip*.

making pathways available to SOFC actors. Constructing new “logics” around which they could base their future decisions.

Superimposing the notion of “materials logics” on the development of the SOFC it can be argued that the adoption of thick-film technologies was one of the most significant shifts which allowed developers to construct a new set of potential pathways, reshaping the visions and promises of the SOFC. These new thick-film processes could be said to have changed the existing logics around cell and stack design. The shift to thick-film processing allowed new designs of cells, which in turn permitted new sets of materials to be employed. Together, these new materials and designs allowed developers to address the reduction of operating temperature, which had been adopted as a significant research agenda by many in the SOFC community. These new processes also involved far lower infrastructure and equipment costs than the vapour deposition methods which had become common up until that point. This vastly reduced the cost of entry to participate in SOFC development and resulted in a significant increase in the number of actors engaged in the field.

These new cells also resulted in higher cell performance which in turn supported designs of high-power, compact stacks which matched the need from the emergent distributed power sector, especially those developers promoting microscale combined heat and power at the domestic level (1-5kW). I argue that the confluences of new methods of processing, increasing numbers of developers and the changing relations around the energy market across the early 1990s laid the foundation for the SOFC and stationary fuel cell hype which emerged later that decade.[8] With thick-film processing techniques remaining as the most common fabrication methods across the SOFC sector, I contend that the accounts detailed in this dissertation show that the adoption of thick-film processing techniques to manufacture SOFCs was one of the most significant developments in shaping our current view of the technology over the sixty years of the technologies development.

Returning to the changing social and contextual influences, Harold Wallace referred to these as being an important factor not only in defining the differences that underpinned each successive attempt to commercialise the fuel cell, but also in

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[8] Ruef and Markard, "What Happens after a Hype? How Changing Expectations Affected Innovation Activities in the Case of Stationary Fuel Cells"; Konrad, et al., "Strategic Responses to Fuel Cell Hype and Disappointment".

helping to maintain the validity of the promise of fuel cells for the next attempt. Matthew Eisler highlighted how the political economy in which the fuel cell was developed privileged laboratory-based metrics such as current density. These became normalised as measures of progress while wider issues around systems development were underplayed. Together these trends both created expectation that the fuel cell would be an important part of future energy imaginaries while simultaneously creating multiple assumptions around the fuel cells place within these, creating tensions and contradictions which were never satisfactorily reconciled across the various interest groups.[9] As French sociologist of science Michel Callon had also noted, these assumptions were often accompanied by simplifications of the systems, necessitated by the need to appeal to a diverse range of institutional and commercial sponsors. These simplifications reduced fuel cell systems to a point where they were almost abstract entities and the technical specificity demanded to address potential problems was lost, and as such underlying issues remained unaddressed.[10]

My work looks to add to this scholarship in discussing how similar simplifications existed within SOFC expectations, such as bold extrapolation of promising laboratory results, the conflation of isolated demonstrations in protected spaces with pre-commercial prototypes and misunderstandings of the place of the SOFC in discourse around future energy imaginaries. All contributed to construction of misplaced optimism around the state of development of the SOFC and its place in potential future energy frameworks. I contend this is the first account of a history of the SOFC considering the wider contextual influences affecting and shaping the development of the technology and adds to the collective accounts of fuel cell and SOFC history. Previous accounts have either taken an internalist view of the immediate technological influences in SOFC development, or where wider contextual influences have been taken into account, these have related to fuel cells in general and not specifically considered the SOFC.

This dissertation has highlighted several contextual factors across almost six decades of SOFC research which have not only influenced different sponsors and advocates of the SOFC but have also shaped development decisions by technical

[9] Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*.
[10] Callon, "The State and Technical Innovation: A Case Study of the Electrical Vehicle in France".

actors. Increasingly, postwar society was built around assumptions of cheap and plentiful energy. This was especially the case in the US, whereby the late 1960s and early 1970s demand began to outstrip supply. Commonly much of this pressure on supply was often attributed to the impacts of geopolitical crises, however a significant portion also reflected structural and environmental concerns.[11] One way in which the SOFC played an important social role for policymakers in these areas was through its technical and interpretive flexibility. This allowed both policymakers and technical actors to reframe the device as a potential contribution to the solution of the current issue or crisis of the moment.

Fuel cell applications such as the military batteries of “Project Lorraine”, the Gemini and Apollo programmes, and more recently transportation, have attracted a lot of attention and held a prominent place in the public imagination. It is from these origins that historians such as Eisler discuss the quasi-military genesis of the fuel cell, which for the lower temperature variants of the device was often the case, being products of military or aerospace projects.[12] The link to the military was perhaps not such a stark relationship with the SOFC, whose roots are more closely linked to the needs of the coal industry. Coal research and development did not stimulate the public imagination quite as much as the space programme, so while attention was focussed on the Gemini or Apollo the developers of the SOFC worked quietly away in a temporal parallel within the cloistered environment of the 1960s corporate research laboratory.

Even during the hype cycles of the late 1990s, the SOFC never really emerged into the wider public consciousness in the same way as the PEM for automotive applications. What awareness there was of the SOFC tended to reside within more specialist interests relating to distributed generation. The hype around fuel cells around this time has been linked to the collective expectations arising from deregulation of energy, emerging environmental legislation and financial speculations with increasing levels of press coverage working to validate and

[11] Lifset, "A New Understanding of the American Energy Crisis of the 1970s".
[12] Eisler, "Dreams of Grandeur", p. 325.

legitimise the expectation.[13] However, the place of the SOFC within this expectation was often misunderstood, with the SOFC commonly being conflated with wider fuel cell imaginaries around hydrogen and transportation. This misunderstanding of the SOFC was most evident in the zeroing of the SECA budget in the early tears of the Obama administration in response to misgivings about hydrogen in near-term US energy frameworks. In some respects, prominence of fuel cells for transportation and hydrogen applications resulted in the SOFC becoming a somewhat of a forgotten variant of the fuel cell family, only meriting a small mention in the wider history of fuel cell development.[14]

Although the SOFC may not have been as closely or directly tied to military or quasi-military projects as the other fuel cell types it did not mean that it was immune to what Eisler referred to as the “techno-bureaucracy” of the large US government institutions.[15] Through the political shifts in the organisation of energy research and development brought on by the energy crises of the 1970s, the SOFC eventually found a long term sponsor in the US Department of Energy (DOE). The DOE was a prime example of the quintessential quasi-military organisation. While a great deal of focus was on its roles within civilian energy policy and research, many forget the vast majority of its budget revolved around the development and maintenance of the US nuclear weapons arsenal. Indeed, such misconceptions even went to the heart of US Government, as with the Reagan administration campaign promises to disband the DOE, after its perceived role in the late 1970s oil shortages, being quietly dropped when the extent of the departments involvement in the nuclear weapons programme was realised by the incoming administration.[16]

In the 1960s the initial development of SOFC was spurred by the promise that the technology could be a part of helping a drive to increase the role of coal in

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[13] Konrad, et al., "Strategic Responses to Fuel Cell Hype and Disappointment"; Ruef and Markard, "What Happens after a Hype? How Changing Expectations Affected Innovation Activities in the Case of Stationary Fuel Cells"; Budde, B., 'Hopes, Hypes and Disappointments: On the Role of Expectations for Sustainability Transitions : A Case Study on Hydrogen and Fuel Cell Technology for Transport', (Utrecht University, 2015).
[14] Examples of this can be seen in Wallace, "Fuel Cells: A Challenging History". where very few lines of the paper refer to the SOFC and also in Eisler, *Overpotential : Fuel Cells, Futurism, and the Making of a Power Panacea*. where the SOFC is only referred to a couple of times and then only in passing.
[15] Eisler, "Dreams of Grandeur", p. 326.
[16] Gray "Will the Department of Energy Finally Stop Nuking America: Prospects for National Energy Reform".

electricity generation, which was becoming increasingly dominated by oil and the emergence of nuclear energy. Although the developers of the SOFC did not deliver on these initial promises made for the technology, the oil shocks and energy crises of the 1970s gave US government policymakers reason to re-engage with the promise of the SOFC. The issues this time were framed around the energy security of the nation and, just too great to ignore, the promise of clean efficient electricity generation from domestic energy sources that the SOFC advocates continued to promote. The tangibility of realising this promise was heightened by the technical progress highlighted by the materials scientists in the Westinghouse R&D laboratory. The continued gains in the materials science of the cells convinced officials within the Department of Energy that with just a little more effort and a little more money the SOFC would be able to break out of the laboratory.

Elsewhere, other contextual changes within the energy markets were taking place, that when aligned with new ideas of ceramic processing, would allow SOFC developers to shift notions of the device and its place in the energy landscape. The emergence of market-oriented neoliberal thinking and privatisation would not only break up the dominance of the large corporate research laboratories, such as Westinghouse, as principal sites of technological innovation, but would also lead to increasing deregulation across the energy industry and enhance notions of decentralised electricity generation based on compact turbines running on increasingly available natural gas.[17] In parallel to this, SOFC developers were demonstrating considerable laboratory scale success fabricating SOFCs using inexpensive and easily attainable thick-film processing. These new processing techniques promised scalable routes to market for smaller systems which matched the emerging ideas of distributed generation, down to the level of individual dwellings. The lower cost of entry afforded by thick-film processing led to a rapid growth of fuel cell development activity, fed by a growing market appetite for the potential of large returns on speculative technologies whether these be internet, telecommunications or alternative energy.

[17] Winskel, "When Systems Are Overthrown: The 'Dash for Gas' in the British Electricity Supply Industry".

While many global SOFC developers began to look towards the distributed energy market for SOFC applications, sponsorship by the DOE and previous US government energy institutions had exposed US developers of the SOFC to a worldview of energy policy based around large, centralised generation facilities for the generation of electricity. Such worldviews of these policymakers had been reinforced by the needs of the civil nuclear industry which had been a central tenet of US energy policy for much of the postwar years, but also had roots in the efficiency needs of combustion-based systems especially those based on coal.

This seemingly irreversible pull of US SOFC development towards large multi megawatt scale systems was best illustrated by the course of the SECA programme in the early 2000s. This programme was conceived around taking advantage of the of the smaller distributed micro-CHP units which had showed promise in the hype of the late 1990s and capitalising on the opportunities opened up by thick-film processing. The SECA programme looked to address potential gaps which had emerged in US knowledge and technical leadership through its previous focus on large scale systems, however this repositioning towards small scale applications did not last long.

Within a few years the SECA programme had been absorbed into the large “FutureGen” programme which revolved around deep-rooted ideas of large centralised systems delivering notions of “clean coal” and brought the SOFC back into the sphere of multi-megawatt systems. This was described by Eric Wachsman as being a result of the “stove-piping” of the SOFC into the coal programme. He contended that this programmatic link to fuel types restricted US developers from pursuing emerging options which could have provided more promising avenues for SOFC system development such as small natural gas fuelled systems.[18]

Predicated on promises of high energy conversion efficiencies and low emissions when compared to combustion-based technologies the fuel cell became an important component of energy and environmental discourse, especially as these converged around the need to reduce carbon dioxide emissions. These would also see the SOFC positioned within a range of options for reducing carbon dioxide emissions

[18] Wachsman, Eric D., 'Fuel Cell Future', *Issues in Science and Technology*, 29 (2013); Wachsman Interview

as part of the emerging environmental crises of the 1990s and 2000s. Importantly the SOFC would become framed as a bridging technology promising environmental progress within existing carbon-based energy regimes. Most recently the increase in renewable energy generation has seen a further reframing of the device back towards a role as an energy convertor, able to locally store excess renewable electricity thereby being presented as a solution to intermittency and grid capacity issues.[19]

The regular reframing of the SOFC helped maintain the legitimacy of this promissory device. To continually be seen as part of the solution to the next problem as the contexts of the energy landscape changed around it. However, each successive crisis would require a slightly different variation of the SOFC, demanding a new material or slight redesign, resulting in the need for further laboratory work or bench testing. This played to the strengths of the materials scientists and engineers as it retained design privilege within the cell and stack with the promise directed towards the cells and stacks and a reductive focus on the materials from which they were constructed. While it was possible to attain very promising electrochemical results in a controlled laboratory-based setting where the SOFC was often nursed by several PhD engineers or scientists it was a completely different task to get similar results unattended when in a real-world setting. Some SOFC developers interviewed as part of this work discussed how they felt there had been a naivety about the difficulties involved in packaging a system into a form suitable for market entry.[20]

The continual reframing also revealed the ability of the SOFC to be somewhat of a technological chameleon, able to be represented over a range of issues, being altered slightly each time to meet the new set of requirements. Eisler described this ability of the fuel cell as being able to be "all things to all people".[21] However, this notion suggests the fuel cell as a single entity seen differently by different groups. In the case of the SOFC, I suggest it was subtly different. Over the decades of its development, SOFC developers produced many variants on to which were projected differing identities. These multiple identities appealed to different groups at different times as a promissory solution to different crises. Therefore,

[19] Lemmon, "Reimagine Fuel Cells".
[20] Several interview participants involved in trying to develop a commercial system commented on this naivety, Pastula Interview 5 Apr 22; Anonymous Interview 12 Mar 22
[21] Eisler, "Dreams of Grandeur", p. 334.

rather than being all things to all people, the SOFC could be argued as being different things to different people at different times.

From the perspectives of the policymakers this enduring future promise of the SOFC carried value. The various and successive crises around energy carried significant political implications. The strong cultural and social norms which had been constructed around the use of oil were evident across the developed world but were most apparent in the US. From the suburban sprawl, the freeways, the out-of-town shopping mall, ever larger household appliances and air conditioning, it was a society which had not only grown up around the profligate use of energy but had learned to embrace ever increasing energy use and conflate it as a measure of progress.[22] Therefore, any energy issues which threatened this lifestyle carried a huge political cost. It was within these social and political contexts that the SOFC could be presented as a potential solution which would work within existing energy regimes, which would allow the status quo to be maintained. This avoided the need for the difficult and complex decisions around the need for social and cultural change which carried so much political risk. In this respect the SOFC carried the hallmarks of the "technical fix", the "idea that technology can solve social problems."[23]

The energy imaginaries which were constructed by politicians and policymakers were built on a foundation of technological optimism, the expectation and belief in the role of technology to always find a solution, a solution which would not only preserve the current way of life but also allow for continually improving conditions of both society and the environment.[24] Such expectation was built around the perceived causal links of science, technology and engineering to the improvement and modernisation of society and the quality of life within it, defining its "progress". While such direct correlations of science and technology driving history have been long contested and shown to be tenuous, the idea the remains powerful.[25] As Eisler commented, "American understanding of progress as a series of technological fixes" remained deeply embedded in cultural attitudes to

[22] Nye, *Consuming Power*, pp. 210-215.
[23] Oelschlaeger, "The Myth of the Technological Fix", p. 43.
[24] Harrabin, "Kerry Comments Criticised".
[25] Smith, Merritt Roe and Leo Marx, 'Does Technnology Drive History? The Dilema of Technological Determinism', (Cambridge, Massachusetts: MIT Press, 1994).

expectations of what science and technology could achieve.[26] Such notions of a technological solution to problems which in many cases reside in cultural attitudes and social relations remains strong across politicians and policymakers looking for ways to sidestep the difficult decisions required to reconcile energy use and the needs of the environment.[27]

The requirement to have a near-term solution was an important part of technological optimism. Rather than take difficult decisions now is it easier to convince ourselves that in the near future technology will save us from having to make these choices, that in five years time technologies such as fuel cells will emerge to save us. Whether it be as means of extending existing hydrocarbon regimes by increased efficiency, forming a bridge to future energy imaginaries often constructed around hydrogen, or facilitating increased deployment of renewables, the underlying promise of the SOFC which makes it such enduring and powerful part of this optimism remains the same. This promise was the ability to maintain and continue with energy intensive lifestyles without the social and cultural changes which some future energy scenarios were demanding. Further, as this promised magical future was just around the corner there was no need to make any changes in the short term and business could continue as usual.

These imaginaries bring both the SOFC and the materials from which it is fabricated beyond the laboratory and suggests it also had a social and cultural role. From the accounts presented in this dissertation it can be suggested the SOFC and its materials inhabit both of the two worlds suggested by anthropologist Tim Ingold, “the materials world” and “the world of materials.”[28] The first represents the world of the laboratory defined by physical measurements and experiments, while the second is the world of ideas, a world in which the technical optimism of future imaginaries is couched. Together these two worlds acted in concert to construct futures where the SOFC could flourish. The former provided the data and metrics which could be used to construct the shared expectations required to legitimise the future imaginaries of the latter. What new worlds could be constructed on the back of these materials and the devices which can be built from them? This duality of the

[26] Eisler, "Dreams of Grandeur", p. 332.
[27] Harrabin, "Technology No Silver Bullet".
[28] Ingold, "Materials against Materiality", p. 14.

SOFC helps remind us that energy transitions are not just exercises in technical prowess, and that if barriers to low carbon energy frameworks are to be overcome, then we need to understand technologies within the social and cultural contexts in which they are both created and exist. This dissertation adds to these calls.

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