1 **Progress and outlook for solid oxide fuel cells for transportation applications**

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4 **Abstract**

5 With their high temperatures and brittle ceramic components, solid oxide fuel cells (SOFCs) might
6 not seem the obvious fit for a power source for transportation applications. However, over recent
7 years advances in materials and cell design have begun to mitigate these issues, leading to the
8 advantages of SOFCs such as fuel flexibility and high efficiency being exploited in vehicles. Here we
9 review the advances in SOFC technology which have led to this, look at the vehicles that SOFCs have
10 already been used in, and discuss the areas which need improvement for full commercial
11 breakthrough, and the ways in which catalysis science can assist with these. In particular we identify
12 lifetime and degradation, fuel flexibility, efficiency and power density for improvement, and areas of
13 catalysis science ranging from surface science and computational materials design to improvements
14 in reforming catalysts and reformer design as key to this.

15 **Main**

16 Decarbonising transport is one of the largest challenges in the global response to climate change.
17 Globally, transport is responsible for 23% of emissions and currently relies on hydrocarbons for 92%
18 of its energy¹. Decarbonisation is particularly difficult for transportation, because one of the key
19 requirements for the energy source is portability, and hydrocarbons are one of the most energy
20 dense substances available. In addition, the public health burden from pollutants such as
21 particulates, nitrogen oxides and sulfur oxides emitted by vehicles is large, so cleaner energy sources
22 are required.

23 Efforts in transportation have focussed on batteries and polymer electrolyte fuel cells (PEFCs)
24 running on hydrogen, alongside efficiency improvements and fuel switching. Although over the last
25 decade batteries have been the dominant technology because they have advantages over fuel cells
26 in manufacturing, cost, responsiveness in a vehicle and availability of supporting infrastructure, in
27 the longer-term fuel cells may have advantages in some areas. The clearest advantage of fuel cells is
28 high energy density, where it's not known whether battery technology will ever advance far enough
29 to power long-distance transportation such as ships or intercontinental flights. In the area of
30 passenger vehicles, with high battery vehicle penetration, much of the local grid infrastructure such
31 as substations may not be able to cope and may have to be replaced – it is not clear at the moment
32 whether this will be more expensive and disruptive than the rollout of the hydrogen-fuelling
33 network which would be needed to support fuel cell vehicles. In applications such as buses where
34 fast charging/refuelling is needed, fuel cells also possess an innate advantage. Finally, the wider
35 advantage of switching to a hydrogen-fuelled transportation system is that electrolyzers can be used
36 to smooth the intermittent supply from renewable energy, while at the same time producing
37 hydrogen fuel for vehicles.

38 One technology which was until relatively recently deemed unsuitable for transportation, but
39 nevertheless has unique advantages relative to batteries and PEFCs is the solid oxide fuel cell (SOFC).
40 SOFCs operate on the same principle as other fuel cells, in that fuel and air are physically separated
41 by an impermeable and electronically-insulating electrolyte, with the half-reactions taking place at
42 electrodes either side of the electrolyte, and ion transport through the electrolyte and electron flow
43 through an external circuit completing the circuit and producing usable electrical energy.

The fundamental difference, and source of both their advantages and disadvantages, is that the electrolyte in an SOFC is a solid ceramic. The main disadvantages of this, and the reason why SOFCs were long discounted for use in transportation, is that the conduction has a much higher activation energy than PEFCs and so requires higher temperatures, and that the ceramics are brittle. This means that historically SOFCs have been vulnerable to shock, and difficult to start up and shut down rapidly. Conversely, SOFCs have properties which are extremely attractive for transportation use, such as the ability to use hydrocarbon fuels, high efficiency, relative tolerance towards fuel impurities and no requirement for expensive and rare platinum group metals. The overcoming of the disadvantages over the past twenty years has been achieved through materials and systems advances and has led to SOFCs being considered in modes of transportation including ships, cars, trucks and even aviation.

A potential fuel for SOFCs is hydrogen, which has a gravimetric energy density higher than hydrocarbons, although its volumetric energy density at 800 bar is only a third that of petrol². However, regarding the use of hydrocarbon fuels, current state-of-the-art SOFCs have a 50% system efficiency, and manufacturers are targeting 65% and higher³. This is higher than PEFC efficiency (typically around 40%), meaning that with the energy and exergy costs of separating the reforming process from the oxidation and compression and storage of hydrogen², SOFCs running directly on methane will produce lower carbon emissions than a PEFC running on hydrogen produced from steam reforming. Because of the relative inefficiency of electrolysis, in a country which is in the process of decarbonising its electricity supply like the UK, a car powered by an SOFC running on methane will also produce lower carbon emissions than one powered by a PEFC running on hydrogen produced by electrolysis, and possibly even lower than a battery powered car once manufacturing emissions are taken into account⁴⁻⁶.

In this perspective we find that SOFCs have already been trialled in a number of different transportation applications, and that work is underway for commercial rollout in buses and light commercial vehicles. We then identify areas which still need improvement for further commercial exploitation – lifetime and degradation, fuel flexibility, efficiency and power density. Many skills and techniques relevant to studying these problems and developing solutions are specialities of the wider catalysis science community, particularly in developing novel stable and active materials which are tolerant to poisons, analysing surface reactions and deactivation mechanisms, and development and understanding at the system level and the interplay between the active materials and the overall system.

SOFC components, materials and geometries

Figure 1 shows a generalised SOFC. The heart of an SOFC is the electrolyte. It normally conducts oxide ions, and the archetype is yttria-stabilised zirconia (YSZ), so-called because the addition of yttria stabilises the zirconia into the cubic form rather than the monoclinic structure of undoped zirconia. Other more highly-conducting materials include scandia-stabilised zirconia, cerium gadolinium oxide (CGO) and lanthanum strontium gallium magnesium oxide (LSGM)⁷. These materials typically have an adequate ionic conductivity in the range 600 – 1000 °C. In recent years, ceramic electrolytes which conduct protons have been discovered. The most common of these are based on BaCeO₃ and possess adequate ionic conductivity at or even below 600 °C⁸ and SOFCs based on these are being developed. These would have the advantage of lowering the operation temperature, which reduces degradation, widens the range of materials which can be used and eases problems with start-up times and temperature cycling. Most of the issues relating to catalysis are similar between protonic SOFCs and conventional SOFCs, so they will only be specifically discussed where they differ.

Either side of the electrolyte there is a fuel electrode (anode) and an air electrode (cathode). These need to be both electronically and ionically conducting. At the anode, oxide ions from the electrolyte react with fuel molecules producing oxidised species, and the materials used are typically a mixture of an oxide-conducting ceramic such as YSZ or CGO and an electron-conducting metal such as nickel⁷. This mixture is called a cermet. At the cathode, oxygen molecules are split into oxide ions which are transported into the electrolyte, and the materials used are mixed conductors such as lanthanum strontium cobalt iron oxide (LSCF), often with electrolyte materials such as CGO mixed in to improve the oxide ion conductivity⁷. The final component of an SOFC is the interconnect, which separates the fuel in the anode of one cell from the air in the cathode of the next and allows electron flow to the external circuit. In SOFCs operating close to 600 °C, steel can be used as the interconnect, at higher temperatures ceramics such as lanthanum chromite are used⁹.

Figure 1 – A generalised diagram of an SOFC. A single SOFC cell is arranged into four layers: the anode (green); the electrolyte (light grey); the cathode (blue) and the interconnect (dark grey), the main reactions occur in the porous ceramic anode and cathode and the cells arrange into a stack to provide power for a vehicle

In terms of catalysis, there are several important catalytic and electrocatalytic reactions. At the anode, the most important reaction is hydrogen electro-oxidation – this reaction is relatively facile so improvements to hydrogen-fuelled anodes focus on microstructure to increase electrochemically active areas and ion and gas transport rather than faster catalysts. More interesting catalytically are anodic reactions where carbon-containing molecules are used. In these systems reforming reactions and water-gas shift are important, along with the Boudouard reaction. Electrocatalytic oxidation of CO to CO_2 is also important. Direct electrocatalytic oxidation of more complex species is still a matter of some debate – it is thought that most carbonaceous species are conventionally reformed or partially oxidised to hydrogen and carbon monoxide before electrocatalytic oxidation takes place. One important difference compared to conventional catalytic reactors is that, especially at the fuel gas inlet, a large proportion of the oxygen originates in the solid state and so the kinetics of reactions involving solid state oxide ions needs to be considered. At the cathode, the only reaction is the oxygen reduction reaction, where dioxygen molecules are incorporated into the solid cathode as oxide ions. At both electrodes various poisoning reactions are important, particularly sulfur at the anode and chromium at the cathode.

Unless the SOFC is powered by pure hydrogen, a reformer and possibly gas cleaning may be needed¹⁰. While in the future SOFCs may be able to run on unreformed hydrocarbons, at the moment they use reformers. Because SOFCs are able to use carbon monoxide and low levels of hydrocarbons as fuel, only reforming is needed, with no requirement for shifting or methanation to remove carbon monoxide as there is with PEFCs. Similarly, gas cleaning to remove especially sulfur compounds is less stringent than in PEFC systems, but still usually necessary at the moment.

Current technological approaches to SOFCs in transportation

As mentioned above, historically SOFCs have not been considered for use in transportation, but as the technology has improved, research has been undertaken to assess the use of SOFCs. An early example from 2006 is the ZEBRA battery – SOFC hybrid (ZEBRA standing for “Zeolite Battery Research in Africa” after the research project which developed it). The ZEBRA battery is a high temperature (300 °C) battery which before the rapid recent development of the Li-ion battery was one of the leading candidates for battery electric vehicles. The ZEBRA battery would supply the immediate power and intermediate energy, with the SOFC supplying a relatively constant flow of power to keep the battery charged¹¹. This hybrid approach has attractions because similarly to PEFCs, SOFCs are relatively slow to react, and the cost per kW is higher for a fuel cell compared to a battery. Because both components need to be maintained at elevated temperature even when the vehicle is not moving, the system was only feasible for vehicles which require power for more than ten hours per day¹². The concept was tested at the lab scale using a 300 W fuel cell and a 45 Ah ZEBRA battery with a maximum current of 100 A¹³.

As noted, SOFCs seem most feasible in vehicles which are operational all, or most, of the time, as this reduces the importance of the long start-up times. One of the earliest full-scale trials, completed in 2010, was as an auxiliary power unit (APU) on a truck, where the APU provides electricity for onboard services on overnight stops. Delphi developed a 3kW stack which was incorporated into a truck and used to supply all the power using reformed diesel from the main fuel tank, demonstrating a 50% improvement in efficiency compared to a diesel generator¹⁴. One of the problems they encountered was that there were no suitable technologies for sulfur removal at 750 °C, and cooling the gas stream after reforming was not feasible. They solved this by oversizing the SOFC to cope with the reduction in power caused by the sulfur, although this is obviously not an ideal solution. A similar system was developed by AVL and installed on a Volvo truck, with similar results¹⁵. Larger systems have also been built for auxiliary power roles on ships, with Wärtsilä (now Convion Oy) installing a 20 kW system using anode-supported cells powered by methanol on a car carrier¹⁶, and Thyssen Krupp and Sunfire developing a 50 kW SOFC powered by diesel for a freighter¹⁷.

All the systems discussed so far have used planar cells, where the cells are sealed around the edges. Recently however, Atrex Energy (formerly Accumetrics) have displayed the potential of tubular cells (which are sealed at the ends of the tube) by installing a 1 kW system on an all-terrain vehicle, and testing it off-road using compressed natural gas for over 100 miles¹⁸. The system used a third of the fuel compared to a petrol-powered vehicle. Interestingly, they were able to dispense with the reformer, with obvious savings in weight and complexity. Microtubular cells are also being developed for use in unmanned air vehicles¹⁹.

Another system which has attracted attention for more mobile applications is Ceres Power’s metal-supported cell. Because all the ceramic layers are only a few microns thick, metal-supported cells can be highly tolerant to thermal cycling and redox cycling, with shorter start-up times. Stacks based on the cells have shown start-up times less than 10 minutes, with over 2500 thermal cycles with efficiencies over 50%²⁰, and in the last two years this has led to agreements with Nissan and Weichei

Power for development of their cells for vans and buses respectively. Importantly, the deal with Weichei Power includes a potential joint venture to set up a manufacturing plant in China, meaning these could be the first SOFCs for transportation applications to enter full production²¹.

SOFCs are at a stage of development where they have been incorporated into test vehicles in a variety of applications, a massive advance given that at the start of this century there was no consideration that SOFCs could be used in transport, but clearly they are still short of full commercial adoption. What are the aspects of SOFCs that need to be improved for this to happen? Lifetime and degradation are still important issues despite improvements in recent years, and particularly relevant for transportation is temperature cycling and tolerance to impurities in air. Improving the fuel tolerance and flexibility will help with the range of systems which SOFCs can be used in and reduce requirements for reformers and fuel processors. Improving efficiency will reduce lifetime costs and carbon emissions. Efficiency gains together with improvements in volumetric power density will extend the range of uses to smaller cars and even aeroplanes, as well as lowering the cost of SOFC systems and reducing the physical size and weight of systems.

Lifetime and degradation

Fuel cell stacks differ from engines in that they cannot readily be repaired and parts replaced – they have to be replaced as a whole. In fuel cell electric vehicles, similarly to battery electric vehicles, the lifetime of the fuel cell is intended to be the lifetime of the vehicle. Degradation of fuel cells will affect both the maximum power of the fuel cell and likely its efficiency as well. It is therefore essential that the performance does not deteriorate to an unacceptable level such that the fuel cell, or the vehicle, has to be replaced. There are several important modes of degradation in SOFCs, either during continuous operation, or caused by cycling. Degradation caused by cycling is caused by different thermal expansion coefficients during heating or cooling or the expansion of nickel during oxidation in the case of air ingress into the anode²². Of prime importance in studying these degradation modes is tomographic imaging to quantify changes in the microstructure²³. Figure 2 summarises some of the most important degradation modes.

During continuous operation, with current materials, the degradation is dominated by cathode degradation and increases in series resistance²⁴. This degradation is largely caused by interfacial reactions – between different materials in the fuel cell and at solid-air interfaces. These are exacerbated by higher temperatures and typically involve the formation of insulating layers at the interface. Three of the more well-known examples include the formation of Cr₂O₃ scales on the surface of metallic interconnects⁹, formation of a strontium zirconate layer at the interface between the electrolyte and the cathode, and the strontium enrichment of the surface of the cathode. While the first example is well-studied from decades of corrosion research, the latter two examples are much more complicated. They both involve formation of phases at levels below the ability of the likes of XRD to determine, so their existence has been determined by techniques such as neutron diffraction²⁵, TEM^{26,27} or FIB-SEM²⁸ while a more comprehensive understanding of the phenomena occurring at a real interface requires multiple complementary techniques^{29,30}, or in situ techniques such as one which used in situ electrochemical impedance spectroscopy during PLD modification of a cathode surface to deduce that only 4% of a monolayer of SrO severely deactivates an LSC cathode³¹. In the catalyst science field there is expertise in tools and techniques for studying these kinds of interfacial reactions at the atomic scale, as well as experience in the modification of surfaces to prevent or hinder such reactions. These kinds of studies will need to continue for the new materials which are under development, especially for the new protonic SOFCs, where a reliable suite of complementary anode and cathode materials need to be developed, and problems with instability in

high CO₂ atmospheres need to be solved. There is also a need for new oxygen reduction electrocatalysts which don't suffer from these problems³².

Researchers have also found that levels of sulfur at the ppb level in the form of SO₂ can cause serious performance degradation in cathodes³³. This seems to be related to the surface strontium enrichment described above, with surface strontium forming SrSO₄, likely triggering the local decomposition of the cathode material or reducing the strontium content in the bulk enough to reduce the conductivity³⁴. Sulfur tolerant cathode materials need to be developed, as the current solution is a chemical sulfur scrubber, which inevitably increases cost and decreases efficiency and power density. As sulfur poisoning was identified as an issue by laboratories carrying out long term tests with real world air, so too new problems may be identified once SOFCs begin to be used outside the lab, in environments which may contain high levels of pollutants such as NO_x, or particulates which may contain significant amounts of over a dozen elements in an urban environment³⁵. The interaction between air pollutants and catalytic materials is well-advanced in catalysis science. In the field of SOFCs, more work is needed on the interactions between current and potential cathode materials and these other pollutants.

Figure 2 – Degradation modes in SOFC electrodes. Schematic illustrating some of the main issues relating to degradation, lifetime and fuel flexibility relating to the anode and the cathode. For the anode, the metallic phase is green and the oxide phase is orange, while for the cathode the cathode material is blue and the electrolyte is light grey.

Fuel tolerance and flexibility

In current transportation there are a wide variety of fuels used, ranging from hydrogen fuel cell powered cars to planes running on jet fuel and ships running on bunker oil. Any SOFC will be able to run efficiently on any currently available hydrogen due to its ease of oxidation and lack of contaminants. For carbon-containing fuel there can be problems depending on the fuel - carbon deposition for most hydrocarbons or the opposite problem of slow kinetics for methane, while contaminants, especially sulfur and aromatic compounds, can be a problem with the heavier hydrocarbons. For most of the current generation of SOFC anode materials any carbon-containing

fuel must be reformed, although the Atrex Energy tubular SOFC discussed earlier is claimed to be able to work without a reformer for methane and propane. The problems with carbon and sulfur tolerance are similar regarding SOFCs and catalysts, and have been jointly reviewed recently¹⁰, with the main difference being that in an SOFC all or most of the oxidant is supplied through the electrolyte, whereas in a catalyst all the oxidants are supplied in the feed gas.

For hydrocarbons with no impurities, the current generation of materials are adequate for fully reformed fuel, so the main goal of development is to reduce the specification of the reformer, or even eliminate it altogether. This is particularly important for heavier hydrocarbons, which may contain aromatics that can cause carbon deposition even outside thermodynamic regimes favouring such reactions, and can form other problematic molecules such as ethylene during the reforming process³⁶. Of particular interest are the mechanisms and location of carbon oxidation in an SOFC, when the oxygen is coming largely from the electrolyte, similar to the Mars-van Krevelen mechanism postulated in catalysis³⁷, and the effect of active supports such as doped cerias on carbon deposition. A further consideration is that for SOFCs fuelled by lighter hydrocarbons, especially methane, the kinetics of internal reforming can be very slow with current materials, so that high fuel utilisation is not possible with partially reformed hydrocarbons³. In this case, improving the reforming performance of the materials is of interest.

In the special case of protonic fuel cells, because the ion transported through the electrolyte is the proton, this means that only hydrogen can be electrocatalytically oxidised, and only oxidants introduced with the fuel are available for reforming reactions. This makes reforming and shift reactions more important when using carbonaceous fuels. On the other hand, the most important electrolyte materials in protonic SOFCs offer intrinsic carbon tolerance³⁸.

With sulfur poisoning, current materials are capable of running stably with ultra-low sulfur diesel (ULSD) levels of sulfur (<15 ppm of sulfur), or with the levels of sulfur present in natural gas, albeit with a performance loss, so the objective of research in this area is to reduce the performance loss at these levels of sulfur, or to develop materials which are able to withstand the much higher levels of sulfur present in shipping and aviation fuel so as to be able to eliminate the desulfuriser. In the last few years, attention has focussed on oxide anode materials which can be stable in very high levels of sulfur^{39,40} but their activity towards methane needs to be improved. While in the catalysis literature, it is standard to test sulfur tolerance in a representative reaction mixture, in SOFCs most studies use hydrogen contaminated by sulfur to test sulfur tolerance of materials and to study the mechanisms of sulfur poisoning, despite the fact that it is known that the presence of carbon species changes the effect of sulfur⁴¹. Because of this there is a lack of knowledge of the effect of reformat gas contaminated with sulfur on SOFC anode materials and in real electrodes, especially in new materials.

Efficiency

Efficiency is already one of the main advantages of SOFCs compared to other power sources used in transportation – with no Carnot limit the theoretical efficiency of an SOFC is close to 100% directly oxidising dry methane, while with carbon monoxide or hydrogen the theoretical efficiency is still around 70%. In reality of course, there are parasitic losses which reduce the efficiency. In a vehicle this reduction in efficiency has the effect of making the fuel cell larger and heavier than it would otherwise be for a given power output, increasing the cost and increasing the amount of fuel required for a journey, so improving the efficiency is of vital importance for the adoption of SOFCs in transportation and expanding the range of applications. For example, Ceres Power recently announced that they had achieved 65% stack efficiency operating on methane³.

As a result, developers have targeted several areas for improvement. Increasing internal reforming improves the efficiency by reducing the exothermic nature of the stack thereby reducing the need for active cooling (typically achieved by oversupplying the cathode with air), reducing heat losses from the reformer and the thermal coupling between the SOFC and the reformer. As discussed above, there are two opposing issues with increasing internal utilisation – for methane it is the poor internal reforming performance of current materials, while for other carbonaceous molecules it is the risk of carbon deposition. In both these cases advances in the catalysts are key to achieving the required gains. One approach which may achieve some success is changing the microstructure of the anode to optimise the amount and location of nickel, such as by impregnating the nickel (or other metals or alloys) into an oxide scaffold^{42,43}. Addition of extra reforming catalysts is also possible, and these can be incorporated into a barrier layer above the electrode which also helps reduce carbon deposition (figure 3a)^{44,45}.

Improving internal reforming (or improving direct oxidation) can also reduce the amount of oxidant which needs to be used on the anode side, again improving efficiency. Greatly reducing or eliminating the need for oxidants may require a step change beyond nickel cermet, and in this sense there are two recent breakthroughs in catalyst design which look promising: single site catalysis (figure 3b) and exsolution (figure 3c). Both could have the potential to provide the improvement in catalysis required with the requisite stability. A Ni and Ru-doped ceria was recently used as a catalyst in a methane fuelled SOFC, which was able to operate stably with addition of only 3% H₂O⁴⁶. Meanwhile, exsolved materials – materials where the active metal is incorporated in the crystal structure of the support and forms metal particles directly on reduction – show remarkable stability of the nanoparticles towards high temperatures and dry methane, and offer the possibility of unique catalytic properties caused by epitaxial strain of the nanoparticles^{47,48}.

Figure 3 – Improving efficiency in SOFCs. Schematic illustrating some of the potential approaches to improving the efficiency of SOFCs. A catalyst reforming layer (light orange) deposited on top of the anode, improving the internal reforming (a); a single adatom doped onto an oxide surface creating an active site for conversion of hydrocarbons (b) and an exsolved particle socketed into the oxide surface on the right, providing a greater stability towards carbon deposition and sintering compared to a hemispherical particle loosely resting on the oxide surface on the left (c).

Increasing power density

Finally, improving volumetric power density will allow SOFCs to be used in a wider range of applications. Typical commercial SOFCs are currently in the 0.1 – 1 kW/L range³ and much of the research into improving this has focussed on the geometry and manufacturing – FCO Power report that their stack can achieve 3 kW/L through an all-printed design with no support, although this hasn't been commercialised yet⁴⁹.

It is clear, however, that catalysis science could supplement these efforts, through lightweight or compact reformers and desulfurisers, but also through better electrocatalysts. In terms of SOFCs, the biggest polarisation losses are due to the oxygen reduction reaction at the cathode. Polarisation

losses have two consequences – they reduce the maximum possible power density of the fuel cell, and they reduce the voltage for a given power output. Since degradation may be promoted by lower voltages (although whether voltage or current density is more important for degradation is still a matter of research), this limits the viable longer-term power density as well as the maximum power density.

Structurally, SOFC cathode electrocatalysts tend to be quite different to heterogeneous catalysts, they are typically single-phase oxides, where the entire surface is active. Because the material has to perform three functions (electrocatalysis, electronic and ionic conduction), finding suitable oxides tends to involve combining several metals in a perovskite or double perovskite structure⁵⁰. In recent years computational methods have been employed to find better materials, for example by correlating O p-band centre with catalytic activity, then calculating this for new compositions, along with stability (figure 4a)⁵¹, or by computationally combining known modules of crystal structures in new ways to predict complex layered structures with favourable properties (figure 4b)⁵². With advances in creating nanoscale layers, for example by atomic layer deposition, there have been efforts to separate the electrocatalytic function from the conduction by depositing an electrocatalytically active thin film on a conductive bulk (figure 4c)^{53,54}. These efforts are at an early stage and it could be that large advances in activity for the oxygen reduction reaction are possible.

Figure 4 – Improving power density in SOFCs. A schematic illustrating some approaches towards improving the cathodic polarisation losses. Correlation between O p-band centre and oxygen reduction reaction activity (a); computational combining of different solid state modules forming new layered structures (b) and deposition of a catalytically-active thin film over the surface of the cathode (c)

Summary and outlook

Development of lower carbon and lower pollution solutions for the transport sector is vital for the fight against climate change and air pollution, and it's clear that SOFCs could be a viable technology, given advances in the performance over the next few years. For current applications, improvements in lifetime, fuel flexibility, pollution tolerance and efficiency are key, as these all reduce system costs. For future applications power density is also important. From the anode side, advances in reforming catalysis and carbon and sulfur tolerance should be pursued, and there are two routes which could yield benefits – modification of conventional materials or novel materials. With conventional materials, modification with barium, proton conductors or oxygen storage materials look promising, while novel materials such as single site catalysts or exsolved perovskites like nickel-doped lanthanum strontium titanate are further from commercialisation but could provide huge advances. On the cathode side, computational materials design seems likely to become more important as the materials become more complex with increasing numbers of elements and different structures. Alternatively, nanoscale modification of surfaces by, for example ALD could allow separation of the catalysis and conduction functions of the cathode. Finally, in the electrolyte, lower temperature

361 materials such as proton conductors and/or thin film electrolytes will allow lower temperatures,
362 enhancing the potential for SOFCs to be used in transport.

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Sulfur poisoning

Cycling

Strontium segregation

Carbon deposition

Interphase formation