An investigation into end-of-life management of solid oxide fuel cells

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ABSTRACT

Solid oxide fuel cell (SOFC) systems offer an alternative technology for power generation in stationary plants. The environmental benefits of this technology in the use phase are well understood and stem from improved fuel efficiencies when compared with combustion-based systems. These benefits have driven technology development towards commercialisation. Recent trends in environmental policy have highlighted the need to manage products responsibly throughout their entire life-cycle, including the end-of-life (EoL) phase. At present EoL management of SOFC stacks is not well understood and requires consideration prior to market entry. Using the waste management hierarchy as a framework for the development of an EoL strategy a methodology is proposed to move from a reactive approach to a proactive approach. This paper presents results from the initial steps of this methodology. Analysis of existing SOFC stack design has provided an initial definition of the EoL problem. By drawing parallels with EoL problems faced by other more mature product streams and existing waste management solutions, a body of knowledge is built. This knowledge will support the development of a reactive short-term solution to EoL management of SOFC stacks, and will provide input to the longer-term development of a proactive approach to minimising the environmental burden of this future waste stream.

Introduction

Solid oxide fuel cell (SOFC) systems offer an alternative technology for power generation in stationary plants. Systems currently under development range from small domestic units providing power to a single home, to larger units offering power outputs of several Megawatts [1]. The environmental benefits of SOFC technology have driven its development, especially in recent decades when a reliance on fossil-fuels and combustion-based technologies has been recognized as unsustainable and detrimental to the local and global environment. Indeed, SOFC systems have the potential to offer a highly efficient means of converting hydrogen-rich fuels into electricity, with a reduction in carbon dioxide emissions and virtual elimination of the release of other pollutants, including oxides of nitrogen and sulphur and particulate matter [2].

The commercialisation of SOFC systems is being pursued by several companies in Europe, North America and Asia [3]. However, prior to the release of a significant volume of products into the market-place, a solution for the end-of-life (EoL) is required. This requirement is driven by:

i) Legislative developments

Environmental legislation is increasingly concerned with EoL management of products. The automotive and electrical/electronics sectors have been set mandatory recovery and recycling targets by recent European legislation [4, 5]. Although no legislation currently applies directly to EoL management of SOFC systems, development of this observed trend to encompass a wider range of product-types should be anticipated. In addition, a lack of provision for EoL management may preclude the incorporation of SOFC technology as a power source in products which themselves are subject to legislated recycling requirements. For example, SOFC-based auxiliary power units are being developed for automotive applications [6]. If these are not readily recyclable then their adoption by car manufacturers may conflict with the requirements imposed by legislation such as the European End-of-Life Vehicles Directive [4, 7].

ii) Customer expectations

Although SOFC technology offers increased efficiency and reduced emissions during operation, the environmental impacts of all life-cycle stages must be taken into account when evaluating the benefits of the technology. Previous authors have identified a lack of information regarding EoL management of the technology as a barrier to understanding the total life-cycle impacts [6, 8, 9]. Since SOFC systems are promoted as a "green" source of power generation, it would be highly damaging to their commercialisation if any aspect of the life-cycle were to be exposed as presenting an unreasonable environmental burden.

For the purposes of the current work it is assumed that sub-assemblies within the SOFC system which are based on conventional technologies will follow established EoL routes exploiting existing waste management capability. These sub-assemblies include pipe work for fuel and air supplies, vessels and containers, electrical and electronic systems and fuel processing equipment. Therefore the scope of the current study is limited to the SOFC stack, which is the term for an assembly of individual fuel cells.

Methodological considerations

It is proposed that the waste management hierarchy be used as the foundation for the development of an EoL management strategy for SOFC stacks. This hierarchy defines a preferred route to waste minimisation, and has been adopted at an international level [10]. The hierarchy identifies the reduction of waste at source as the preferred approach to waste management, followed by reuse, recycling and, only as a last resort, disposal to landfill. Where the waste management hierarchy is applied specifically to wastes arising from EoL products, it can be considered to be a hierarchy for EoL management.

Figure 1 shows a schematic of the waste management hierarchy and outlines the means by which compliance with the principle can be approached within EoL management. Reduction of waste volume and toxicity by addressing the primary source (namely the product design) can be considered to be a proactive approach. This requires early consideration of how design and materials selection define the waste streams arising from EoL products. Similarly opportunities for reuse of components will be significantly improved if disassembly considerations are incorporated at the design stage.

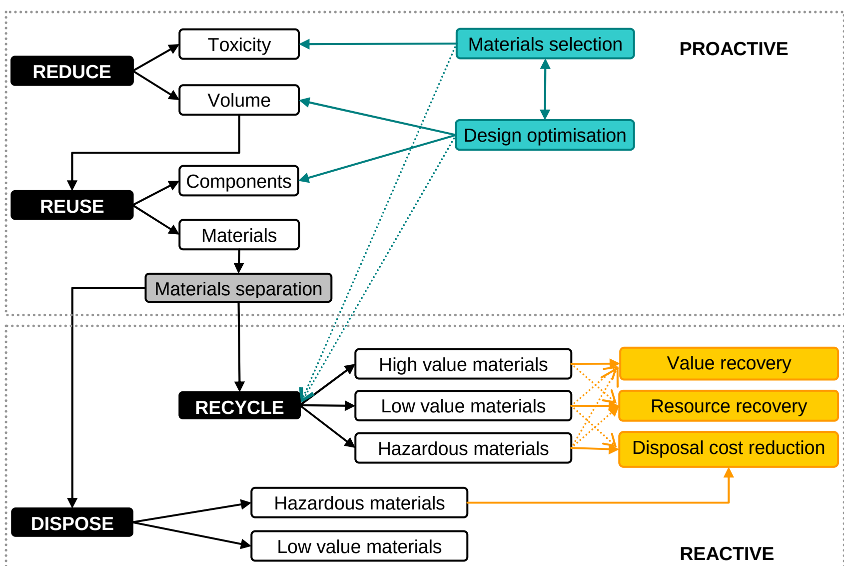

Figure 1: Hierarchical approach to end-of-life management

Reducing waste by recycling the materials contained within EoL products requires an additional level of processing. Segregation and purification of different material-types are required in order to produce useful inputs to downstream processes, whether in closed-loop or open-loop scenarios.

Although incorporating recyclability into design by careful materials selection is a proactive approach to EoL management, recycling can also be applied in a reactive approach. Although product design may limit the technical and/or economic feasibility of pursuing recycling as a viable EoL strategy, most EoL products offer opportunities for the recovery of useful materials. As a last resort, disposal may be considered for any non-recyclable fraction. The separation of hazardous materials from a non-hazardous bulk waste stream prior to disposal may have benefits from both environmental and economic perspectives.

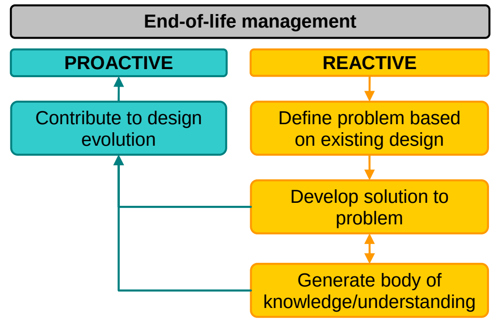

Figure 2: Methodology applied to the development of a proactive end-of-life strategy

Although a proactive approach to end-of-life management supports the preferred routes of reducing waste at source and reusing components, there may be barriers to applying this approach to novel products which are based on immature technologies. During early product or technology development, the focus of the design process is likely to be heavily dominated by technical requirements, reliability and cost. Therefore the initial solution to EoL management must be developed in reaction to an initial product (or prototype) design. During the development of this solution, a body-of- knowledge will be generated. This body-of-knowledge should determine the limitations of existing waste management capability in coping with the requirements posed by the novel product. Where limitations exist these may be eliminated either by modification of the design in future product development, or, if this is not possible, by the development of new waste management processes. It is anticipated that most product manufacturers will not wish to invest in a bespoke waste treatment capability, therefore using the body-of-knowledge to influence design development will be the preferred option. The EoL management strategy therefore begins with a reactive approach and develops into a proactive approach (Figure 2).

This methodology is being applied to the development of an EoL strategy for SOFC stacks in the ongoing project work. This paper presents the initial part of the work including:

i) The definition of the EoL management problem based on analysis of existing SOFC stack design;
ii) Preliminary steps towards the compilation of a body-of-knowledge based on existing EoL management solutions from other product sectors.

Given the status of SOFC-based products with regard to commercialisation it is hoped that a proactive EoL management strategy can be implemented prior to large-volume manufacture.

Results and discussion

Definition of existing problem

The existing EoL management problem is characterised primarily by the material composition of the waste stream. During SOFC development, a common set of materials has emerged which satisfy the requirements of electrochemical performance and stability. Although improved performance is pursued through ongoing materials development it is likely that the first commercial products will utilise the materials shown in Table 1 [11]. The contribution of each material to the composition of the EoL waste stream is defined by the cell and stack design. The dominating material will come from the layer providing structural support.

Table 1: Common SOFC materials

Component	Material	Material classification*	Hazardous waste threshold**	Material value
Electrolyte	Yttria-stabilized zirconia	Non-hazardous	N/A	Med
Anode* **	Nickel oxide Nickel	Cat. 1 carcinogen Cat. 3 carcinogen	> 0.1 wt% > 1 wt%	Med
Cathode	Strontium-doped lanthanum manganite	Irritant	> 20 wt%	Med
Interconnect	Doped lanthanum chromate	Irritant, harmful	> 20 wt%	Med
	Inert metals/alloys	Non-hazardous	N/A	High
Sealant	Glass/Glass-ceramic	Non-hazardous	N/A	Low
Substrate	Ceramic	Non-hazardous	N/A	Low

* As defined on Material Safety Data Sheets provided by material suppliers.
** As defined by the European Waste Catalogue. If materials are present in compositions greater than this threshold value, the entire waste stream is classified as hazardous.
*** Under controlled shut-down conditions all nickel in the anode will be present in metallic form. Nickel oxide would therefore only be present in end-of-life stack experiencing abnormal shut-down conditions or in end-of-life stack which had never been exposed to a fuel environment.

This can be any functional layer (electrolyte, anode, cathode or interconnect) or an external substrate [1].

The Integrated-Planar SOFC stack design under development at Rolls-Royce Fuel Cell Systems Limited utilises an external substrate as a support for the functional fuel cell layers. The substrate material is a low-cost ceramic which minimises the use of high-value fuel cell materials [12]. The waste stream will consist mainly of inert ceramic, highly integrated with a small amount of hazardous and valuable materials. It is assumed that common SOFC materials are used for each of the active layers.

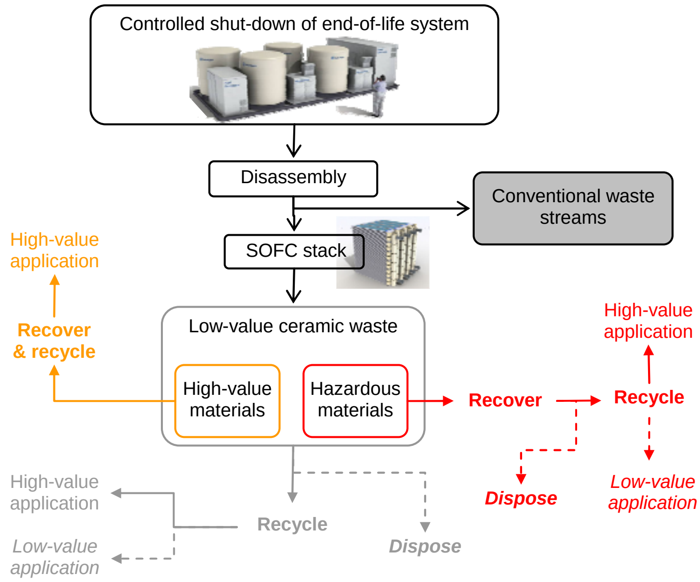

Figure 3: Proposed strategy for end-of-life management of SOFC system. Dashed lines and italic text indicate the least-preferred route.

As a reactive approach to the management of waste from this existing design, the strategy shown in Figure 3 is proposed. High-value and hazardous materials will be recovered from the low-value ceramic waste. It is anticipated that the high-value materials will be readily recycled in a high-value application. Recovery of hazardous materials from the bulk waste stream should be carried out primarily to minimise the volume of hazardous waste produced. Following the recovery process the hazardous content may be available for recycling and, depending on purity, may be suited to high or low-value applications. Recycling of the material in a low-value application would be preferable to disposal. Following the recovery of the high-value and hazardous materials the bulk waste stream, which consists of low-value ceramic material, is available for recycling. Disposal of the low-value ceramic waste should be avoided; however, if no suitable recycling application can be found then the previous extraction of hazardous and high-value materials will have minimised the negative impacts of disposal.

The feasibility of pursuing this approach has been explored by investigating existing waste-management capability from other product sectors.

Recovery of hazardous and valuable metals from end-of-life catalysts

Ceramic-supported catalysts are used in a range of applications and present an end-of-life waste stream with similarities to that arising from EoL SOFC stacks. Of particular interest with respect to the current work are catalysts which incorporate valuable metals or nickel/nickel oxide as the active material. These find application in the automotive and petrochemical industries [13-16]. The environmental implications of disposing of nickel oxide catalysts to landfill have prompted the development of a recovery process for nickel oxide [13]. The process is based on the reaction of nickel oxide with sulphuric acid to form nickel sulphate. A maximum recovery rate of 99% was achieved under optimised conditions. Nickel sulphate is a useful feedstock for the electroplating industry, providing an opportunity for recycling in a high-value application.

The recovery of valuable metals from EoL catalyst waste is driven by economic return and increasing demand for raw materials [15-17]. Recovery is often carried out using traditional metallurgical routes similar to the smelting process required for extraction of virgin metals from ore. Recent research has investigated alternatives to the recovery of valuable metals, including chemical leaching followed by ion-exchange and pyrolysis [15] and the use of microbiological processes [16].

Metal extraction from electrical and electronic equipment
Recovery of metals from electrical and electronic equipment is an area of growth, especially given recent legislative developments setting mandatory recycling targets for the industry [5]. In addition to traditional thermal and metallurgical methods, initial materials separation is carried out by mechanical means. EoL waste is shredded: from the residue ferrous metals are recovered using magnetic separation, and eddy current separation is used to recover non-ferrous metals. These techniques are dependent on discrete particles containing high concentrations of metals and eddy current separation methods do not work when non-separable materials encase separable materials [18].

Recycling of ceramics
The high energy requirements associated with ceramic processing and the inherent low material value do not encourage recycling of this waste stream. Some success has been reported in closed-loop recycling of refractory ceramics [19] in response to the environmental concerns of resource depletion and disposal to landfill. With regard to the recycling of the bulk ceramic waste stream from end-of-life SOFC stacks it is unlikely that a closed-loop solution would be easily developed. The high temperature environments required during cell fabrication promote the migration of chemical species and the presence of contaminants, even in trace amounts, will lead to performance degradation [20]. It is likely that the economic and environmental costs of obtaining a high-purity recycled material would outweigh any benefits gained in waste management. Recycling ceramics in down-graded applications removes the requirements for extensive processing. The construction industry is a potential user of recovered ceramic waste and the use of fired pottery ware in brick manufacture has been reported [21]. Ceramic is also a potential replacement for aggregate in the manufacture of concrete. One study reports the successful use of waste from the electrical insulator industry in this application [22].

Conclusions and further work
A methodology has been presented for the development of a proactive approach to the development of an EoL management strategy for products based on novel technologies. It has been proposed that the initial approach must be reactive in response to early product/prototype design. The reactive approach attempts to provide a suitable EoL management solution by exploiting existing capability from the waste management of other product types. The body-of-knowledge generated through the development of this reactive solution provides direction for future design improvement activities.

This methodology is being applied to the development of an EoL strategy for SOFC stacks. The EoL problem based on early SOFC stack design has been identified and some of the materials-related issues have been related to existing EoL product streams including catalysts, electrical and electronic equipment and ceramics. Many techniques exist for the recovery of hazardous and valuable materials from existing EoL wastes. These need to be explored in further depth and their application to SOFC stacks investigated. Some experimental work is required to evaluate the efficiency of material recovery when these processes are applied to a novel product-type. With regard to the recycling of the bulk ceramic waste stream, it is unlikely that a closed-loop solution would be easily developed; therefore the reuse of this material in lower-grade applications should be explored. Further investigative activity should explore the recovery of the more unusual medium-value SOFC materials, including those used in the cathode and current collectors.

These initial findings provide direction for future research, which should include more detailed analysis of how existing materials separation processes might be applied to existing SOFC stack designs. This analysis will lead to an appreciation of the limitations of existing waste management capability in processing this novel waste stream. An understanding of the limitations and challenges will direct the development of a proactive approach to EoL management of SOFC stacks.

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