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Integrating Life-Cycle Planning Considerations into Design through the Innovation Based Design Process

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ABSTRACT
Military ground vehicles often have service lives that exceed their original design targets. For this reason, these vehicles typically require technology upgrades during their useful life. When considering design trade-offs, both mature as well as less mature or developing technologies need to be considered against the anticipated service life for the vehicle. Early adoption of technologies that are not sufficiently mature can result in operational reliability and availability issues and increased sustainment costs. However, failure to anticipate technology refresh requirements during the original design phase may result in a platform that cannot be cost effectively upgraded as technology or functional requirements change, limiting the functionality and utility. This paper presents an Innovation Based Design (IBD) process as part of a systems engineering approach that facilitates technology refresh cycles via platform remanufacturing throughout the life of the platform. The IBD process is demonstrated for a solid oxide fuel cell (SOFC) Auxiliary Power Unit (APU) for ground vehicles.

INTRODUCTION

"Life-cycle Engineering (LCE) is an objective process that evaluates the constraints and dependencies associated with developing and operating a product or service; maximizing the product value while minimizing its cost of ownership over the entire life-cycle [1]." Life-cycle Costing (LCC) is a component of the Life-cycle Engineering process which constitutes a methodology for determining the cost of ownership of an asset over its entire life-cycle. Phases that comprise the life-cycle of a product or asset include: conceptualization, design and development, manufacture, operation and support (including maintenance and refurbishment or remanufacturing), technology upgrade, and end-of-life disposition and disposal. The design phase of the life-cycle is often said to "have a long shadow," meaning that while the cost of the design phase is often a relatively small fraction of the overall ownership cost, the decisions made during the design phase have major implications in regards to the operational effectiveness, maintainability and availability, and the total ownership cost. While life-cycle engineering processes can be applied after manufacturing, it is important to consider "design for x" during the initial design phase (e.g., design for manufacture, design for maintainability/service, design for reliability, design for remanufacturing, design for upgradeability, design for disassembly and recycling, etc.).

LCE principles should be applied as an integral component of a systems engineering process. Systems engineering is a structured top-down process for cost effective realization of systems that meet defined functional requirements. The U.S. Department of Defense (DoD) defense acquisition procedures document describes systems engineering as:

> An approach to translate approved operational needs and requirements into operationally suitable blocks of systems. The approach shall consist of a top-down, iterative process of requirements analysis, functional analysis and allocation, design synthesis and verification, and system analysis and control. Systems engineering shall permeate design, manufacturing, test and evaluation, and support of the product. Systems engineering principles shall influence the balance between performance, risk, cost, and schedule [2].

A subsequent paragraph extends the consideration of life-cycle to: operations, training and disposal. DoD weapon platforms typically have very long life-cycles and often undergo multiple refurbishment or technology upgrade cycles during their lifetime in order to maintain reliability and availability, supportability (repair parts availability), and to maintain (or upgrade) platform functionality. While systems engineering and LCE principles can be applied at the point of refurbishment or upgrade planning, if the technology upgrades were considered as a part of the system engineering process when the asset was originally designed these upgrades can usually be made more cost effectively and provide higher levels of functionality.

Figure 1 shows the benefits of technology insertion, which are greater if it has been planned for during the design phase. The upper graphic represents deployment of a system without any technology refresh. In this case, as market technology advances relative to the deployed technology, there is an increasing level of obsolescence risk associated with operation and support of the system. These risks include

- System becomes expensive to support due to obsolescence and limited availability of repair parts,
- System becomes less reliable because it uses components that are not the current state-of-the-art technology, and,
- System performance levels are significantly lower than possible with current technologies (loss of competitive advantage).

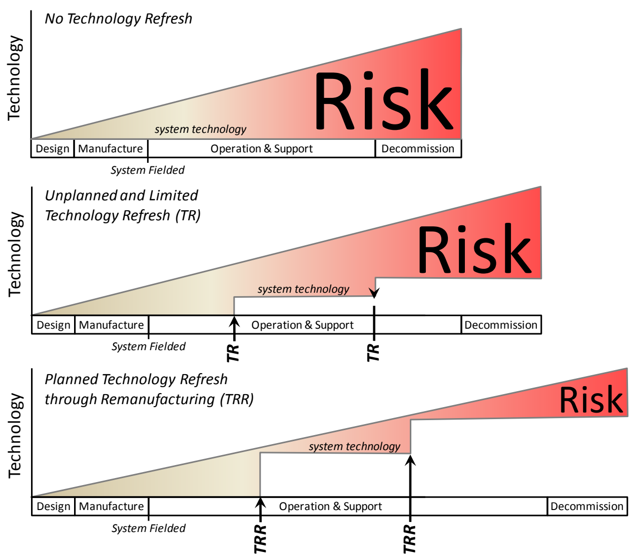

Figure 1: Technology Obsolescence Risks

While most long-life DoD assets go through some level of technology refresh, the level of technology refresh that can be accommodated is determined not only by technical limitations, but also by cost effectiveness. If technology upgrades are considered (and planned for) during the design phase, it is more likely that the upgrades can be realized when the technology is ready. In addition to design planning, technology upgrades can also be planned for on the manufacturing side through scheduled system remanufacturing (and upgrade) cycles, potentially utilizing the original manufacturing systems. Substantial system modifications are more likely to be cost effective if they can be managed in this manner.

The bottom graph in Figure 1 represents the best case, where the system is cost effectively brought up to close to state-of-the-technology performance levels through scheduled technology insertion.

There are two other interesting observations relative to Figure 1. In projects with long design and manufacturing cycles, technology can evolve substantially, even during the pre-operational stages of the life-cycle. System architectures that facilitate technology upgrades also can allow for delays in final technology decisions during design and manufacturing. Many DoD programs have manufacturing cycles that last well past the time when the first assets are deployed for operation. In these cases, the production design configuration will likely undergo upgrades within the system life-cycle and it is advantageous to bring existing systems up to the current production configuration when they are brought in to be upgraded. Finally, technology insertion offers the potential to extend the useful design life of systems, as well as the useful life of individual assets.

TECHNOLOGY INSERTION PLANNING

When planning for technology insertion, the following questions should be considered. What are the potentially significant technology change vectors, and how would those changes impact system performance? How can the overall system architecture and design be best configured to accommodate technology changes? What are the key technology triggers that would justify a new design configuration for the system? A major system upgrade will require additional design and (re)manufacturing efforts that need to be scheduled. When the technology is available and the upgrade is ready to be applied, which existing assets should be updated first? These questions will be considered below.

A key early step in the development process is to relate overall system requirements to subsystem requirements and functions and to develop a functional hierarchy for the system. As the design matures, the system functions are allocated to physical systems within the overall design. The draft standard Mil-Std-499B [3] illustrates this process (see Figure 2 below).

During the synthesis process the various available technology options are considered to determine (through system analysis) which combination of technologies best meets the key program requirements: functional performance, reliability availability and maintainability (RAM), total ownership cost (TOC), etc. In a design for planned technology refresh scenario, nascent and evolving technologies should be considered during the synthesis process for future system upgrades. This requires research into alternative system concepts and technologies, and development of a technology roadmap for those technologies judged to be promising. An understanding of the relative importance of the system performance requirements can be used to identify the system functions (and therefore the system physical elements) for which improvement would yield the greatest system performance benefit. It should be noted that the process shown in Figure 2 is performed iteratively across the entire system and at multiple levels of hierarchy (both functional and physical) for subsystems, components, etc.

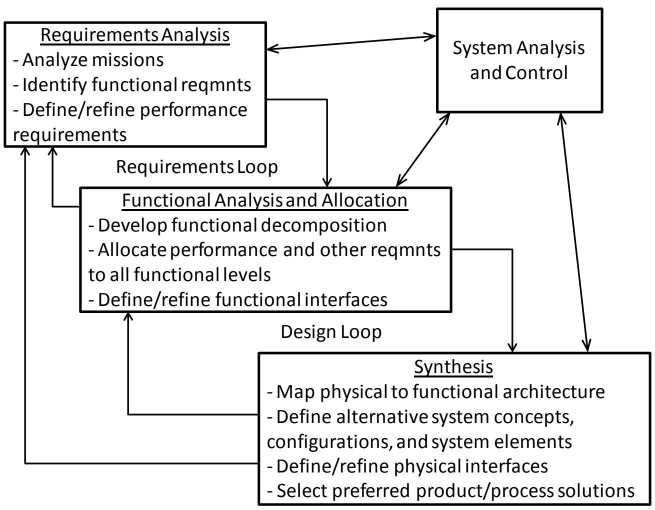

Figure 2: Systems Engineering Process (MIL-499B)

In order to analyze the potential benefits of different technologies, models that assess the impact of the technology changes on system functional performance, RAM, and TOC are needed. In a traditional development process, these technology evaluations will consider only technologies that will reasonably be available within the initial manufacturing timeline. However, when designing for technology insertion, technologies that may offer significant functional benefits within the system life-span, even if in the very early development stages, should be considered. Four technology evaluation criteria that should be considered include:

System performance impact: Performance specs for candidate subsystem/component technologies (functional benefits) => roll-up to system performance benefits

- What is the anticipated development curve for performance of the technology (when will it be ready), and what potential benefits does it offer (faster, more efficient, more durable, lighter, more capacity, …)?

Subsystem/component reliability, availability, maintainability, and supportability specs:

- When will technology meet or exceed platform reliability/availability requirements?
- What changes in support equipment and training will be required?
- Will current technologies become obsolete and hard to procure and support?

Technology cost implications

- Is technology inherently more costly to manufacture, will support costs be higher? What will the impact on life-cycle cost be (as a function of implementation date)?
- If key technologies are dual purpose (military and commercial) when will volumes increase with commensurate reduction in cost?

Implementation Details

- Can system architecture be designed to facilitate insertion of new technology?
- What level of maintenance support is required for upgrade? Is technology in form of field swappable LRU?
- Considering the anticipated refurbishment/upgrade needs of other subsystems, what is the best point(s) in the life-cycle to plan for technology upgrade?

There are other subsystem or component design attributes that have an impact on the elements of a planned technology refresh and directly affect the evaluation criteria discussed above; some of these attributes are described below:

Modularity (minimize interface complexity): modularity deals with the simplicity in interface design between different physical subsystems or components (each subsystem interfaces to a minimum number of different components). Modularity is determined by how the functional architecture maps to the physical architecture. A modular design promotes ease in repair, as well as design and redesign (or upgrade) of subsystems and components.

Open system interfaces (OSI): OSI typically applies to electrical, information, or software interfaces. Use of OSI promotes ease of technology upgrades, particularly in the use of COTS technologies which often have high rates of technology advancement.

Market life for COTS components: Use of COTS components can often reduce the development cost of DoD systems. As noted above, COTS technology often evolves quickly, which provides opportunities for upgrades, but also may drive a requirement to do upgrades due to the lack of availability of earlier generation technologies.

Maintainability, Supportability: These development criteria support effectiveness of repair; for large complex systems repair is typically affected by replacement of LRUs (Line Replaceable Units). Modularity of key functions aids in the effective specification of LRUs. Ability to diagnose and isolate failures or performance degradation is also important. LRUs can be readily targeted for technology insertion that can be deployed during normal maintenance cycles.

Ease of Disassembly, Remanufacturability: Technology insertion through remanufacturing can be applied at the platform level or at the LRU level. At both levels, the ability to disassemble, assess component conditions, and reuse or recondition components is critical to remanufacturing. Using remanufacturing as a technology insertion strategy maximizes the use of already manufactured durable materials/components and should result in lower cost technology insertion.

What is the "right" durability for key components: Items that have a short technology life can be designed to lower durability standards if there is a plan for scheduled technology refresh, this can promote lower cost, lighter weight systems. While durability criteria (time to wear-out) can be relaxed, reliability criteria (probability of failure) must meet operational reliability and availability requirements.

INNOVATION BASED DESIGN (IBD)

Innovation Based Design is a methodology that can be used to aid in defining a product architecture to enable technology insertion through system remanufacturing and component replacement. The defined IBD process consists of three parts: Value analysis, Technology Forecasting, and Assessment. The outcomes of the three parts were then used to:

- Define a system architecture which would be optimized for technology insertion.
- Identify potential technology growth options and.
- Identify components or subsystems that are candidates for technology insertion through remanufacturing or replacement.

Figure 3 below shows the proposed IBD process (in dashed lines) overlaid on a conventional design process. In a conventional process, some candidate technologies can be eliminated from consideration due to lack of maturity, which may represent excessive performance, cost, or reliability/durability risks. In the IBD process, the future state of these technologies, as well as the potential benefits and risks to the overall system performance are considered. Then, using a risk/benefit analysis, new technologies that have the potential to improve the operation of the system and have a reasonable likelihood of timely maturation are followed for a potential planned technology insertion.

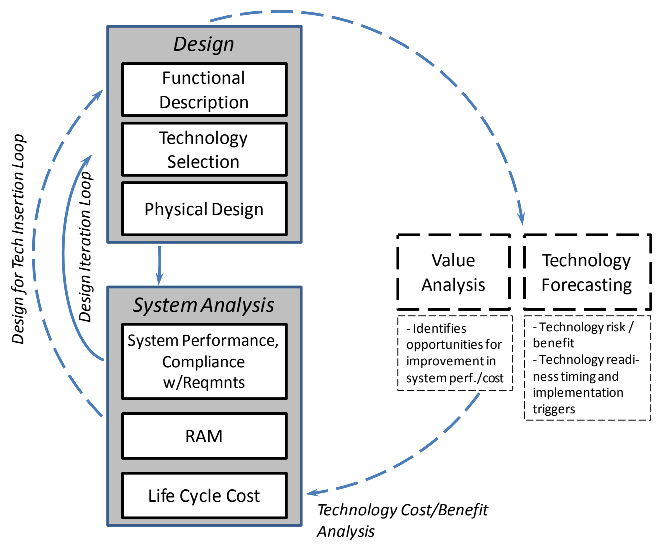

Figure 3: Innovation Based Design

SOLID OXIDE FUEL CELL TECHNOLOGY

Fuel cells offer potential for efficient and clean conversion of chemical energy stored in fuels into electrical energy. Solid Oxide Fuel Cell (SOFC) technology has several advantages over other fuel cell technologies; one of these advantages is that they are relatively robust and provide better fuel flexibility than other fuel cell technologies. On the other hand, SOFC technology operates at very high temperatures (as high as 700-800C) and therefore takes quite a long time to start up and shut down. The technology is therefore more suited to longer term power generation technologies. Applications within the DoD include power generation for military bases (portable and stationary systems) and auxiliary electric power generation for military vehicles to extend silent (engine off) operations. Generating electrical power on mobile assets consumes a large amount of battlefield fuel, and the use of higher efficiency fuel cell systems should reduce overall fuel consumption. In addition, these vehicle systems can also be linked into a base power grid when the vehicles are not being used.

Key top level functions of mobile SOFC systems include:

- Converting sulfur-containing hydrocarbon fuels and air into a regulated direct electrical current, supplying variable electrical loads

- Automatic management of heat up and cool down within required thresholds
- Exhausting non-toxic gases from the system at a safe temperature with minimal environmentally damaging pollutants
- Maintaining safe external temperatures, and providing low acoustic, electromagnetic, and heat signatures
- Withstanding environmental conditions of application (maintain reliability, durability and performance)

An Office of Naval Research solicitation (ONR BAA 08-024) for design of a SOFC based auxiliary power unit for Marine Corps vehicles defines some specific performance goals for the technology; a subset of the requirements is shown below in Table 1.

Attribute / Parameter	Requirement
Output Power	10 KW (threshold), 15 KW (objective)
Output Voltage	26.5 < Output Voltage < 29.5
Packaging	30 Watts/Liter, 35Watts/kg
Package Size (H x L x W)	Not to exceed 37" x 62" x 32"
Start-up Time	To full capacity in <30 minutes
Fuels	JP-5, JP-8, ULSD, Zero Sulfur Synthetic Diesel
Elevation (rated power performance)	4000ft (threshold), 6000ft (objective)
Operational Gradient	15 degree incline
System Life	Mean time between overhauls > 5000 hrs

Table 1: Requirements for Mobile SOFC Aux Power System

Typically during the system design process, different requirements may drive design choices in conflicting directions. The requirements above anticipate that with respect to output power and elevation performance, the desired values may be difficult to achieve. Therefore, minimal "threshold" values for the requirements are defined as well as target "objective" values. This approach to requirements definition allows for more effective tradeoffs to resolve design conflicts. It also provides direction for technology insertion planning. If the technology is implemented at the threshold level, an opportunity is available for future technology insertion to achieve desired objective values.

A more detailed description of the system and subsystem functions for SOFC is shown below in Figure 4. Particular subsystems with continuing research and development needs are: the SOFC stack (improved performance and durability), the reformer (improved control of reformate quality), and the desulfurizer (size, effectiveness, and means of purging sulfur).

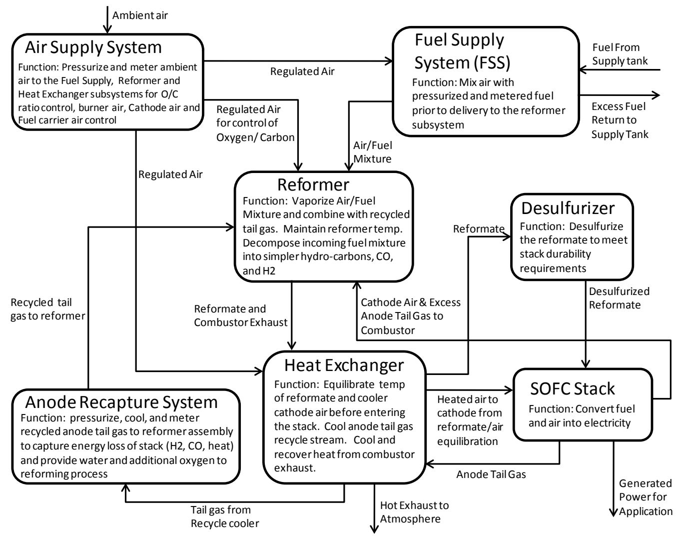

Figure 4: SOFC Subsystem Functions

Improvements in the reforming process are a research interest at the Golisano Institute for Sustainability (GIS). In particular, GIS is researching improved designs and controls with the goal to reduce production of carbon compounds in reformate, to facilitate variation in fuel compositions, and to extend the useful life of reformer hardware.

Three types of fuel reforming are currently in use for SOFCs: steam reforming, partial oxidation (POX), and autothermal reforming (ATR). Autothermal reforming is a hybrid of the other two approaches. While steam reforming is a mature technology, it is not ideal for mobile applications because of its slow response time and poor conversion efficiency with heavy hydrocarbons such as diesel [4]. POX and ATR reactors are more effective with heavy hydrocarbons, but catalyst deactivation due to higher operating conditions is a durability challenge [5]. GIS research is focused primarily on improvements in the ATR technology for mobile applications. It may be possible to achieve the system performance thresholds with incremental improvements to the reformer design configuration and controls. However, more significant changes to reformer technologies may be necessary in order to meet performance and durability objectives, as well as to improve flexibility for variable fuel supplies.

Figure 5, below, describes the functions of the reformer subsystem in FAST (Functional Analysis System Technique) format. FAST was conceived by Charles W. Bytheway in 1965, as a way to systematically represent the functional relationships of a technical system [6]. System functions are represented graphically in terms of why the function is important (left-hand side) to how it is implemented (left-hand side) and are stated in verb-noun form. FAST has been used as a key component of Value Engineering (VE) approaches, and is used here to provide a framework for relative valuation of system sub-functions [7].

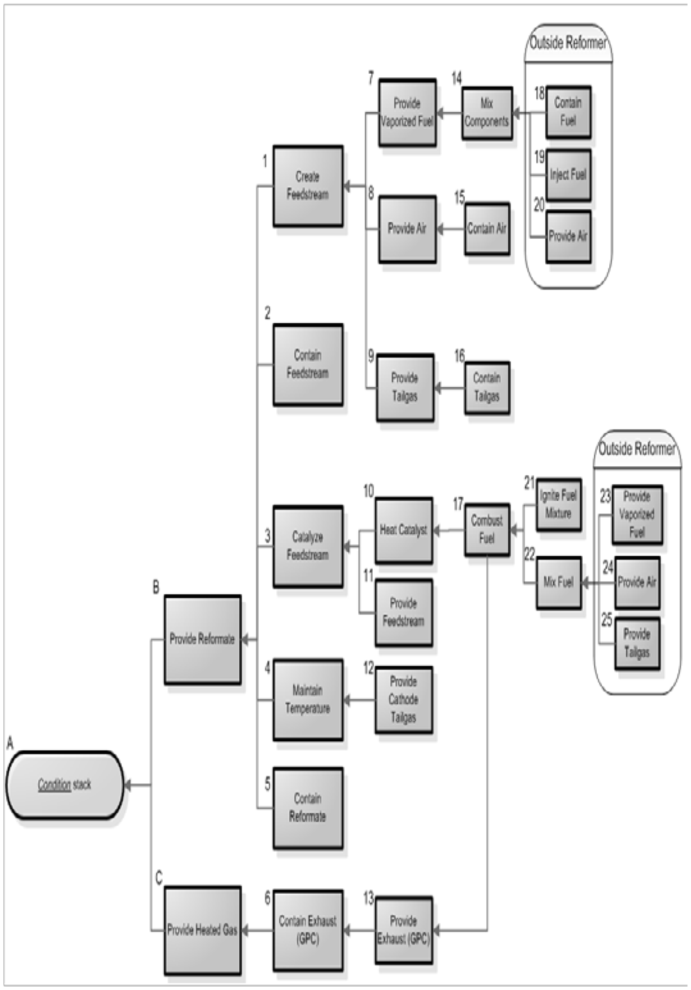

Figure 5: Reformer FAST Diagram

For the SOFC system, the value of functions at the third level of function decomposition was evaluated as to their relative importance. Relative functional importance was evaluated using a Paired-Comparison (P-C) approach. Each function was compared to each other function on the following rating scale:

0 = same importance
1 = slightly more important
2 = moderately more important
3 = significantly more important

The results of the P-C analysis are shown below in Table 1. The ratings represent the median rating among project team members. The first number listed represents the number of the more important function, the second number represents how much more important it is than the compared function.

Fn #	Function	Rating						Sum	% Importance
1	Create Feedstream		1-2	0	4-1	1-2	1-2	6	26%
2	Contain Feedstream			3-3	4-2	0	0	0	0%
3	Catalyze Feedstream				3-1	3-3	3-3	10	43%
4	Maintain Temperature					4-2	4-2	6	26%
5	Contain Reformate						6-1	0	0%
6	Contain Exhaust							1	4%
		Create Feedstream	Contain Feedstream	Catalyze Feedstream	Maintain Temperature	Contain Reformate	Contain Exhaust		

Table 2: Relative Importance of SOFC Functions

Using the initial prototype ATR reformer design, the physical components were allocated among the 6 functions from the P-C analysis.

Figure 6 shows the relative functional importance compared to the relative functional percent cost. The graph provides a quick view of relative value; functions located above the line represent high relative value, while functions located below the line represent low relative value. The analysis suggests that the functions "contain exhaust" and "contain reformate" are relatively low in value and they represent VE opportunities. The primary technical challenge with these functions is the high material cost associated with the materials that are being used in the reference design due to the high operating temperatures. Material or process breakthroughs may be necessary for improvement in this area. The function "maintain temperature" is relatively high value, partially because waste heat is being used to perform this function in the reference design. The functions "create feedstream" and "catalyze feedstream" are relatively more expensive; however, the cost is also reflected in their value rating. These two functions provide the greatest opportunity for reformer technology insertion.

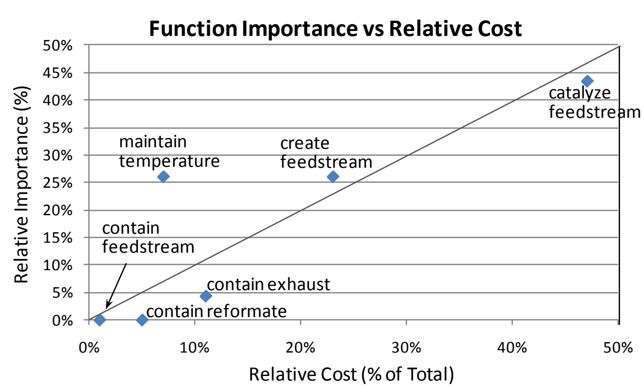

Figure 6: Function Value Relationships

The target life-cycle for an SOFC system design is 10-20 years. The physical life of many of the core components in a mobile SOFC system (reformer, stack, and desulfurizer) is likely considerably less than that. As a new technology such as SOFC is put into service, there is significant risk that major design or configuration changes will be needed early in the technology life-cycle. Technology insertion planning can improve the likelihood that new technologies can be integrated into the original design architecture, thus extending the design life.

The 5000hr overhaul requirement stated in Table 1 would suggest a 1-3 year overhaul interval if the system was operated at 20-50% duty cycle. If the mobile SOFC system was used solely for auxiliary power for military vehicles, the duty cycle is likely to be on the low side of the range. However, in military applications that use the mobile system as part of the base power grid, or for commercial trucking applications, the duty cycles are likely to be much higher.

Assuming that major components need to be replaced, reconditioned, or remanufactured on a 1-5 year basis, a decision needs to be made regarding the residual component value that can be extracted from the used system (and the effort to recondition) versus the option of retire/recycle and replace with new. This analysis is a key component of the life-cycle planning process but is beyond the scope of this paper. Assuming that the used system has significant residual value, then a plan for reconditioning or remanufacturing is needed. The technologies that have been identified through the technology forecasting process should be considered for potential replacement during these refresh cycles.

If evolving technologies are important for achieving anticipated future performance goals, research and development funds should be allocated during the original development process and should be included in the life-cycle cost considerations.

SOFC REFORMER TECHNOLOGY FORECASTING

Within the overall SOFC system, the reformer, desulfurizer (if required), and the power producing "stack" are three of the most important components and both likely to see technology advances over time. However in this paper, only the potential technology advances in the reformer subsystem were evaluated. Active research and development in reformer technologies was researched by reviewing journal publications, patents, and research grant solicitations (in particular, SBIRs). The investigation identified organizations with active research or development programs in reformer technology, as well as some of the stated drawbacks of current technologies and potential benefits of new technologies being considered.

Reforming of heavy diesel-like fuels is very challenging. Technical challenges include: fuel vaporization and mixing with other reactants, catalyst durability to carbon deposition or sulfur poisoning, and carbon or coke emissions from the reformer that result in downstream system degradation [8]. Technology forecasts were done for 3 technology aspects of the reformer: catalyst and substrate, fuel and oxidant mixing, and variations on ATR method (means of maintaining and controlling the reaction).

ATR Catalyst Technologies

Critical considerations in catalyst development include: weight, size, activity, cost, versatility to reform different fuels/compositions, and durability and fuel processing efficiency. A desirable catalyst is one which catalyzes at low temperatures, is resistant to coke formation, and is tolerant of different concentrations of poison (e.g., sulfur, halogens, heavy metals, etc.) for extended periods.

One currently used diesel reforming catalyst contains rhodium (Rh) as the key active ingredient on an aluminum oxide or refractory metal (high-surface-area iron alloy structure) substrate. Although this catalyst configuration has a good hydrogen yield and reforming efficiency, it is not resistant to coking and has very little sulfur poisoning resistance. Therefore, there is a need for an alternative to the Rh catalyst. This alternative must have better resistance to both coking and sulfur poisoning with minimal increase in cost.

General factors that were considered in evaluating alternative catalyst and substrate technologies are: maturity (anticipated development effort/time), reliability and durability (service life), and cost to implement. Considerations specific to evaluating catalyst technologies included: sulfur resistance, thermal resistance, conversion efficiency (hydrogen-H_2 yield), and resistance to carbon deposits.

Based on the research and analysis conducted, the following technologies were recommended for consideration as technology insertion candidates:

- **Rh catalyst deposited on a Cerium-Oxide (CeO_2) support**. This is a low-risk, lower benefit technology that should be able to be implemented with the next 5 years. This catalyst system has been successfully demonstrated in various catalyst applications. One significant drawback is its cost to implement [9,10].
- **Noble metals (Platinum-Pt) on ceramic CeO_2 or pervoskite supports** should be monitored for application within the next 10 years. These supports will enhance the catalyst performance and durability. In addition, mixing Ni in with the noble metals will reduce the cost to implement the catalyst system [11,12].
- **Doping of noble metals in fluoride, pervoskite, or pyrochlore lattice structures** is a longer range catalyst option that should be monitored. This approach provides better dispersion of the catalyst and also improved

binding to the substrate resulting in improved thermal stability, sulfur tolerance, and effectiveness. This technology has only been demonstrated on laboratory scale reformers and significant research and development work still is required to reach the level that the technology can be applied to a commercial diesel fuel reformer [13,14].

Anticipating that the reformer body structure has a longer physical and technology life than the catalyst, the reformer should be designed in such a way that the catalyst can be readily replaced during SOFC overhaul or remanufacturing cycles. Constraints on physical size and form factor of the catalyst substrate (if known) should also be considered during the design phase.

Alternative technologies for ATR reforming and for Fuel/Oxidant mixing in ATR reformers

In addition to the diesel reforming challenges discussed earlier, the following additional factors affect the effectiveness of the reforming process as well as the likelihood of coke/carbon formation on the catalyst or within the reformer or other SOFC components:

- High temperatures are required to obtain continuous and maximum hydrogen production, uniform temperature distributions produce better results but are difficult to achieve
- Poor fuel and oxidant injection and mixing can result in low effectiveness, hot/cold spots and carbon generation
- Reactor design affects flow path of reactants and heat gradients within reaction

The baseline technology for injection and mixing in ATR reformers is low-pressure injection with fuel vaporization and mechanical mixing of reactants. The level of homogeneity needed in the fuel/oxidant mixture is difficult to achieve for all operating conditions. High-pressure injection is also a relatively mature technology and results in improved fuel dispersion but greater challenges in fuel/oxidant mixing [15].

Atomizing liquid diesel fuel with high-temperature steam in a fuel injector has produced a highly dispersed mixture of diesel and steam [16,17]. This approach resulted in less coking formation on the catalyst compared to a process low-pressure injection with mechanical mixing. Ultrasonic fuel injection was resulted in an increase the reformer efficiency of approximately twenty percent, extended stable performance, and significant reductions in Ethylene-C_2H_4 (a known carbon precursor) in the reformate stream [18].

Optimization of the mixing chamber to improve fuel/oxidant mixing performance is a design activity that should have significant effort during the original development phase. Through increased understanding of how to design and model this process, improved evolutionary designs for mixing are likely. If the mixing chamber is physically separable from the main body of the reformer, or the mixing is accomplished via inserts, these evolutionary designs can be implemented during overhaul or upgrade cycles.

Ultrasonic fuel injection currently has some limited applications and offers greater potential benefits. If the technology is not fully validated for the mobile diesel fuel applications at the time of original SOFC production, it would be prudent to evaluate current injector designs in order to provide a physical “drop-in” option, if possible. Implementation of new controls for the ultrasonic injection may also be necessary. It is likely that this technology could be ready within 5 years but would likely require more system changes than an upgrade to the mixing chamber.

Fuel atomization with high temperature steam or stack recycle gas flow offers the greatest potential performance benefits but also is the least mature and offers the highest risk. It is likely that the technology could be ready for implementation within a 5-10 year window. Retrofit of this option may require more significant design modifications (for example plumbing) at the time of implementation.

A variety of different methods have been considered for controlling the ATR reforming reaction prior to catalysis. Thermal plasmas and non-thermal plasmas have been considered with mixed results [19-21]. The results to date have not been promising enough to include these methods on the technology forecast. Microchannel and membrane-based designs have shown more promise.

Reforming diesel fuel in a microchannel reactor has several advantages over conventional reactors. Since the ratio of active catalytic surface to reactor volume determines the reactor/system dimensions, the large surface-to-volume ratios contained in microchannel reactors are necessary for designing small and compact fuel-processing systems for mobile fuel cell applications [22].

The use of microchannels enables maintaining isothermal conditions in the reforming reactor due to significantly improved heat management possibilities. Heat supply can easily be coupled with reforming channels by locating these channels adjacent to heat exchanger channels or to channels with an exothermal combustion reaction and hence providing stable temperature conditions within the reactor volume. The advantage of using this technology is that microchannel fuel reformers have shown rapid reforming kinetics due to the low thermal resistance and large surface area [23]. The microchannels also act as flame arrestors, preventing auto-combustion from occurring,

As mentioned previously one of the major issues in reforming of diesel fuel is coking or the deposition of carbon onto the reactor walls and catalyst, as well as post-reformer carbon deposition. Membrane reactors have been developed as a solution to carbon deposition on critical reformer surfaces [24,25]. In membrane reactors, air is introduced into the reformer through porous reactor walls. Oxygen is maintained at very high partial pressures near the inner reactor walls and the oxygen suppresses the deposition of carbon in the cool zones of the reactor feed. Thus the walls of the membrane reactors are designed to be self-cleaning [26]. An advantage of this type of reformer is that the volatile compounds from diesel fuel can be introduced to the reformer in a gaseous form, eliminating the need for the liquid-fuel injectors and mixing chambers.

Microchannel Reformer designs have demonstrated significantly increased reforming efficiency compared to conventional reformers. However, hot spots remain a concern with the technology (due to management of heat transfer characteristics) and improved methods for catalyst application are needed. It is likely that this technology could be configured as a drop in to a conventional ATR and be matured for use in 1-5 years.

Membrane Reformers are a newer technology that offers greater potential for reducing catalyst hot spots and carbon formation. The overall performance benefits need to be better understood and much more development with respect to materials and physical design configurations. An anticipated maturation timeframe is 5-10 years and it is likely to require more substantial physical changes to the reformer configuration.

Technology Insertion Roadmap

There are additional important life-cycle planning considerations that have not been specifically addressed for the SOFC system in this paper. What is the anticipated life span for key functional and cost components of the fuel cell design? Is it cost effective to recover and remanufacture the SOFC system? Which components can be reconditioned or recertified for reuse? What are the triggers (time, usage, condition) to take the system out of service for overhaul or remanufacturing?

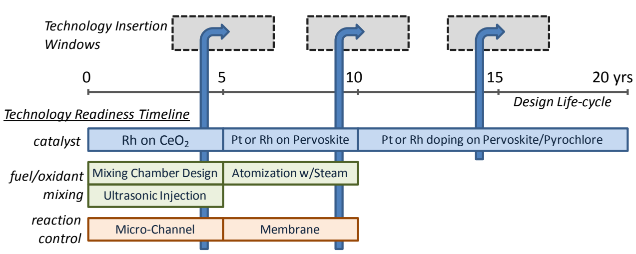

Figure 7: SOFC Technology Insertion Roadmap

The life span of key functional components, along with the feasibility of unit remanufacturing and technology insertion will determine what the actual physical life-span of a system will be. Assuming that overhaul or remanufacturing cycles are justified, disposition of particular components will depend on the economics and the component wear-out characteristics. At an overhaul interval, particular components may be scheduled for reuse, remanufacturing, replacement, or replacement with technology upgrade.

If the anticipated life of the system design architecture is longer than the physical life of the system, the technology insertion plan should consider the longer time period. This can reduce the life-cycle costs associated with redesign and modifications to manufacturing systems.

Figure 7 provides an overview of a proposed technology insertion plan for an SOFC system. The technology readiness bars indicate a range of possible maturity dates for the technology (assuming active development). The technology insertion bars provide likely windows for technology insertion opportunities. For existing (fielded) systems, the actual upgrade time would depend when the system was fielded, the system usage, and the designed durability.

Within the 3-5 year time period the catalyst upgrade (Rh on CeO2, or Noble metal on pervoskite), modified mixing chamber design, and micro-channel technologies should be planned for. This upgrade good be readily effected given proper design modularization.

Ultrasonic fuel injection might be feasible in the same time frame if it is a physical drop in and the control modifications can be cost effectively accommodated. Implementation of membrane reactor technology will require replacement of much of the reformer system, and may require coincident changes in fuel/oxidant mixing and catalyst. Fuel atomization is a fuel/oxidant mixing alternative that will also require significant system changes. Assuming a 20 year design life cycle, which ever of these technologies provides the best benefit/cost ratio should be planned as a mid life-cycle upgrade. The noble metal doped catalyst technology could be implemented at the same time, or at a later date if not fully mature. It would, however, be important to narrow down the potential design envelopes for the technology so that it can be planned for as part of the mid life-cycle upgrade.

CONCLUSION

Solid Oxide Fuel Cell technology has potential as a mobile source of auxiliary vehicle power. In military operations, or in civilian emergency situations, there is potential to use these mobile generators as distributed generation sources. While there are a variety of large stationary commercial systems that are natural gas fueled, the design challenges associated with SOFC systems using vehicle fuels in mobile application environments are still being met.

As this technology moves towards being fielded for these applications, there are a variety of risk factors to be considered and managed: reliability and durability of fielded hardware; cost competitiveness of technology; rate of future technology innovations that improve performance, reliability and durability, or cost. The high operating temperatures in the SOFC technology drive material cost and design complexity.

While there may be opportunities to reduce design cost over time, a strategy to reduce the effective system cost is to try to extend the life-cycle of the produced systems. As life-cycles are increased, the risks associated with technology innovation also increase. These risks can be managed through technology forecasting and adopting a design strategy that generally supports technology insertion and more specifically anticipates particular technical innovations that are identified through technology forecasting.

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