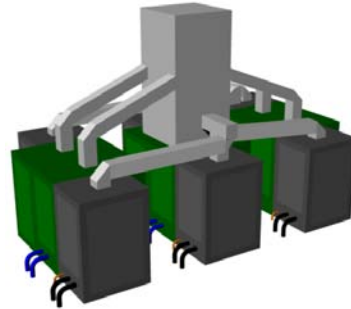


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Investigation into the implications of fuel cell shipboard integration into the T-AGOS 19 class



INTRODUCTION

Fuel cells have long promised to be the next significant development in power systems technology across all industries. The Navy, with the support of the Office of Naval Research (ONR), has undertaken a range of fuel cell technology developments at NSWC Carderock SSES that support the potential future use in shipboard powering. To date, the focus has been on demonstrating fuel cell technology with marine fuels and the associated risk mitigation of fuel processing systems. There has been, to date, less of a focus on the assessment of the potential navy ship integration aspects.

This paper reviews aspects of a study that aimed to assess the potential marine fuel cell technologies, their potential integration issues, and their likely impact on a representative naval ship design. While the first phases of the study took an in-depth look at potential fuel cell technologies, this paper focuses on the outputs and conclusions from the last two phases of the study. In these phases, a range of potential fuel cell based power systems for the Military Sealift Command's (MSC) T-AGOS 19 class were developed before being assessed against a range of both generic ship and specific naval requirements such as noise propagation, emissions, and fuel consumption. Finally the outputs from a more detailed integration exercise of a hybrid fuel cell system onto T-AGOS 19 are reviewed and discussed.

STUDY AIMS

The study had three broad aims:

1. Determine the feasibility & implications of integrating fuel cell systems into a naval ship design;
2. Provide direction for future Navy/ ONR fuel cell research & development plans; and
3. Integrate a candidate fuel cell based power system into a notional Navy ship design.

ASSESSMENT OF CANDIDATE FUEL CELL TECHNOLOGIES

Fuel cell technology development has been underway in earnest since the late 1950s^(Ref. 1) and has been principally driven by advances in materials. Currently five principal fuel cell families are available with each defined by its fundamental electrolyte:

- i. Alkali Fuel Cells (AFC)
- ii. Polymer Exchange Membrane (PEM)
- iii. Phosphoric Acid Fuel Cells (PAFC)
- iv. Molten Carbonate Fuel Cells (MCFC)
- v. Solid Oxide Fuel Cells (SOFC)

The characteristics of these technologies and those of two sub-types of the PEM family (High Temperature – HTPEM and Direct Methanol Fuel Cells – DMFC) were assessed against a range of basic ship requirements including fuel compatibility, performance, responsiveness, start-

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up times, and power density. Of these requirements, fuel compatibility was identified as a key discriminator for naval applications.

Most commercial fuel cell systems operate on either pure hydrogen or natural gas. Whereas the development of potentially fuel-cell-friendly natural gas (stored as LNG) powered marine systems is progressing in the commercial sector, there is a continued need for the Navy to maintain its common use of power-dense marine diesel fuels such as F-76. To convert marine diesel fuels to hydrogen or reformat gas streams, a fuel cell must incorporate a fuel reformer within its Balance of Plant (BOP). Technologies to achieve this have been an ONR focus to date. The test and evaluation of these technologies has shown that the reformer design often dictates the overall system performance and response with the more complex systems seeing the most significant performance impacts. Equally, the sulfur content of current marine diesel fuels is seen as the biggest issue in adapting fuel cells for marine use due to sulfur's severe poisoning effect on fuel cells with even low concentrations.

Based on this need for fuel compatibility and on the need for availability of fuel cell stacks in 100⁺ kW power range for realistic marine applications, two technologies can be quickly discounted, namely – AFC, DMFC.

PEM (low temperature) is attractive from a gravimetric power density perspective and is technologically mature. PEM was also discounted as, when matched to the BOP required for marine diesel fuels, PEM fails to offer any significant efficiency, density, or performance advantage over current marine diesel systems.

HTPEM shares a similar chemical process to PAFC technology but offers the best mix of characteristics in the sub 250°C 'low-temperature' technologies.

Of the high temperature fuel cell technologies (600-1,000°C), SOFC offers the highest power density and potential efficiency as well as more rapid starting times when compared to the MCFC. High operating temperatures have the potential to provide the highest efficiency if suitable shipboard uses for their waste heat can be identified.

Based on these conclusions, the study considered both HTPEM and SOFC technologies in its analysis of integration issues.

GENERIC INTREGRATION RISK ASSESSMENT – HTPEM & SOFC

A risk assessment matrix was developed to consider the potential risks involved with integrating any new power system into a generic ship. Five main risk categories were identified:

- Commercial Market
- Installation
- Survivability
- Build & support
- Performance Characteristics
- Environmental

HTPEM and SOFC technologies were then assessed against this matrix. Principal among the identified risks from this process were:

Commercial Market - Whereas both energy and marine sector manufacturers are demonstrating at least research and development in SOFC technology, far less evidence was found for widespread market support for HTPEM technology at the powers of interest. SOFC is currently a higher technical development risk than HTPEM, but is likely in the longer term to have a more secure, broader market.

Installation – Key risks in this area are in the development of a reliable, cost effective BOP capable of managing standard marine/naval fuels, or in securing a reliable, cost acceptable source of low sulfur fuel. The control of a fuel cell system, especially in hybrid marine applications is an area which also needs further research. HTPEM systems offer a dynamic response to load changes similar to that of current marine diesels. SOFC systems have poorer load response (assuming BOP for Diesel fuel) and are likely to need hybridization. This issue is less critical in commercial or naval auxiliary designs with predictable operating profiles, but is an important risk for combatants.

Survivability – The majority of high risks identified within the survivability category are the result of either no demonstration of capability to

date or due to a lack of supporting evidence to prove capability. Areas such as fire protection, gas management, and shock survivability are considered solvable but require validation.

Performance characteristics – Fuel cell system operation in a scenario where no electrical power is available (black/cold-start) needs further consideration. The long start-up times associated with larger HTPEM and SOFC systems also have implications for naval ships requiring rapid power availability or black/cold-start operations.

Build and Support – No significant risk considerations.

Environmental – No significant risk considerations.

ASSESSMENT OF FUEL CELL SYSTEMS FOR T-AGOS 19

Having selected suitable fuel cell technologies and highlighted key risk areas, it became necessary to identify a suitable candidate ship on which to consider their integration in more detail and to develop a range of fuel cell based power system concepts to meet the ship’s requirements. These systems could then be assessed against a range of metrics to identify a single system for more detailed integration in the final phase of the study.

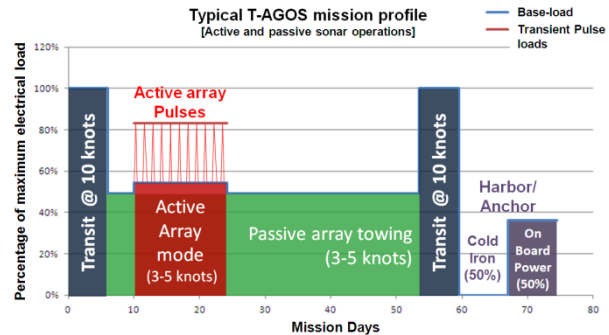
Basis ship selection – T-AGOS 19

A key aim of the study was to identify a ship design that demonstrated the integration issues associated with fuel cells and offered a realistic implementation path in the medium term; hence, it was concluded that the chosen design should:

- Be a military design to capture military specific integration issues;
- Not be a front-line combatant - avoiding some survivability and power density risks;
- Have a potential follow on replacement and, hence, a continuing future mission need;
- Have requirements supporting the use of fuel cells not only for efficiency gains but for other benefits such as low noise or emissions;
- Have a mission profile that supports multiple possible fuel cell integration options and developmental steps.

MSC’s Small Waterplane Area Twin Hull (SWATH) T-AGOS 19 class is designed to collect, process, and transmit acoustic data from both its passive and active towed array systems. It meets the selection criteria and provides several additional benefits. It has a relative low installed power, a continuing mission requirement, and an expected replacement program in the mid 2020’s. It operates independently from the fleet allowing the option for alternative fuels to be considered. It has a stringent requirement for low noise to maximize the effectiveness of its mission sonar arrays, allowing the assessment of the impacts of fuel cells on noise. Finally the ship has a mission profile (Figure 1) that combines steady-state transit and long periods of low speed passive towed array operations punctuated by shorter periods of active sonar operation requiring high-power short-pulse loads. This generates a range of fuel cell implementation options to be considered.

Figure 1: Typical mission profile for T-AGOS 19



Power system concepts considered

A range of fuel cell and diesel generator (DG) power systems were developed matching the requirements of the T-AGOS 19 and its mission.

Four fuel cell based systems were developed each with varying proportions of hybridization with DGs. In addition, two DG based systems were developed to facilitate meaningful comparisons. In four of the systems, energy storage was included to reflect the need for redundancy, transient performance, and to reduce the impact of the active sonar pulse loads on the main electrical generators. An overview of each system and its key components is shown in Table 1.

Table 1: Overview of power systems analyzed

System	Baseline	Sys. 1	Sys. 2	Sys. 3	Sys. 4	Sys. 5
DGs	× 4	× 4	× 3	× 3	× 2	0
FCs	0	× 3	0	× 3	× 6	× 11
ES	0	0	× 4	× 2	× 3	× 4
Installed power (not inc. Energy Storage)						
kW _e	3,972	4,722	2,979	3,729	3,486	3,000

Notes: Diesel (DG) – Caterpillar 12V C32 @ 993kW_e (Ref.2); Energy Storage (ES) – 250kW_e flywheel module (Ref.3); Fuel Cells (FC) – 250kW_e SOFC/HTPEM modules

Each of the systems had a broad design intent associated with it; these were:

Baseline – provide a modern equivalent to the current T-AGOS 19 power system. This allows a fair comparison of the other five systems with a system including modern diesel technology and its associated power density and emission levels.

System option 1 – This system has all the baseline option components but also assumes additional separate fuel cells sized to meet the in-harbor generation needs of T-AGOS 19. It was considered to investigate the impact of fuel cells on emissions and tax costs in harbor. This system has the potential for nearer-term implementation by offering the opportunity for pier-side and modular on-board demonstration.

System option 2 – This system adds energy storage to the baseline system to manage the active sonar pulsed loads. Sufficient energy storage is also included to provide ride-through capability, and, hence, investigate the removal of a DG set. This system could be implemented in the near-term as an alternative to the baseline, offering acquisition, maintenance, and operational benefits.

System option 3 – This system replaces a diesel in the baseline with three fuel cells and includes energy storage to meet the mission pulse load requirements. This system is considered to demonstrate the potential for fuel cells to provide fuel consumption and emissions benefits when providing base-load power – a typical current industrial application. This system reduces overall risk by avoiding the potential transient response issues of fuel cells as these are managed by the residual diesels and energy storage system.

System option 4 – This system builds on Option 3, but includes sufficient fuel cell power to

provide all of the ship’s power needs during sonar array operations. The system retains two diesels to support transit and provide redundancy and risk reduction. This option was considered to assess the impact of the low noise characteristics of fuel cells on T-AGOS mission effectiveness.

System option 5 – This system uses only fuel cells and energy storage for all of the ship’s power needs and, hence, explores the potential benefits and challenges of a 100% fuel cell system.

Assessment of system options

The six systems were assessed against each other, with each of the fuel cell based systems being considered with both HTPEM and SOFC technology. Initial system level comparisons were made in high level areas including: installed power, volume and weight impacts, noise, fuel consumption, emissions, risk, and cost. Some of these are discussed below. The aim was to highlight key design characteristics and provide a mechanism for the selection of a single system for the more detailed integration study.

INSTALLED POWER

Comparisons of the total installed power of the systems highlighted the effects of using larger numbers of low powered generators. The fuel cell modules have a quarter of the power of a single DG set and, hence, can meet the redundancy and availability targets with a lower installed power – i.e. it is easier to match the installed power to the ship’s requirement. This would be equally true if a larger number of diesels were used; however, efficiency and power density of diesels does not appear to scale as linearly as they do for fuel cells.

The impact of energy storage is also notable as this can remove the need to install excess power to manage often limited occurrences of high power transients such as the T-AGOS active sonar loads.

EMISSIONS

Fuel cells inherently produce lower levels of the emissions that are of international concern. The broad trend in the comparisons, as might be predicted, shows an overall reduction based on the level of installed fuel cell power in each system. The emissions of carbon dioxide (CO₂), particulate

matter (PM), nitrogen oxides (NO_x), and sulfur oxides (SO_x) were analyzed.

CO₂ emissions are directly linked to efficiency, so the fuel cell systems demonstrated a small to moderate reduction in CO₂ emissions reflecting their efficiency improvements over DGs. The impact of the use of diesel fuel and, hence, the matching BOP design, limits the overall efficiency benefit of both fuel cell technologies with SOFC showing larger gains than HTPEM and HTPEM being very close to that of current DG sets as illustrated in Figure 2.

PM and NO_x emissions are now trivial as no combustion occurs in a fuel cell system. Their output levels easily meet future EPA and IMO requirements.

SO_x emissions are directly linked to the sulfur content of fuel. Although there is pressure to drop the sulfur content of marine fuels, the current and predicted future concentrations of sulfur are several orders of magnitude higher than can be safely processed by fuel cells.

Figure 2: CO₂ emission comparisons

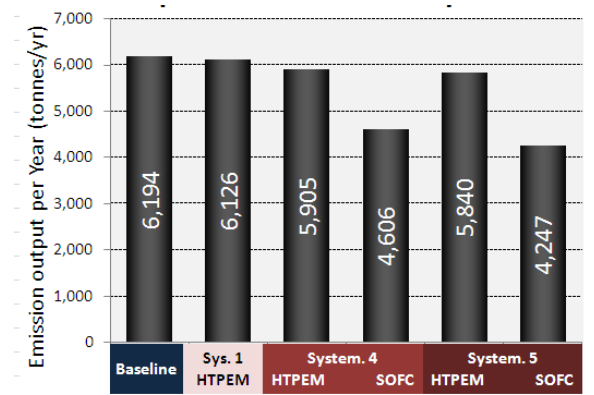


Table 2: Fuel sulfur content

F-76 sulfur content (2005) ^(Ref. 4)	Max 1.0%; Min 0%; Mean 0.56% m/m
F-76 sulfur content (2009) ^(Ref. 5)	Max 0.5%; Min 0%; Mean 0.28% m/m
IMO ECA limits (2015)	0.10% m/m (1,000ppm)
ULSD (EPA limit)	15ppm m/m (0.0015%)

Notes: m/m – mass as a proportion of total fuel mass; ECA – Emission Control Area under the IMO International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI – regulations 14.1 & 14.4 ^(Ref.6); ULSD – Ultra Low Sulfur Diesel (i.e. for road use) ^(Ref.7)

NSWCCD technology development has indicated that designing a fuel cell BOP to effectively remove this high level of sulfur has a detrimental effect on the system performance, BOP complexity, and cost. It is currently considered, therefore, that the use of low sulfur diesels or bio-fuels offers the best long-term solution for navy fuel cells. The study’s assessment of SO_x emissions from the fuel cell systems is therefore significantly lower than for an F-76 diesel powered system based on the assumed use of road grade Ultra Low Sulfur Diesel (ULSD).

NOISE & VIBRATION

The T-AGOS mission effectiveness is based in part on the ability to minimize the noise generated by the ship (self-noise) and, hence, seen as ‘noise’ on its sonar array. Self-noise is generated by a range of sources and transmitted via a range of transmission paths. It is generally dominated by major machinery such as the main DGs. The current T-AGOS 19 class has a range of features to reduce its self-noise including: DC propulsion to avoid the switching noise inherent to AC systems; noise optimized motors and variable speed drives; and substantial noise attenuation of the main DG mounts. These efforts have weight, volume, and cost impacts on the ship design.

Fuel cell noise and vibration sources are likely to be limited to the BOP’s low power pumps and valves as there are no significant rotating masses or discrete frequency sources such as a cylinder firing. Fuel cells are expected to demonstrate, therefore, significant decreases in both self-noise, and in the cost of noise attenuation when compared to a DG based system. This highlights a synergy between fuel cells and noise critical tasks such as the T-AGOS mission and resulted in significant benefit seen on the systems able to provide array operations on fuel cells alone (system options 4 & 5).

Completing numerical noise level comparisons between a diesel and fuel cell systems is complex given the immaturity of the assessed fuel cell system; however a comparison of measured acoustic noise illustrates the expected scale of benefit.

Ship Service Fuel Cell demonstrator
60-65 dB ^(NSWCCD Code 90 measured data)

Medium speed (900rpm) DG
80-103 dB [depends on frequency] ^(Ref. 8)

T-AGOS INTEGRATION RISKS

An assessment of risks was considered necessary due to the variation in maturity between the technologies considered and considered risks specific to T-AGOS integration. In general, there are low risks associated with DG technology, medium level risks associated with integrating energy storage, and higher level risks associated with fuel cells. Assessing risk gives an indication of design and development costs and maturity time associated with each system option.

Principal risks identified, based on current perception, were not associated with fuel cell technology, but with the lack of definition of marine fuel cell packages and their BOP, and hence, the risk in predicting their impact on a ship’s space, weight, and auxiliary systems. Electrical integration and control of a hybrid diesel, fuel cell, and energy storage based system was also considered an area requiring further de-risking as was the definition of suitable class society and naval rules for liquid fueled fuel cell systems. While hybrid systems may have some negative impacts on through-life maintainability, training and systems commonality, the retention of diesels and the addition of energy storage is considered as significant de-risking to the use of fuel cells at sea.

TOTAL OWNERSHIP COST

Total ownership cost (TOC) assessments attempt to capture the cost of a given system throughout its life and can encompass issues as diverse as development, operating, and disposal costs. For this study, three areas were considered: power system acquisition costs; through life fuel and lube oil costs; and maintenance costs.

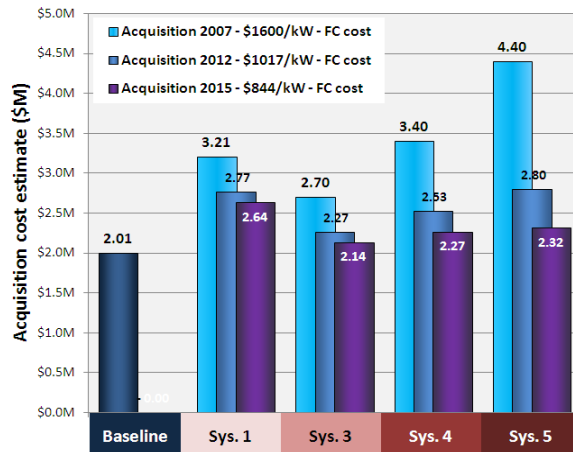
Predicting acquisition cost impacts is complex due to the widely differing maturities of DG sets and fuel cells. The cost estimates shown in Figure 3 are, in reality, comparing mature historic costs for the DG sets with current DOE and ONR estimates for future fuel cell costs. This data also reflects a certain production volume and, hence, the fact that the marine sector will be reliant on market growth in other markets. It should be noted that costs

only consider prime mover costs and not the cost impact on distribution and auxiliary systems.

The costs shown highlight the current significant cost implications of fuel cells, the fact that there is a trend downwards, and that hybridization limits the cost impact to a degree. Cost trends will be driven by production volumes, so it is important that the Navy attempts to utilize technologies with wide potential markets. These costs are also likely to be higher reflecting the potentially unique BOP design required for processing liquid fuels.

Through-life fuel costs are generally the dominant TOC element. After conducting an analysis of fuel consumption based on typical T-AGOS mission data, a through-life fuel and lube oil cost estimate was made for each system. This is shown in Figure 4. April 2011 fuel costs for F-76 naval fuel, commercial Marine Diesel Oil (MDO), and road ULSD, were used for comparison.

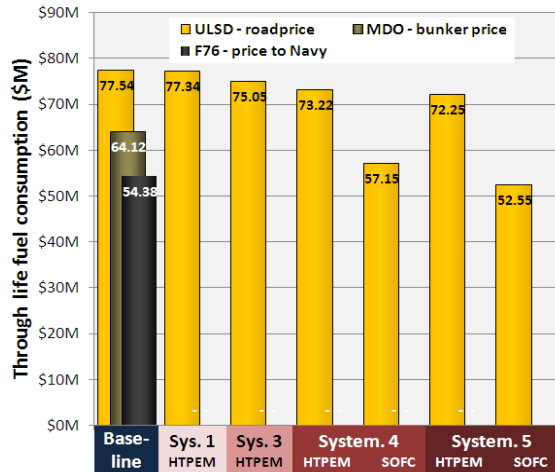
Figure 3: Primary power generator cost estimates



Notes: 2007 data from ONR estimates for marine use ^(Ref. 9); 2010 & 2105 data from DOE estimates for PEM based stationary power ^(Ref. 10) based on 2,000 unit production pa. Price comparisons are in reality difficult because the fuel prices shown reflect different supply infrastructures, tax regimes, and buying models. However, using non-navy infrastructure supplied fuel is likely in the short term to result in higher unit costs. Lower sulfur fuels do incur additional cost due to the processing required and this will in the longer term impact marine fuels like F-76. Bio-fuel options are also likely to be significantly higher than even ULSD. If fuel price differentials are ignored, the fuel cell system with significant proportions of fuel cells (systems 4 & 5) show notable through-life benefits. The difference

between expected respective efficiencies of HTPEM and SOFC systems is also clearly shown with SOFC data assuming no use (other than internally within its BOP) for the residual heat generated. If applications for waste heat were identified, fuel burn should be lowered further.

Figure 4: FO & LO through-life cost estimates



Notes: Costs for 30 years; no discounting applied; Fuel prices taken as of April 2011 from (Ref 11, 12).

While it is possible to assess acquisition and fuel costs, it is currently hard to predict the impact of fuel cells on through life cost. Reflecting their technical maturity, diesel systems have many millions of hours of operational data on which to base maintenance schedules whereas fuel cells have only limited operational data to date. While the solid-state nature of fuel cells should ensure relatively low routine maintenance effort, the current stack lives of both HTPEM and SOFC systems are low (typically <15,000 hours) and, hence, would likely require stack changes during the life of a typical naval vessel. A key focus of many fuel cell technology developments and of DOEs investments is in technologies that increase stack lives. The inclusion of a diesel compatible BOP is likely to result in similar low level maintenance requirements to those on current marine diesel fuel auxiliary systems.

Conclusions & selected system for detailed integration analysis

System options 1 and 3 offer limited fuel and emissions benefits at a weight, space and cost penalty. Option 1 does potentially offer a transition path to fuel cell implementation on navy

ships potentially allowing the transitioning from a pier-side trial to an on-board demonstrator with the same modular package.

Option 5 may be a longer term goal but is currently the highest risk option and not matched to the critical requirements of the T-AGOS class.

In order to take full advantage of fuel cell benefits, the selection of the hybrid diesel-fuel cell system, option 4, is desirable. By using just fuel cells in the passive and active array operating modes, there is potential for significant self-noise improvements which are key to T-AGOS mission effectiveness. System 4 is also one of the fuel cell based system options that provides notable reductions in fuel consumption and emissions. Retaining two DG sets provides operational and acquisition de-risking and allows their matching to transit operation where there is no self-noise requirement.

INTEGRATION INTO T-AGOS 19

The aim of this phase was to identify detailed fuel cell integration issues associated with integrating a fuel cell system onto a specific design. This was done by attempting to integrate the power system identified in the last part of the study (option 4) into a modern version of the current T-AGOS 19 ship design. This updated ship design concept is referred to as T-AGOS 19(FC) and includes both the passive and active array systems found on the recently retrofitted T-AGOS 19 class ships and additional modern systems to meet current regulations and requirements.

A range of design issues were considered including potential impacts on ‘softer’ issues such as support infrastructure and training. Three design areas, however, were considered to represent the most significant risks and these are discussed below in more depth. These areas are: the impact of rules & regulations; the impact of electrical system integration; and the impacts of physical system integration.

Fuel cell module assumptions

Conceptual fuel cell modules were developed in conjunction with NSWCCD Code 90 in Philadelphia. These were based on current estimates of fuel cell and BOP power densities.

A SOFC module was selected for detailed integration as it represented the greatest weight and volume impact and, hence, solutions should also ensure the viability of a HTPEM based option. A 3D model and principal dimensions are shown in Figure 5 and Table 3. As shown, the module consists of two sub-modules, one housing the fuel cell stacks (the Hot-box) and the other housing the BOP which includes the reformer system.

Figure 5: Proposed Complete SOFC module

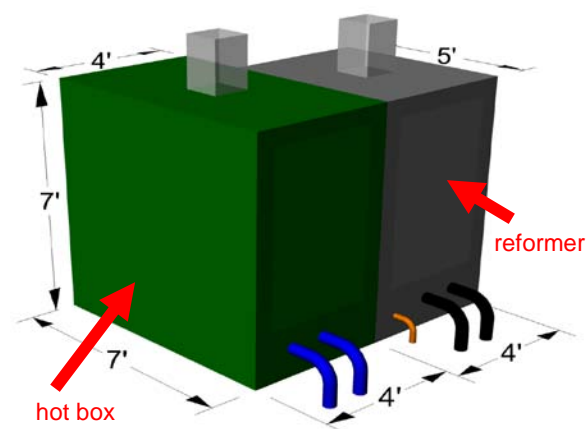


Table 3: SOFC module assumed dimensions

Characteristics	Fuel Cell 'Hot-box'	Reformer
Length	2.13m	1.52m
Width	1.22m	1.22m
Height	2.13m	2.13m
Power Output	2 × 125kW _e stacks - 250 kW _e	
Voltage	2 × 258V in Series – 515V DC	

Design rules & system safety

There are several sets of classification society rules in development relating to fuel cell ship installation. These mostly focus on the use of natural gas (LNG) as a fuel and include rules from *Det Norske Veritas* (DNV), *American Bureau of Shipping* (ABS) and *Germanischer Lloyd* (GL).

The study used the DNV rules for 'classification of high speed, light craft & naval surface craft' found in 'Fuel Cell Installations – Part 6, Chapter 23' (Ref. 14) as a design basis. Under these rules a T-AGOS 19(FC) would be classed under the code "FC-POWER". These rules specify location restrictions and detail the requirement for gas-safe systems, sensors, ventilation, and design features.

Fuel cells have the potential to release hydrogen (H₂) and carbon monoxide (CO), although these risks significantly diminish in a liquid fueled system. Escaped gas, however, needs careful management to prevent fire and, in the case of hydrogen, explosion. This demands that fuel cell spaces are unmanned, separate from diesel or electrical spaces, and have adequate gas sensors, ventilation, and shaping to prevent gas entrapment. This will also require changes to traditional fire-fighting methodology and training.

As the rules are focused on LNG based systems, there is potential to relax some of the regulations for suitably packaged liquid fuel cells. NSWCCD Code 90's proposed SOFC module assumes: a gas tight design; an independent external ventilation system; a pressure differential between the package and space to prevent gas leaks; and an in-module fire suppression system. Many of these features are already proven in gas turbine enclosures and, if developed with class, may allow the module to be treated as a gas-safe compartment rather than the machinery space itself.

It is important that communication between the class societies, fuel cell module designers, and ship designers is developed to ensure that an effective, safe, but not overly onerous, rule set is available for future fuel cell applications.

Electrical Integration

Before physical integration issues were explored, it was necessary to consider integration into the ship's electrical system.

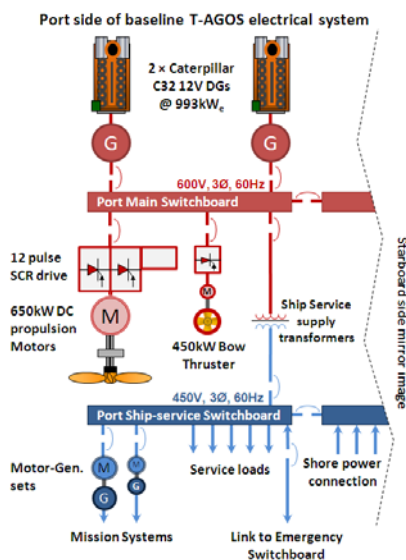
The objective was to design architecture with minimal change thereby investigating the potential impacts to an existing ship modification. More significant changes in new-build design were also considered that could better optimize the system from performance, redundancy, and volume perspectives.

The current system generates power from four DG sets which is then distributed between two main 600V AC switchboards before being supplied to the DC propulsion system, the 450V ship service switchboards, and then the mission systems. A one-line diagram of a proposed modernized version of current system is shown in Figure 6. It

shows the port side system which is mirrored on the starboard side. The diagram also shows the ability of the system to operate with port and starboard sides operating independently (often termed as island operation) or cross-connected as required.

In order to integrate fuel cells into this current system, each fuel cell must be linked to the main switchboards via a transformer to adjust the voltage and an inverter to convert the DC output into an AC current.

Figure 6: Representation of a modernized T-AGOS 19 power system



The energy storage modules which are also DC sources are likely to be most easily integrated between the fuel cells and the inverters. After investigating possible commercial off-the-shelf (COTS) systems, it was clear that it was possible to minimize the weight and volume impact of these systems through intelligent design

The proposed system assumes:

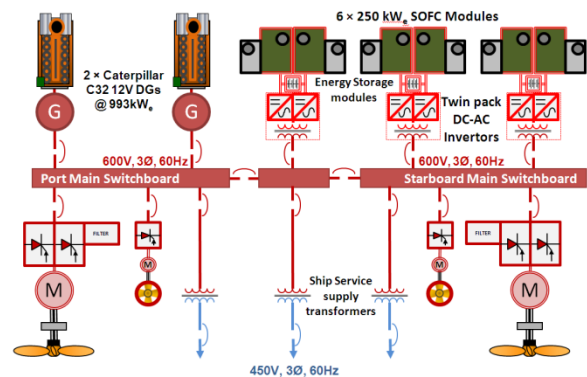
- Each fuel cell module has two fuel cell stacks connected in series to provide a voltage of 515V. As this is close to the 600V used by the switchboard, it is possible to use the inverter’s own transformer and remove the need for an additional external transformer.
- It was possible to use the more space efficient dual inverter, single package designs. This retained a higher redundancy than the four DG sets but reduced the overall system volume.

- By combining inverter modules, it is also possible to share an energy storage module between two fuel cells. This reduced system volume but retained adequate redundancy.
- The three twin-pack SOFC modules and matching power systems are connected to a single main switchboard with the DG sets connected to the other. This retains a broadly even power split between switchboards and allows for independent operation of the technologies.

The proposed system shown in Figure 7 was used as the basis for the physical integration exercise discussed in the next section.

As fuel cells and some energy storage systems are inherently DC in design, DC distribution is also attractive. In a less constrained new build of a T-AGOS, several benefits could be realized. These benefits could include; reduced electrical system noise and, hence, reduced self-noise; a reduction in the number of invertors required; the potential to use more economical variable frequency diesel generators, and the potential to allow the energy storage to be more centrally connected.

Figure 7: Proposed T-AGOS 19(FC) electrical system for physical integration



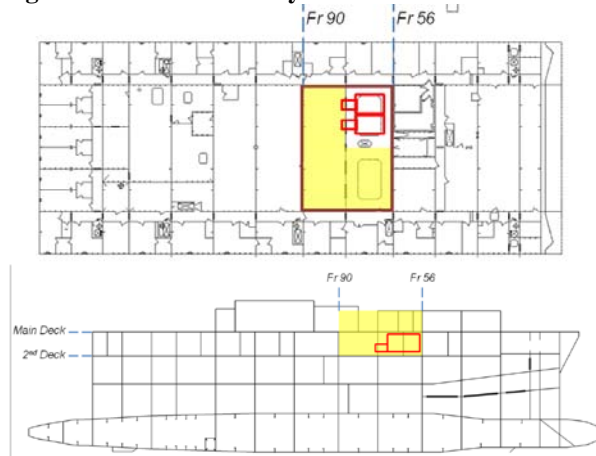
Physical integration

While attempting to integrate the new system into the T-AGOS 19, several design iterations were explored. As a key aim of this study is to identify the key ship and system integration issues associated with fuel cells, this design process is discussed here to highlight some of the issues identified. A second aim was to minimize the overall structural and layout impact to the current design. This approach, although perhaps overly

restrictive, was considered to represent the most challenging integration scenario and, hence, highlight the full range of potential integration issues.

Arrangement modifications were restricted to the currently defined main machinery block spanning the upper two decks of the ship as shown within the red outlines in Figure 8.

Figure 8: Main machinery block – T-AGOS 19



The yellow shading in Figure 8 shows the area in which changes were made and residual white area shows the general location of the two retained DG sets. A new independent SOFC machinery space was created on the starboard side of the original main generator room (MGR) with a longitudinal bulkhead. This allowed better separation of the fuel cells from the both the main and emergency diesel generator space which was considered both advantageous from a safety and redundancy perspective and also provided the best lateral weight distribution.

Fuel cell module arrangement options

The overall arrangement decisions were dominated by the need to efficiently position the fuel cell modules while providing adequate maintenance access and realistic ducting routes. It should be noted that the after part of the MGR is only single height restricting several of the design options considered.

Option A (Figure 10) considered mounting the six SOFC modules on the lower (2nd) deck evenly spread within the center of the space to provide equal access to all sides of each module. This option was considered impractical due to limited

useable maintenance space around the modules and the complex web of air intake and exhaust ducts. Issues also arose with routing the ducting from the rear two modules within the available single deck height.

Option B (Figure 10) moved the hot-box side of the SOFC modules against the outer bulkheads. This provided superior access and removal space around the preferred BOP side of the modules but reduced access to the hot-box. This option may be adequate if the fuel cell stacks in each hot-box could be removed from the sides. This option allowed the air intakes to be centralized but pushed the exhaust ducts into two separate stacks, one on each side of the space. Finally, this option did not overcome the deck height issue at the aft of the space, and potentially restricted the air cooling flow available to the modules.

Figure 9: Arrangement option A.

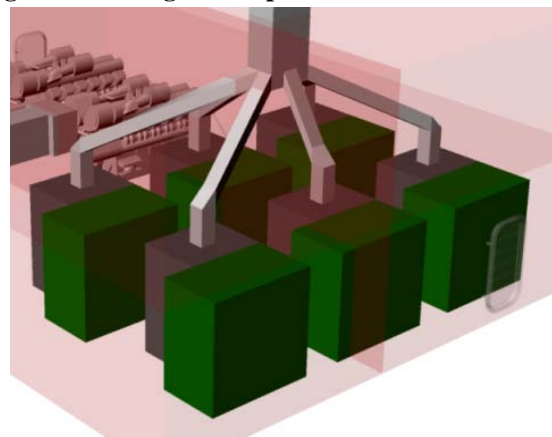
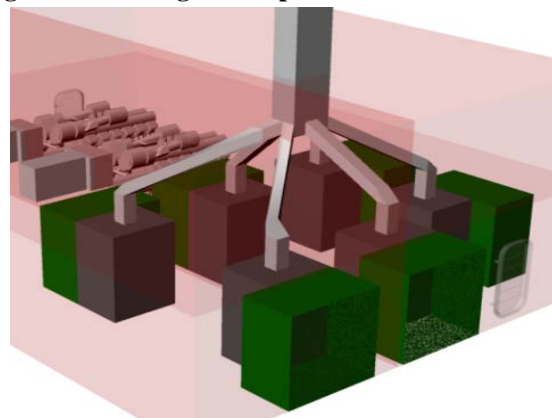


Figure 10: Arrangement option B.

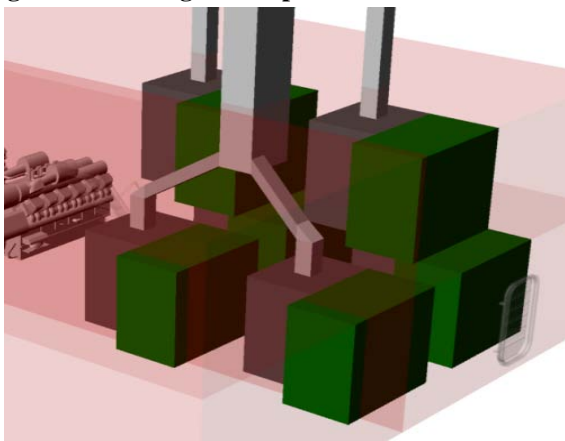


Option C considered the potential for mounting two of the modules on a mezzanine deck within the space removing the need to use the space with

a single deck height. The option, however, has similar space, access, and ducting issues to option A, and also has a higher packing density raising concerns over removal routes, ventilation and gas entrapment.

Option D was a variation of option C which had similar issues, but showed the advantage of placing the hot-box of two modules back to back. This arrangement allowed the grouping of the exhaust ducts together into a central stack with the air intakes split to either side potentially matching two air filtration system units on either side or on the rear of an exhaust stack.

Figure 11: Arrangement option C.



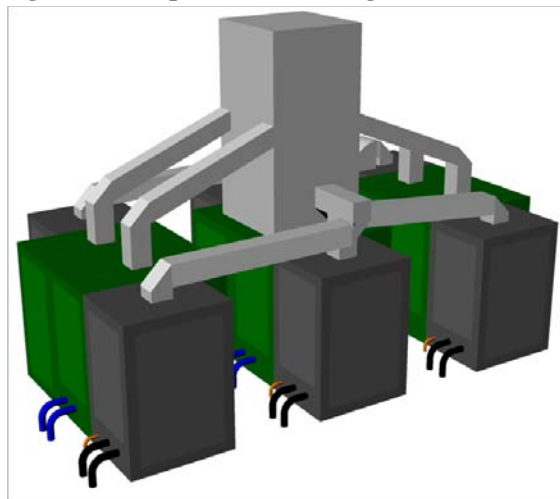
The selected option took the ducting arrangement benefits of option D but mounted the modules one deck higher on the main deck. The fuel cells are grouped together in pairs to optimize space while providing good levels of maintenance access. Displaced systems from the aft auxiliary machinery space and engine control space were re-distributed around the 2nd deck. Although the whole fuel cell space is now within only a single deck height, this option was believed to offer several advantages:

- The deck height, although low, could easily be raised with only minimal impact to visibility aft of the bridge.
- Designing for gas safety is considerably easier in the uppermost space in the ship.
- Ducting can be centralized with some of the system managed above the main deck within a stack arrangement incorporating the air intake and additional ventilation systems;
- The location opens up the possibility for easier access to the space; emergency ventilation

hatches for gas safety; and even the potential for construction of a module containing all the fuel cells that could then be dropped into the ship's structure late in build.

This final option retains a number of risk areas, however, including the impact of packing density on ventilation effectiveness and the limited access to the hot-box sub-modules. The option also relies on the ability to raise the deck height. Other risks include the validity of the proposed grouping configuration and the design of the matching Heating Ventilation and Air-Conditioning (HVAC) system. Routing of water, electric, and fuel supplies within the space also needs further analysis.

Figure 12: Proposed final arrangement



Arrangement lessons learned

In the process of developing a viable arrangement for the selected hybrid system on the T-AGOS 19(FC), several recurring design issues arose. These are described below and it is recommended that these should be considered in any fuel cell based design.

Ventilation & gas safety - Compartment ventilation with a fuel cell system is an area that needs focus on two fronts – gas safety and cooling. Some of these issues are aided by mounting fuel cells high in the design as achievable in T-AGOS 19. The designer must also ensure that the packing density of the fuel cell room supports good air flow and ensures cooling effectiveness.

Ducting - As is the case for a combustion engine, a fuel cell requires air intake and exhaust ducting.

HTPEM fuel cells have requirements similar to a diesel but SOFCs require considerably more air nearing the levels required by a gas turbine for a given power. This coupled with the larger number of units needed results in ducting design becoming a key design driver. Solutions such as arranging the modules for centralized ducting may avoid complex ducting configurations.

Access - The largest single component that could potentially be removed from a ship is an individual fuel cell stack. This should be considered early in a design and may restrict positioning of fuel cell modules. It was determined that the reformer sub-module is likely to need more maintenance than the fuel cell hot-box so maximizing access to this sub-module was desirable. It is important to note that the highlighted SOFC package layout, although volumetrically and gravimetrically characteristic of a SOFC solution, still has flexibility in its relative dimensions and proportions.

Compartment height - Although the current SOFC module is conceptual, the height of the module, its ducting requirements, and the potential need to lift out stacks are likely to require similar double-height space requirements to those required by current diesel or gas turbine systems.

Overview of final design concept

Table 4 reviews the final characteristics of the T-AGOS 19(FC) concept and compares them against the baseline ‘modern’ T-AGOS 19 design used as the basis for the weights and performance.

Table 4: Ship characteristics for T-AGOS 19(FC)

Characteristic	T-AGOS 19 [Modern]	T-AGOS19(FC) [Power sys. 4]
Lightship	-	+54tonnes
Full load displacement	3,455tonnes [maintained for constant trim]	
Length	LOA -71.5m; LBP- 57.9m	
Beam/Draft	29.4m / 7.6m	
Speed	~10knots sustained	
DGs	Caterpillar C32 V12 @ 993kW _e	
	× 4	× 2
SOFCs	None	250kW _e × 6
Installed power	3,972kW _e	3,486kW _e

Characteristic	T-AGOS 19 [Modern]	T-AGOS19(FC) [Power sys. 4]
Energy storage	None	3 × < 250kW
Propulsion	650kW DC motors × 2	
Power system architecture	Diesel Electric; 60Hz 600V AC with 6 pulse Silicon Controlled Rectifiers (SCR) DC drives	

CONCLUSIONS

The primary objective of this study was to determine the feasibility and implications of integrating fuel cell systems into a naval ship design. While integration challenges are evident in the T-AGOS 19, the study showed that their installation is feasible at moderate powers offering performance, emissions, and operational advantages to the ship and mission effectiveness.

SOFCs are likely to become the dominant high power fuel cell technology across all markets and, hence be attractive within the marine industry. However, the technology is still immature and will require work to optimize package design for often highly dynamic marine loads. Hybridization is likely and, hence, there is a need for energy storage development and the identification of shipboard uses for SOFC’s waste heat. The benefits of HTPEMs over a diesel system are valuable, but more limited. The technology is, however, less dependent on full hybridization. HTPEM is likely to offer a nearer term solution and, hence, be a good de-risking technology for the shipboard demonstration of liquid fueled marine fuel cells.

While the potential modularity benefits of fuel cells are often discussed, integration of the proposed modules highlighted that in many ways fuel cells are no different to current diesel systems in that they are likely to have similar positioning restrictions defined by access and air system ducting needs. These issues are amplified by the use of a larger number of lower power modules. In larger power applications there will be a need to develop a method of scaling fuel cell package design to avoid some of these issues. While considerable government sponsored technology development has been undertaken at the package sub-systems level, development is now at a stage where focused work is needed in formulating

potential marine package designs. It is hoped this study will help to inform this work.

The Navy's continued use of diesel fuel is justified on many levels but the impact of diesel use on fuel cells is noteworthy. Diesel reformer systems add complexity, cost, volume, and limited overall performance. Critically, they reduce overall system efficiency and in the case of HTPEM, to a level near that of a current diesel system. Use of lower sulfur liquid fuels removes some of the performance restrictions due to desulfurization systems but retains the fuel's energy density and supports hybrid operation with traditional diesel or gas turbine systems.

Despite only modest improvements in fuel consumption, overall emissions are reduced and, as tax structures change to reflect emissions, this has the potential to reduce future through life costs.

The study also highlighted that efficiency benefits are not necessarily the only justification for the use of fuel cells and that, in naval designs, their impact in areas such as self-noise show the potential to promote earlier adoption of fuel cell technologies.

Finally, the study demonstrated that the T-AGOS mission and the current T-AGOS SWATH design have the potential to offer a good demonstration opportunity for fuel cell, energy storage, and hybrid system technology.

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