# HYBRID NUCLEAR/FUEL-CELL SUBMARINE

BY

LIEUTENANT R. H. GOODENOUGH
*ROYAL NAVY*
*MINISTRY OF DEFENCE UK*

DR. A. GREIG
*UNIVERSITY COLLEGE LONDON, UK*

ABSTRACT

This paper describes the concept design for a hybrid nuclear/fuel-cell power plant for a submarine capable of nuclear powered high speed transits and fuel-cell powered slow speed operations. Additionally, the concept provides a fully air independent auxiliary power source to increase safety in the event of unplanned reactor shutdowns during under-ice operations and high sea states. The PEM fuel-cells provide 477kW, sufficient to power the 3,000 tonne submarine to a maximum sustainable 8 knot dived speed. Sufficient hydrogen and compressed oxygen is carried to provide 7 days fuel-cell operations at an average 6 knots; the fuel-cell system could either be distributed around the hull or inserted as a 5.6m plug. The selection of reversible fuel-cells allows onboard hydrogen and oxygen regeneration whilst in nuclear mode, negating the requirement for separate electrolysers. A full safety analysis failed to identify any risk from hydrogen although using compressed pure oxygen requires further investigation.

## NOMENCLATURE

| | |
|---|---|
| AIP | Air Independent Propulsion |
| BOP | Balance of Plant |
| GMP | Gas Management Plant |
| HCWT | Hydride Cylinder Water Tank |
| HPA | High Pressure Air |
| LOX | Liquid Oxygen |
| PEMFC | Proton Exchange Membrane Fuel-Cell |
| RFC | Reversible Fuel Cell |

## INTRODUCTION

Increasing environmental concerns and ever-dwindling fossil fuel reserves are demanding cleaner, more efficient power generation. As a result a number of recent ship designs have incorporated fuel-cells into their power plants as either a prime mover or an auxiliary power generator. This paper, based on part of a MSc thesis on the Integration and Safety of Fuel-Cells in Ships[1], describes the concept design for a hybrid nuclear/fuel-cell power plant for a submarine capable of nuclear powered high speed transits and fuel-cell powered slow speed operations. The design is reliant on a number of novel technologies and raises serious safety concerns; these are addressed as well as carrying out basic calculations to provide an indication of weight and volume requirements of the fuel-cell plant and to quantify the safety risk.

## BACKGROUND

The German U212/4 class has already proven the concept of a fuel-cell equipped conventional submarine (SSK) and therefore the opportunity was taken to investigate the integration of fuel-cells into a nuclear powered attack submarine (SSN). In addition to the reactor, SSNs have standby batteries and diesel generators to provide short and long term backup power during planned or unplanned reactor shutdowns. In order of increasing complexity and innovation the possible options for a fuel-cell equipped SSN are as follows:

- Option 1. Partially replace the battery with a fuel-cell system to provide longer duration/higher available power during a reactor scram (unplanned reactor shut-down for safety purposes) than is possible with existing lead-acid or lithium-ion batteries;

- Option 2. Replace the diesel generators with a fuel-cell system to reduce noise, vibrations, maintenance requirements and air dependence;

- Option 3. Design a hybrid nuclear/fuel-cell plant for a submarine capable of high speed transits and quiet operations. Though of a similar system design the fuel-cell system size would be significantly greater than that in Option 2 which would be sized for emergency power only.

In order to fully explore the concept of a hybrid nuclear/fuel-cell submarine Option 3 was selected for further investigation.

## REQUIREMENT

Fitting fuel-cells to a submarine, results in a significant operational advantage. With both hydrogen and oxygen stored onboard, a fuel-cell equipped SSK can remain submerged for many weeks without the requirement to snorkel and run diesel generators with the attendant signature issues (noise and visual signature of the snort induction and diesel exhaust masts). Whilst a SSN has no requirement to snort and can therefore remain submerged indefinitely (personnel dependent) the noise of continually running pumps and the large quantity of waste heat rejected to the sea significantly increase the submarine's signature. A fuel-cell equipped SSN could shut down the reactor for quieter performance during operational patrols, remain on task following a scram giving ships staff time to rectify the defect and recover to normal reactor operation and maintain a fully air independent auxiliary power source for under-ice operations.

FIG.1 – RUBIS, COLLINS AND U212 CLASS SUBMARINES[2]

**Other Benefits**

- Removal of dangerous (in a fire) hydrocarbon fuel;
- Nil emissions when on auxiliary power source therefore future proof to IMO legislation;
- Easier build and maintenance as the components of the fuel-cell system are small and can be removed through existing hatches. The exception is the metal hydride cylinders depending on whether they are located internally or externally. This is in contrast to diesel engines which require hull cuts for removal;
- During an emergency, surface compressed oxygen tanks could contribute to emergency blow air;
- No requirement for oxygen candles in a DISSUB environment thus reducing the potential for a HMS TIRELESS type fire and explosion;
- Fuel-cells can be rapidly "switched on" following a scram thus significantly reducing the required battery size, diesels can only be run once the submarine reaches the surface and the snort mast has been raised.

In general these points give the platform greater flexibility and reduce the risk of mission compromise but the limited energy density of hydrogen and oxygen storage results in a lower fuel-cell range than that available from diesel generators.

## SUBMARINE CHARACTERISTICS

In the absence of a defined operational requirement a number of assumptions were made as to the SSN's role, size and power requirements. The exact displacement was not required but was assumed to be similar to a small SSN/large SSK (RUBIS/COLLINS class, i.e. 2–3,000 tonnes) making it approximately twice the displacement of the U212/4 class.

The operating profile was assumed to consist of high speed transits under nuclear power to operational patrol areas where the fuel-cells would take over and the reactor shut down into a stand-by state. Despite recent advances critical nuclear reactors almost always require some rotating machinery running and hence can never be totally silent. With an appropriate reactor design (i.e. encompassing natural circulation cooling when shut down) such a submarine could rival the acoustic signature of a SSK.

Therefore, the fuel-cell system has been sized for the typically low speeds used on operations. Though not considered within this investigation the reactor would be of a suitable power to achieve the required maximum transit speed and though reduced, a battery bank would still be required for immediate stand-by power in the event of a reactor scram and sprint speeds whilst running on fuel-cells. It is recognised that this concept of operations is impossible with today's generation of reactors and hence would require a new design. However, next generation naval nuclear power plants are already heading in the direction of low shut down power and increased passive safety, both of which are major requirements for such a stop/start operating concept.

## POWER CALCULATIONS

The following specifications were chosen, roughly equivalent to the COLLINS class SSK:

TABLE 1 - *Submarine Specifications*

| | |
|---|---|
| Effective length | 75 m |
| Diameter | 8 m |
| Surface area | 1885 $m^2$ |
| L/B ratio | 9.375 |
| Block coefficient | 0.72 |

These figures were used to determine a power speed curve for the submarine as described in Concepts in Submarine Design[3]:

$$P_E = 1/2.\rho.V^3.S_{ref}.C_{TS} \quad (1)$$

Where $P_E$ = effective power, ρ = sea water density, V = submarine speed, $S_{ref}$ = total wetted surface area and:

$$C_{TS} = C_{FS} + C_R + C_A \quad (2)$$

$C_R + C_A$ are obtained from graphs (ref [3] pp.294) depending on the L/B ratio and block coefficient and:

$$C_{FS} = 0.075/(\log_{10}Re_L - 2)^2 \quad (3)$$

Using a seawater density of 1025 $kg/m^3$ and kinematic viscosity of $1x10^{-6}$ $m^2/s$ the power-speed curve was calculated, the low speed section of which is at Figure 2. Selecting a maximum sustained operational speed of 8 knots (short term sprints can be achieved using the battery although it should be noted that most fuel-cells are capable of considerable short term overload) results in an effective power of 187kW. Assuming the following efficiencies: propeller 75%, motor 95% and power electronics 95% results in an installed propulsive power requirement from the fuel-cells of 277kW. By comparison the U214 class has 240kW of fuel cells installed. It is interesting to note that the air breathing PEMFC developed for automobiles are rated in the range of 30 - 50kW.

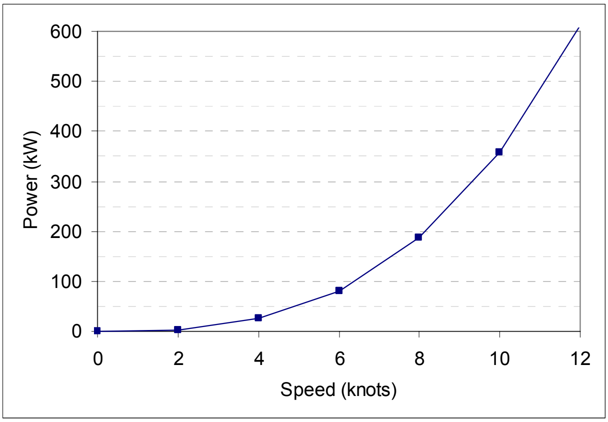


FIG.2 – LOW SPEED POWER-SPEED CURVE

It is assumed that there is a 100kW hotel service load (obtained from similar size UCL Submarine Design Exercise concepts) and in the absence of any data for an appropriately sized nuclear power plant the reactor safety load was estimated as also equalling 100kW; **note this figure is not representative of current class SSNs**. Therefore, the fuel-cells are required to produce a total of 477kW. However, the average speed on operations was assumed to be 6 knots which equates to 81kW effective power and a total average power of 320kW; this figure was used for duration calculations. In the absence of a dedicated mission profile it was assumed that the submarine would be required to conduct fuel-cell operations for a period of up to 7 days.

## POWER PLANT

An IFEP plant has been selected with a single reactor driving 2 steam turbo-generators feeding onto a DC busbar, also supplied from four 120kW fuel-cell stacks providing a total of 480kW. No diesel generators are required with all auxiliary power coming from the fuel-cells if needed. All propulsion, ship, reactor, weapon and hotel service loads are supplied from the busbar with propulsion being achieved with an appropriate electric motor mounted directly onto the shaft as on contemporary SSKs.

### Fuel-Cell Selection

In order to minimise thermal signature, provide adequate start up and response times and reduce onboard cooling requirements, a low temperature fuel-cell would be required. Of these, Proton Exchange Membrane Fuel-Cells (PEMFCs) provide the high power density required by submarines and though a pure oxygen breathing version differs to the air breathing types being developed by the automotive industry they can still benefit from technology transfer. Balance Of Plant (BOP) systems (thermal, gas and water management systems, control circuitry etc.) were assumed to occupy the same volume again as the fuel-cell stacks. Air-breathing PEMFCs have an efficiency range of 45-60% although the higher values are projected only. As part of the MSc thesis[1] a literature survey was undertaken and realistic, representative efficiency values determined for each major fuel-cell type. 49% was settled on for the PEMFC although as pure oxygen increases efficiency by approximately 20%[4] a total system efficiency of 69% was used for calculations.

## Fuel Storage Selection

The chosen fuel storage system must be volumetrically efficient owing to the restricted space available within a submarine, Table 2 summarises the potential options. The peculiar packing properties of hydrogen are also demonstrated, for example a litre of water contains more hydrogen than a litre of pure liquid hydrogen. Compressed and liquid hydrogen storage are considered unsuitable, the former is volumetrically inefficient and the latter requires a significant plant to achieve 70°K to liquefy the hydrogen whilst both require significant containment vessels. The practical alternatives are either metal hydride or fossil fuel reformation. Fossil fuel reformation produces carbon dioxide that must be disposed of either through absorption or overboard discharge.

TABLE 2 – *Comparison of Hydrogen Vectors (excludes containment vessels)*[5]

| | State | Symbol | Atomic mass | Density $kgm^{-3}$ | Volume (litre) and mass (kg) per kg of Hydrogen | |
|---|---|---|---|---|---|---|
| Hydrogen | Gas (STP) | $H_2$ | 2.016 | 0.095 | 10,500 | 1.00 |
| Hydrogen | Gas(250bar) | $H_2$ | 2.016 | 23.75 | 42.00 | 1.00 |
| Hydrogen | Liquid (70K) | $H_2$ | 2.016 | 71 | 14.08 | 1.00 |
| Water | Liquid | $H_2O$ | 18.015 | 1000 | 8.94 | 8.94 |
| Methanol | Liquid | $CH_3OH$ | 32.042 | 794 | 10.01 | 7.95 |
| Ethanol | Liquid | $C_2H_5OH$ | 46.068 | 798 | 9.55 | 7.62 |
| Dodecane (Diesel)* | Liquid | $C_{12}H_{26}$ | 170.340 | 748 | 8.69 | 6.50 |
| Ammonia | Liquid (300K 10bar) | $NH_3$ | 17.032 | 623 | 9.04 | 5.63 |
| Titanium hydride | Solid | $TiFeH_2$ | 105.763 | 5470 | 9.59 | 52.46 |

* Dodecane is accepted as a representative average of the many constituents of Diesel

The former requires dedicated storage space and the latter can increase the submarine's signature. Therefore, metal hydride storage was considered the best option; its two biggest disadvantages (cost and weight) are less relevant to a submarine than for other applications. Submarine designs tend to be volume rather than weight driven and often have ballast added to achieve the desired buoyancy and stability conditions. So where the low gravimetric density of metal hydride storage is a big disadvantage for most transport applications it is less so for a submarine. The metal hydride cylinders as used in the U212/4 class are considered appropriate. Solid storage of hydrogen using metal hydrides or carbon nanotubes is an area of technology that is developing rapidly and significant improvements in performance can be expected in the next decade.

FIG.3 – U212/4 CLASS METAL HYDRIDE CYLINDERS[6]

## Oxidant Storage Selection

Unlike the majority of fuel-cells which use atmospheric oxygen and accept the consequential loss in efficiency for a "free" fuel source, submarine fuel-cells are designed to use a pure oxygen supply. This can either be stored as liquid oxygen (LOX) or as a compressed gas. LOX has a volumetric compression ratio of 860:1 and compressed oxygen of anywhere between 200:1 and 300:1 according to the selected storage pressure. As a result the obvious choice, and that chosen by the U212/4 designers, is LOX. However, as shall be seen below, a liquefaction plant would need to be carried in addition to the storage tanks and as they are bulky and maintenance intensive compressed oxygen was preferred. Oxygen bottles similar to existing UK SSN high pressure air (HPA) bottles of approximately 3.2m$^3$ volume and 500kg mass were used for calculations.

## Reactor Safety

In order to guarantee reactor safety there must be an immediate notice back-up power source in the event of a reactor scram (unplanned shutdown) capable of providing sufficient power until the reactor can be restarted or a suitable port reached. Current SSNs divide this task between a battery and diesel generators. The battery is used for immediate power and lasts long enough for the majority of scram events. In serious cases where longer term power is required the diesel generators are used but these can only be started once the submarine is near the surface and has access to air for the diesels. Broaching the surface may well compromise a mission and not be possible at all under ice.

Were fuel-cells used as the back up power source a small battery would still be required to provide instantaneous power following a scram before the fuel-cell system can be started. This battery would also be used to provide a high speed sprint capability when the reactor is shut down. In addition, sufficient hydrogen and oxygen must be carried to ensure that there is always power available following a scram. If supplies were limited to a single charge of the onboard tanks as per the U212/4 class then reactor safety could be compromised following a series of multiple scrams. Therefore, it is necessary to provide onboard recharging facilities for the oxygen and hydrogen consisting of electrolysers and compressors as required. This has the added advantage of making the submarine independent of shore refuelling.

Without diesel generators the submarine's emergency power comes from the fuel-cells. Therefore, a proportion of the hydrogen and oxygen must be set aside for emergencies in addition to that used on operations. This must be sufficient to provide 137kW for 7 days, i.e. sufficient power to achieve 4 knots (37kW) and maintain an assumed absolute minimum of 50kW each for the reactor and hotel service loads.

**Fuel-Cell System**

A basic system sizing was carried out. In order to minimise the volume taken up by the fuel-cells and electrolysers a reversible PEMFC/electrolyser system was selected (henceforth referred to as RFC). It is understood that this technology is still immature but can be expected to develop rapidly over the next few years as NASA develops it for space applications. Horizon Fuel-Cell Technologies produce a 0.6W single cell RFC for laboratory demonstration with the following specifications:

TABLE 3 – *Reversible PEMFC and Electrolyser Specifications*

| | |
|---|---|
| Rated net power | 0.6 W |
| Rated net current | 1 A |
| DC voltage range | 1.65 V |
| $H_2$ production | 10 ml/min |
| $O_2$ production | 5 ml/min |
| Volume | $1.4 \times 10^{-4}$ m$^3$ |


FIG.4 – HORIZON FUEL-CELL TECHNOLOGIES 0.6W REVERSIBLE FUEL-CELL[7]

The majority of this fuel-cell's depth is taken up by the retaining plate structure, the size of which is largely independent of the number of cells stacked up. Therefore, a linear relationship cannot be used in sizing a larger fuel-cell stack from this example. As a result the (admittedly large) assumption was made that an appropriate device need be no larger than a dedicated PEMFC with each 120kW fuel-cell stack assumed to be the size of a Siemens BZM120 (as fitted to the U214 class), namely 500 litres and 900kg each[8].

FIG.5 – SIEMENS BZM120 PEMFC FUEL-CELL AS FITTED TO THE U214 CLASS, AROUND 1.4M LONG[6]

Any size increase associated with the reversible nature of the fuel-cell is assumed to be offset by continuing improvements in PEMFC power densities. BOP volume is assumed to be equal to the fuel-cell stack.

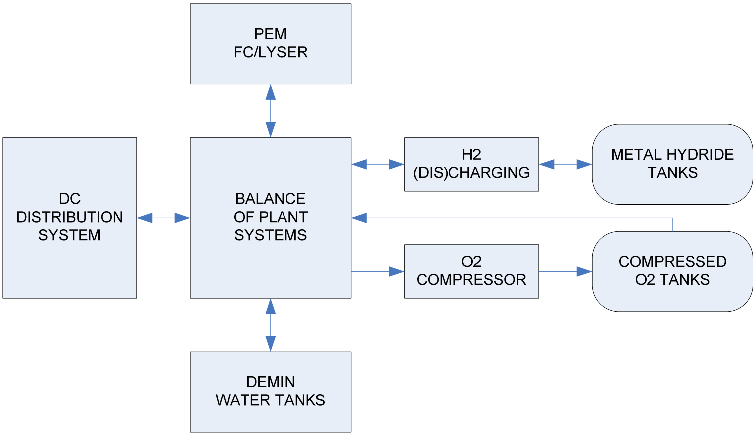


FIG.6 – HYBRID SSN/FC SUBMARINE FUEL-CELL SYSTEM SCHEMATIC

In order to release hydrogen from the metal hydride heat must be applied and vice versa; therefore the charging/discharging mechanism requires a heating/cooling system. Both electrolysers and pressurised water reactors require demineralised water and can therefore share the same water tanks. A single reverse osmosis plant such as the Derwent RO4/2 is sufficient to meet the electrolyser water demand. This would have to be fitted in addition to normal water production needs otherwise water for other uses would be limited during the 2 days required to replace the hydrogen and oxygen used during operations. Additional electrolysers would be required to produce oxygen for crew consumption during SSN mode with a proportion of the compressed oxygen used for the same purpose when in fuel-cell mode.

## System Sizing

The calculations were split into operational and emergency modes. It was found that oxygen required for crew breathing is negligible compared with that for fuel-cells and has no effect on total numbers of oxygen cylinders required.

TABLE 4 – *Metal Hydride Cylinder and $O_2$ Bottle Numbers*

| Scenario | Metal Hydride Cylinders ($H_2$) | $O_2$ Bottles | Water Production (litres/manday) |
|---|---|---|---|
| Operations | 42 | 14 | 43 |
| Emergencies | 18 | 6 | 18 |
| Total | 60 | 20 | / |

Thus a total of 60 hydride cylinders and 20 oxygen bottles are needed. In order to allow cooling and heating of the metal hydride cylinders (required for charging/discharging) and to swiftly detect any leaks, the cylinders are located in seawater tanks fitted with a sounding tube connected to a detector thus providing an immediate leak indicator. The $O_2$ bottles are positioned alongside the HPA bottles within the ballast tanks, the volume of which would require a corresponding increase. On operations the RFCs produce 3 tonnes of water a day, equating to 43 litres/man/day for the 70 man crew (minimum required 23 litres/man/day[9]). At emergency power levels the RFCs still produce 18 litres/man/day which is sufficient for drinking and cooking. In electrolyser mode the RFCs produce 477m$^3$ of hydrogen and 238m$^3$ of oxygen per hour which, taking into account continued crew oxygen consumption, results in a 3 day recharge.

The total volume of the fuel-cell system (RFCs, $H_2$ cylinders, $O_2$ bottles, $O_2$ compressors, RO plants, BOP and a 100% access envelope) is 285m$^3$. This could either be distributed around the hull as shown in Figure 7 (preferred owing to the increased survivability and electricity/water generation capabilities of the fuel-cells in survival situations) or inserted as a dedicated 5.6m plug. The mass is 313 tonnes, roughly 10% of the total displacement. Although exact figures are difficult to obtain very approximate calculations show that this is approximately half the volume and three times the mass of the now-redundant diesel generators and diesel tanks.

## SAFETY ANALYSIS

### Hydrogen Explosion

There are three areas that hydrogen could be released from: the hydride cylinder water tanks (HCWTs), the RFC compartments and the transfer pipework between the two.

*Hydride Cylinders*

The metal hydride cylinders are located low down within the pressure hull. Should a leak develop in a metal hydride cylinder the hydrogen would expand out of the leak site, thus cooling down the surrounding hydride. As the hydrogen release process is endothermic the leak would self-seal. Should a pipework fitting within a HCWT fail hydrogen would displace the water up the sounding tube. The HCWTs temperature ranges from 4°C (lowest realistic sea temperature) to 40°C (heated during discharge) and thus the water expands/contracts by ~1% over an operating cycle. Assuming each HCWT volume is 30% larger than the 30 cylinders inside, each HCWT would hold 10.8m$^3$ water which would expand by 0.1m$^3$ during an operating cycle. The hydrogen leak detector would be designed to only alarm if more than this volume of water was displaced and therefore the worst case undetected leak is 0.1m$^3$, a trivial amount.

Should more hydrogen be released it would be detected and the contents of the containment tank could be flushed overboard using the trim or ballast system. As a result the risk from the metal hydride tanks is considered negligible.

*RFC Compartments*

The RFC compartments would normally be sealed with the exception of a ventilation supply and exhaust each of which would be fitted with flame suppressors and atmosphere monitoring equipment. All ignition sources would be properly sealed and rated for gas-dangerous compartments.

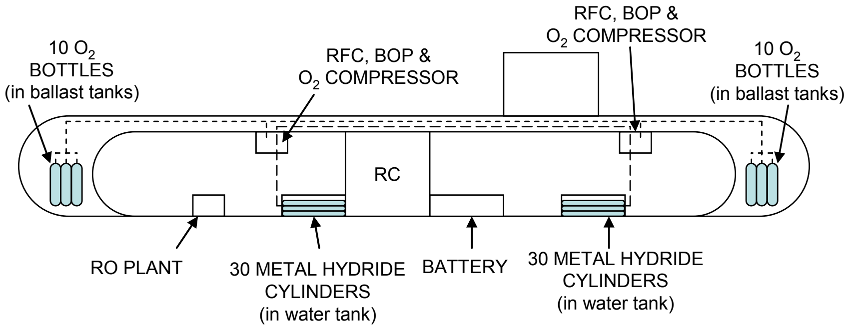


FIG.7 – HYBRID SSN/FC SUBMARINE LAYOUT

Should hydrogen be detected the RFC would automatically shut down, isolation valves shut and a purge cycle started as with the RN's Gas Management Plants (GMPs). Ventilation would continue in order to diffuse the hydrogen throughout the submarine; each RFC compartment is only 0.3% of the internal volume of the submarine, therefore even if a compartment was 100% full of hydrogen the lower flammability limit submarine wide would not be reached. Existing $CO/H_2$ burners would be sufficient to remove any residual hydrogen from the atmosphere.

Were the detection system defective a major leak would still be identified by pressure drop or power loss but a small pinhole leak might be missed by the control systems. Assuming a flow meter comparison system has an accuracy of 1% the trip setting would be set at 5% to allow for transient induced system lag. The maximum hydrogen flow rate in each half of the system is 42l/s, therefore a leak up to 2.1l/s might go unnoticed. Each RFC compartment would contain 8.6m$^3$ free volume and a ventilation flow rate of 72l/s assuming the air is turned over 30 times an hour (the value specified within provisional Lloyd's Register rules for gas fuelled ships[10]). As this is a far higher turnover of air than the leak a dangerous hydrogen build-up would not occur provided the ventilation system has been adequately designed to minimise air pockets, particularly at the top of the pressure hull where the $H_2$ is likely to collect. Even without the fitted $CO/H_2$ burners it would take over 11 days to reach the 4% lower flammability limit within the whole submarine.

*Hydrogen Pipework*

The transfer pipework would be double walled, isolable in the HCWTs and RFC compartments and with no fittings between the two. Internal pipework has been minimised by positioning the HCWTs underneath the RFC compartments and the fore-aft connection routed outside the pressure hull, under the Casing. As a result the risk from the hydrogen pipework is considered negligible. Because hydrogen gas consists of such small energetic molecules special pipework is required to avoid hydrogen embrittlement and welds and seals must be extremely tight.

## Hydrogen Fire

Should a hydrogen fire develop in a RFC compartment (the only credible place it could) the difficulty would most likely come in detection as hydrogen burns with an almost invisible flame. It is worth noting that submariners are experienced with equally hard-to-find steam leaks. Should the 2.1l/s leak calculated above ignite on exit from the leak site (i.e. before it has dispersed) it would produce 23.0kW. Using:

$$\Delta t = \frac{P}{\dot{m}C_p} \tag{4}$$

results in a 2.2°C temperature rise per second which would be easily detected by the fire detectors already fitted throughout RN submarines. The system would be automatically shutdown and a fixed $CO_2$ drench system activated. With proper design the chances of other materials combusting (and hence producing smoke) can be minimised, the only other result from such a fire would be the production of a small amount of water vapour (1.7cc/s). It is the heat from a hydrogen fire that is the main danger followed by oxygen consumption, unlike a hydrocarbon fire where the main danger is the production of toxic gases such as carbon monoxide and soot which can rapidly poison the confined volume of a submarine.

As a result the risk from a hydrogen fire in the RFC compartment is considered negligible.

## Hydrogen Asphyxiation

The effects of oxygen starvation range from a reduction in coordination (15-19%) to coma and subsequent death within 40 seconds (4-6 percent)[11]. For the purposes of this investigation it is assumed that 16% is the cut-off point below which injury may occur either from cellular oxygen starvation or as a result of reduced coordination and decision making. For the oxygen concentration to fall by 4% to 16% requires 20% of the compartment volume to be displaced by hydrogen, i.e. 5 times the lower flammability limit for hydrogen. As it has already been proven that the lower flammability limit cannot be reached there is no danger of hydrogen asphyxiation occurring in general conditions. Furthermore, as hydrogen is so buoyant the usual reaction to oxygen starvation is to collapse thus probably lowering the head below the hydrogen cloud. The only exception to this could be during a tank entry to the HCWTs for maintenance or inspection; under these circumstances normal confined space entry procedures would mitigate the asphyxiation risk to tolerable levels.

## Oxygen Reactivity

Oxygen is a highly reactive gas and when in a pure form can react extremely violently with flammable materials such as oil and grease. By citing the RFCs adjacent to the oxygen compressors, leading the compressor discharge pipework immediately outside the pressure hull and running the fore and aft connection under the Casing the risk of an internal oxygen leak is minimised as far as possible. However, if a leak should occur the risk of fire would be mitigated by maintaining the RFC compartments as “clean” spaces with no flammable materials allowed within. Oxygen can also be toxic if the partial pressure exceeds about 0.5bar (in standard atmosphere it is 0.2bar). As the tanks are stored external to the pressure hull a significant leak into the submarine is unlikely and even if an entire tank were discharged into the submarine the partial pressure of oxygen would only increase to 0.27bar.

In the authors’ opinion the risk posed by compressed oxygen is the greatest risk of the design and a detailed investigation would have to be carried out prior to any further design work.

## Increased Air Independent Propulsion Redundancy

The safety analysis has concentrated on disproving, mitigating or highlighting potential problems; however, their safety advantages must also be considered. These comprise of a number of factors such as greater reliability and reduced temperatures; however, the advantage that stands out the most is the provision of a second Air Independent Propulsion (AIP) system.

Submarines have an extremely low reserve of buoyancy and with a nearly circular cross-section they are liable to roll heavily, causing equipment damage and crew exhaustion, thereby increasing the risk of a potentially fatal incident. In times of rough weather or conflict it is far safer for the submarine to remain deep underwater in the environment for which she is optimised; however, current SSNs are either forced to the surface or periscope depth if they have to run their auxiliary diesels.

An AIP fuel-cell system would not only allow the submarine to remain dived following reactor scrams but would also provide the confidence to engage in unfettered under-ice operations. Whilst SSNs have been operating under the Arctic ice cap since USS NAUTILUS first did so in 1957, there is a caveat. The chance of a reactor scram has meant that such voyages always come with the added degree of risk that a suitable polynia (open area of water within the ice) might not be found within range of the submarine's batteries. The recent interest expressed in the mineral resources believed to be under the Arctic sea bed has led to a correspondingly increased interest in the importance of controlling these waters. A hybrid nuclear/fuel-cell submarine would be able to operate there with a substantially greater margin of safety than contemporary SSNs can achieve.

In an emergency the compressed oxygen could also be used to replenish the air without the need to burn oxygen candles. The recent fatalities onboard HMS TIRELESS, as well as the final cause of death for the KURSK survivors demonstrate the advantages this would bring.

## CONCLUSION

Fuel-cells offer such substantial economical, political, environmental and operational advantages that they will eventually achieve widespread usage. Whilst the automotive and stationary power generation industries are leading their development the technology is likely to be subsequently transferred to the marine industry. The authors believe this hybrid nuclear/fuel-cell submarine concept to be revolutionary with the possibility of potential dramatic improvements in operational capability and submarine safety. However, a number of design tradeoffs must be fully explored before the exact characteristics of such a submarine could be finalised. As a result it is recommended the following are investigated:

- The design tradeoffs between liquid and compressed oxygen storage, in particular with regard to safety;
- The specific temperature requirements for cooling and heating metal hydrides during charging and discharging, in particular with regard to Worldwide variations in seawater temperatures;
- The size, efficiency and reliability tradeoffs between a reversible fuel-cell system or separate PEMFCs and electrolysers;
- The effect of shock upon fuel-cells and their associated systems (not discussed in this report due to lack of information but of critical importance to submarine designers);
- The reliability and chance of failure of component parts of each fuel-cell system;

- Finally, the balance between fuel-cell and reactor powers would require settling for each design depending upon the operational profile and concept of operations.

**ACKNOWLEDGEMENTS**

The support of the following organisations is gratefully acknowledged:

- University College London, in particular from Dr Richard Bucknall, Tim McDonald, Tristan Smith and Colin Wormald;

- Lloyd's Register of Shipping, in particular from Norman Rattenbury and Ed Fort;

- The Royal Navy.

*References*

1. GOODENOUGH, R.H., 'The Integration and Safety of Fuel Cells in Ships', University College London, 2007.
2. http://www.naval-technology.com/projects/#Submarines last accessed 1/9/07 at 1435.
3. BURCHER, R., RYDILL,L., 'Concepts in Submarine Design', Cambridge University Press, 1994, pp.291.
4. BÜCHI,F.N., REUM,M., FREUNBERGER,S.A., DELFINO,A., 'On the efficiency of automotive $H_2/O_2$ PE fuel-cell systems', 3rd European PEFC Forum, July 2005.
5. GREIG, A., 'Fuel-cells and issues for their use in warships', Proc IMarEST 2003, Pt.B, No.B3, pp.9-20.
6. HAMMERSCHMIDT, A.E., 'Fuel-cell propulsion of submarines', Intl. Conf. on Hydrogen and Fuel-Cell Technologies, Munich, 2006.
7. http://www.thehydrogencompany.com/products_54-226.html last accessed 1/9/07 at 1456.
8. BUCKINGHAM, J., HODGE,C., HARDY, T., 'Submarine Power and Propulsion - Trends and Opportunities', Pacific International Maritime Conference 2008.
9. UCL Ship Design Data Book, 2007.
10. 'Provisional rules for the classification of methane gas fuelled ships', Lloyd's Register, Jan 2007.
11. http://ehs.ucdavis.edu/hs/ConfSpace/index.cfm last accessed 30/8/07 at 1518.

**BIBLIOGRAPHY**

1. LI, X., 'Principles of Fuel-Cells', Taylor and Francis, New York/London, 2006.

2. LARMINIE, J., DICKS, A., 'Fuel-cell systems explained', Wiley, New York, 2003.

**AUTHOR'S BIOGRAPHY**

**Rob Goodenough** is a Technology Development Officer in the Fleet Wide Engineering IPT, UK MoD, with a special interest in Surface Ship and Submarine Motion Control. Previous appointments have included an MSc in Marine Engineering at University College London and Section Officer and Nuclear Reactor Supervisor onboard the nuclear-powered attack submarine HMS TURBULENT.

**Alistair Greig** was trained as a Marine Engineer by the UK MoD (RCNC) studying at University College London (UCL). He was appointed as a lecturer in the Department of Mechanical Engineering at UCL in 1989 and a Senior Lecturer in 2001. His research interests include dynamics of ballast water tank systems and marine propulsion system design.