FUEL CELL APPLICATIONS FOR SURFACE SHIPS

(A SPECULATIVE PAPER)

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ABSTRACT

This article examines the possibility of fitting fuel cell generators in place of diesel-electric generators in surface ships. It considers the necessary equipments and compares their performance and size with typical diesel generator sets.

Introduction

As the sub-title indicates, this is a speculative article which expresses the views of the author and does not necessarily represent those of his Department. It examines future possibilities for using fuel cell electric generation to replace diesel-electric generators on board surface ships.

Fuel cells chemically convert fuels into direct current electrical energy and, unlike heat engines, are not limited by the Carnot cycle. Although still an emerging technology, small and high reliability fuel cell plants have been built for space applications and large systems as demonstrators for commercial power generation[1,2]. Fuels generally have to be converted to usable hydrogen which is combined with oxygen in the fuel cell to produce water and usable electric power through a load.

A submarine system based on metal hydride and liquid oxygen stores has been developed in Germany[3], and a prototype system capable of generating 100 kW is being fitted into an extended Type 201 submarine (U1) for the Federal German Navy[4]. For surface ship applications it would be highly desirable to employ fuel cells which can readily operate on diesel oil reformate (assumed to be a mixture of hydrogen and carbon dioxide) as a fuel, and air as an oxidant. This would require the use of on-board diesel reformers.

Advantages and Disadvantages

The advantages of replacing diesel generators with fuel cell systems are seen to be:

(*a*) high efficiency (45% to 50%) resulting in increased endurance if diesel oil can be utilized as the fuel;

(*b*) lower noise output (no moving parts except for pumps for fuel/air supplies) and lower IR signature;

(*c*) lower running and maintenance costs;

(*d*) savings in weight;

(*e*) direct generation of d.c. for supply to low/medium speed electric propulsion motors;

(*f*) the ability to disperse fuel cell generators where required throughout the ship;

(*g*) a preliminary estimate indicates that there is no increase in through-life costs when compared with diesel generators.

Disadvantages of fuel cell systems are seen to be:

(*a*) new development and higher procurement costs than diesel-generators (about three times for procurement);
(*b*) the need for d.c. to a.c. conversion for auxiliaries;
(*c*) present uncertainty of the ability to reform diesel fuel into gases suitable for use with fuel cells;
(*d*) the need to store a special fuel such as methanol if diesel fuel cannot be reformed suitably;
(*e*) the need for new training of naval personnel.

Fuel Cells

Fuel cell technology and performance is very dependent on the type of fuel cell, as well as on the type of fuel and oxidant used. Studies have indicated that cells using either solid polymer electrolyte or alkaline electrolyte will best meet a submarine's needs, due primarily to high power density, low temperature operation and fast start up times[1]. Individual fuel cells must be combined into stacks and it has been found that careful attention needs to be paid to the control of fuel, waste products and power management for any system to be successful.

Several types of fuel cell could be developed for surface ship application, but initially considerations will be restricted to those that are furthest advanced and which can readily use air as an oxidant. Marine fuel such as diesel oil would need to be reformed into a reformate consisting of a mixture of hydrogen and carbon dioxide which could then be used directly in the fuel cell stacks. These criteria limit us to two choices, namely Phosphoric Acid Fuel Cells (PAFC) and Solid Polymer Fuel Cells (SPFC), the latter being preferred due to their higher power density and fast start up times. Other longer-term development possibilities[1,2] are Direct Methanol Fuel Cells (DMFC), Molten Carbonate Fuel Cells (MCFC) or Solid Oxide Fuel Cells (SOFC), and all three offer the possibility of using fuels directly without the need of reforming into usable hydrogen and waste gases. It is possible that both MCFCs and SOFCs may be able to use diesel fuel directly by internal reforming.

PAFCs have been widely tested in land-based demonstrators varying in power output from 40 kW to 4.5 MW and using reformed natural gas as a fuel[1,2]. SPFCs with power output up to 5 kW have been built and larger cell stacks are being developed. Solid polymer electrolyte technology is also employed for electrolysers.

Fuel Reformers

Fuels such as alcohols and hydrocarbons may be reformed to produce a reformate gas consisting of hydrogen and carbon dioxide. This reformate may be fed to the fuel cells where the hydrogen combines with oxygen to form water, and usable power is produced. In practice the fuel process involves steam reforming to produce carbon monoxide and hydrogen, followed by a water gas shift reaction (using steam) to produce further hydrogen and carbon dioxide e.g.:

(*a*) $CH_3OH = CO + 2H_2$ and $CO + H_2O = CO_2 + H_2$ with an overall reaction of $CH_3OH + H_2O = CO_2 + 3H_2$ for methanol,
(*b*) $C_nH_{2n+2} + nH_2O = (2n+1)H_2 + nCO$ and $nCO + nH_2O = nCO_2 + nH_2$ with an overall reaction of $C_nH_{2n+2} + 2nH_2O = (3n+1)H_2 + nCO_2$ for a hydrocarbon such as diesel fuel. The reaction is endothermic and heat would need to be provided by burning a small quantity of diesel fuel.

Steam reforming, as it involves the use of steam, requires feed water. However, each mole of hydrogen produced from the fuel reacts with oxygen in the fuel cells to produce a mole of water:

$$2H_2 + O_2 = 2H_2O$$

Thus, if the water requirement per mole of hydrogen produced is less than unity, then the fuel cells can provide water for both reforming and other purposes. Methanol requires less water than other candidate fuels, more water being required with increase in carbon number. Based on stoichiometric reactions, water needed/mole hydrogen produced is 0.33 for methanol and 0.65 for $C_{12}\ H_{26}$ (an assumed model for diesel oil). In practice however, except for methanol, it is necessary to conduct the reaction in an excess of steam in order to suppress the deposition of carbon on to the catalyst used in the reforming process. Thus, unless the excess water is removed downstream, more will be required than is produced by the fuel cells. Methanol is unusual in that no excess steam is required because it readily thermally decomposes into carbon monoxide and hydrogen which does not lead to carbon deposition.

Another problem associated with fuels such as diesel oil is the possible, but unlikely, presence of additives in readily available products that could poison the catalysts used in the reformer. Desulphurization of the diesel oil is also necessary to avoid poisoning the fuel cell catalyst and this could possibly be achieved after the steam reforming reaction by hydrogenating the sulphur compounds using some of the product hydrogen, thus removing the sulphur as hydrogen sulphide.

The U.S. Department of Defence has funded work on reformers for diesel oil (not in a marine application), but no details of size etc. are known[5].

This programme, for the U.S. Air Force, included the demonstration of processes capable of converting diesel fuel to fuel cell quality hydrogen. It should be noted however that both PAFCs and SPFCs are capable of using directly the reformate mixture (assumed to be mainly hydrogen and carbon dioxide) from such a process. Three demonstrators (Energy Research Corp. (ERC), International Fuel Cells (IFC) and R. M. Parsons Co. (RMP)) were funded in 1985 and run, although the IFC version failed after 20 hours. The ERC plant employed desulphurization followed by steam reforming and completed 400 hours of satisfactory performance. The RMP plant used steam reforming followed by autothermal reforming and sulphur removal; this demonstration was inconclusive due to 'mechanical problems' but the process was considered to be a viable contender[5].

System Engineering

Fuel cells are readily assembled into stacks and stacks into modules and this has been successfully achieved for PAFC systems up to 4.5 MW [1,2]; technical risk is predominantly associated with system management. The risk involved in scaling up SPFCs from the present 5 kW to larger modules for use in practicable systems is therefore assessed as low. A 50 kW to 100 kW module is the minimum thought to be suitable for building up into systems in excess of 1 MW.

In order to power on-board systems it would be necessary either to convert them to d.c. or, as is more likely, to provide d.c. to a.c. conversion equipment. Solid state d.c. to a.c. conversion equipment has been successfully demonstrated with fuel cell systems built as demonstrators for commercial power generation[2] and no problems are foreseen.

There is some technical risk involved with the reforming plant for diesel oil. Additionally, the reforming process cannot readily be moderated to provide fuel to the cells for the generation of intermediate power levels. However, it is envisaged that reformers could also be modularized to provide fuel to each 50 kW or larger fuel cell module.

An alternative to reforming diesel fuel would be to reform methanol but this entails supply and storage of another fuel. The advantage is that commercial methanol reformers are readily available and could be developed at low risk for shipboard use.

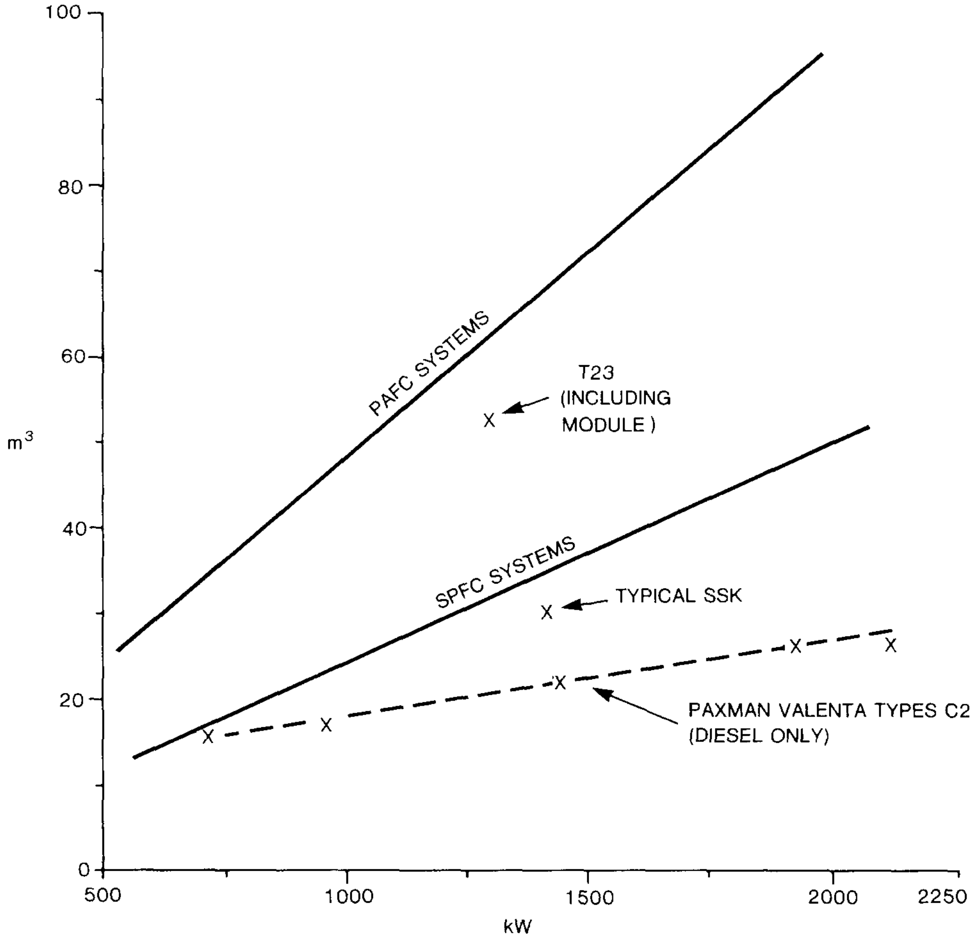

FIG. 1—ESTIMATED OVERALL VOLUMES OF FUEL CELL SYSTEMS COMPARED WITH DIESEL GENERATORS

DG: diesel generators
PAFC: phosphoric acid fuel cell
SPFC: solid polymer fuel cell

System Parameters

Fuel cell systems for submarine application have been studied[1] and much of the data can be used. Surface ship applications are easier in that an oxidant for the fuel cell does not have to be carried and the disposal of waste products such as carbon dioxide and water does not present a severe problem.

When one considers the most suitable types of fuel cell, existing data are only available for PAFCs and SPFCs. Some data on MCFC laboratory prototypes are also available. FIG. 1 gives estimated variations of PAFC and SPFC fuel cell system sizes compared with typical diesel generators. Reformer parameters are more difficult to estimate than those for the fuel cell stacks and are based on land demonstrator units built for natural gas and methanol. Fig. 2 gives estimated weights for fuel cell stacks only, compared with diesel generators.

Estimated fuel consumptions for PAFCs and SPFCs are shown in Fig. 3 for both diesel oil and methanol, and are compared with diesel-generators. The data for fuel cells is based on the steam reforming of the fuels into carbon monoxide and hydrogen followed by a water gas shift reaction to produce further hydrogen and carbon dioxide with an overall 90% conversion efficiency. Duodecane ($C_{12}H_{26}$) is assumed as a suitable model for diesel oil, but the choice of other hydrocarbons as a model would not change the results significantly.

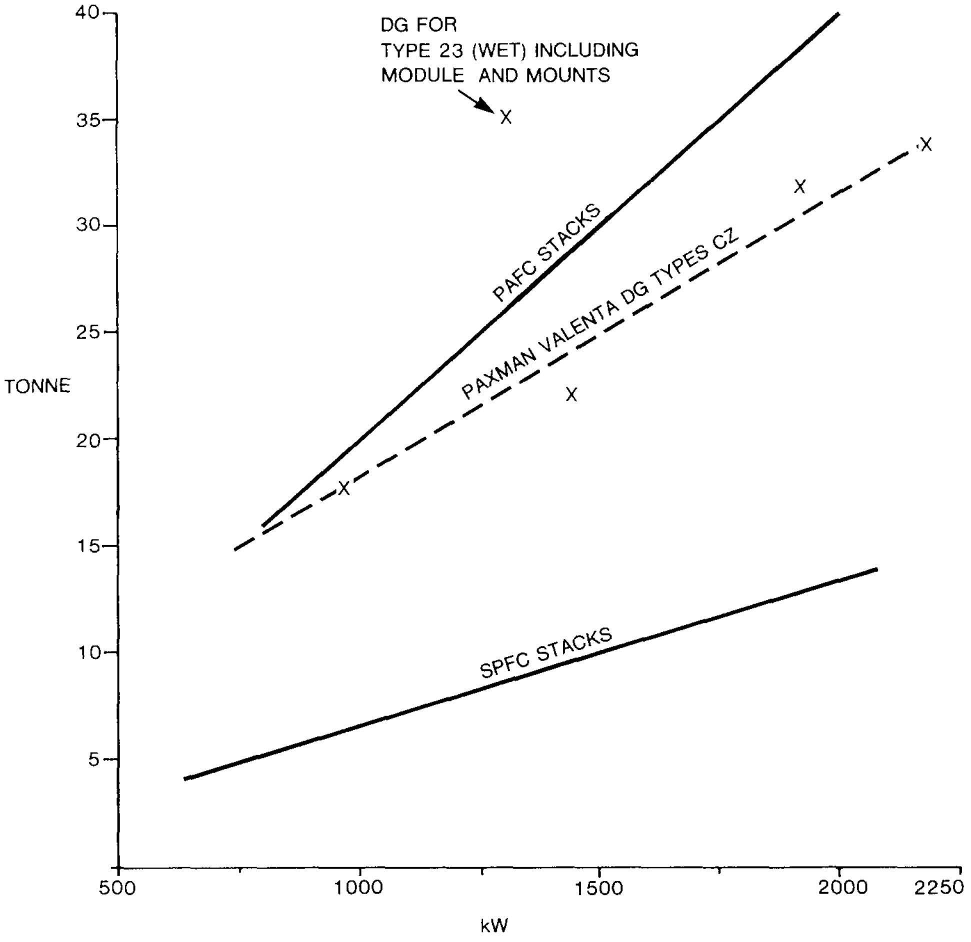

Fig. 2—Estimated weights of fuel cell stacks compared with diesel generators

DG: diesel generators
PAFC: phosphoric acid fuel cell
SPFC: solid polymer fuel cell

In order to give some indication of fuel cell system module sizes, estimated outlines of cell stacks and reformers, based on known developments and proposals, are shown in Fig. 4, together with outlines of typical diesel generators. A possible layout for a 1.4 MW SPFC system is shown in Fig. 5 compared on the same scale with a 1.3 MW diesel generator in its module.

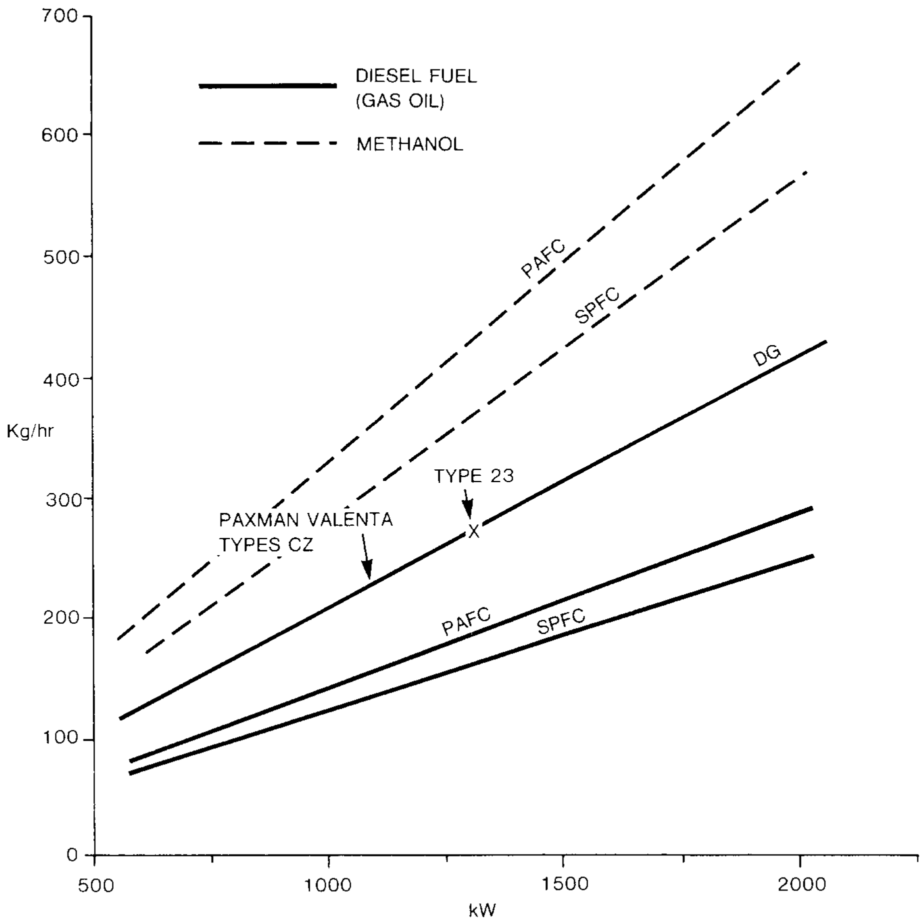

FIG. 3—ESTIMATED FUEL CONSUMPTIONS FOR FUEL CELLS AND DIESEL GENERATORS

DG: diesel generators
PAFC: phosphoric acid fuel cells
SPFC: solid polymer fuel cells

Estimated Costs

In order to assess the relative through-life costs the following assumptions are made:

(*a*) Support costs for fuel cell systems are the same as those for diesel generators. In practice they are almost certain to be less,

(*b*) Capital cost of a 1 MW fuel cell system is £2M,

(*c*) Capital cost of a 750 kW diesel generator is £500K,

(*d*) Fuel costs over a 25 year ship life are based on a 30% usage and the specific fuel consumptions in FIG. 3.

Based on these assumptions, the through-life costs for a 1 MW output are approximately £5.6M for both diesel generator and fuel cell systems.

Conclusions

In terms of power density, power to weight ratio and specific fuel consumption, projected solid polymer electrolyte fuel cell systems are potentially more than competitive when compared with diesel generators.

Although a detailed through-life costing exercise needs to be carried out, indications are that the total through-life costs for a fuel cell system would not exceed that for a diesel generator fit. Against this however, it is necessary to offset the unknown development costs for marine fuel cell systems.

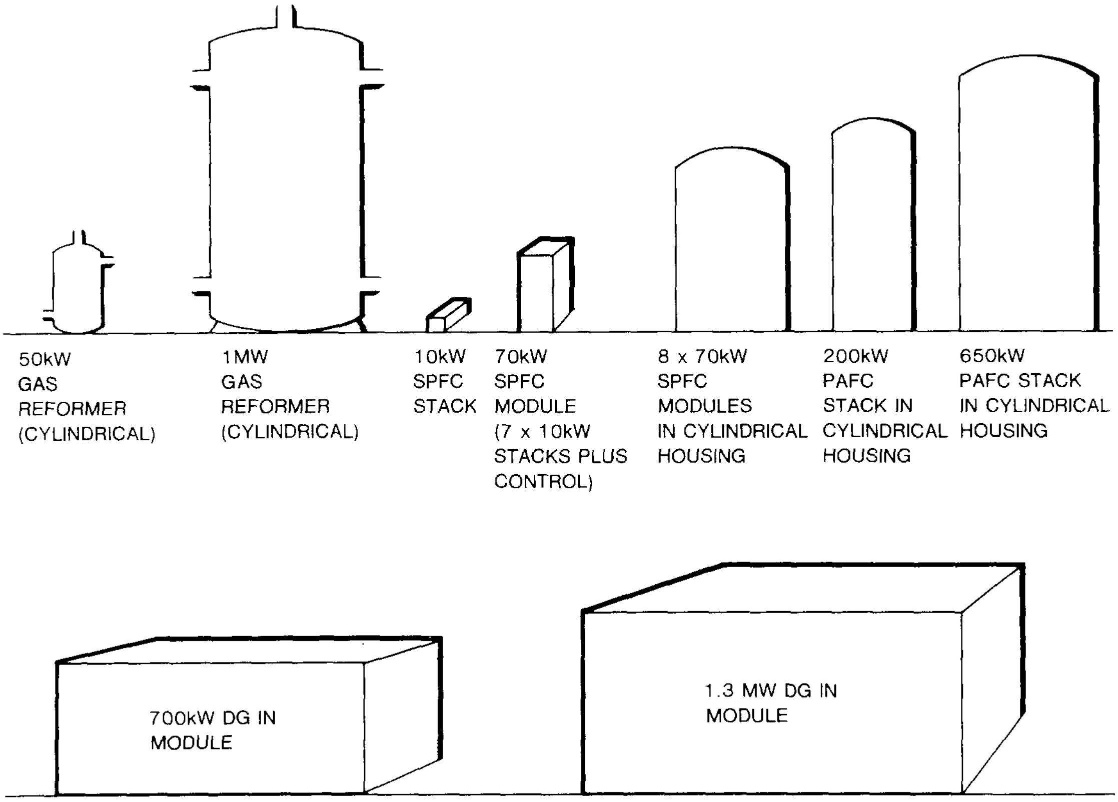

FIG. 4—SCHEMATIC OVERALL SIZES OF DIESEL GENERATORS AND FUEL CELL SYSTEM COMPONENTS TO THE SAME SCALE

DG: diesel generators
PAFC: phosphoric acid fuel cell
SPFC: solid polymer fuel cell

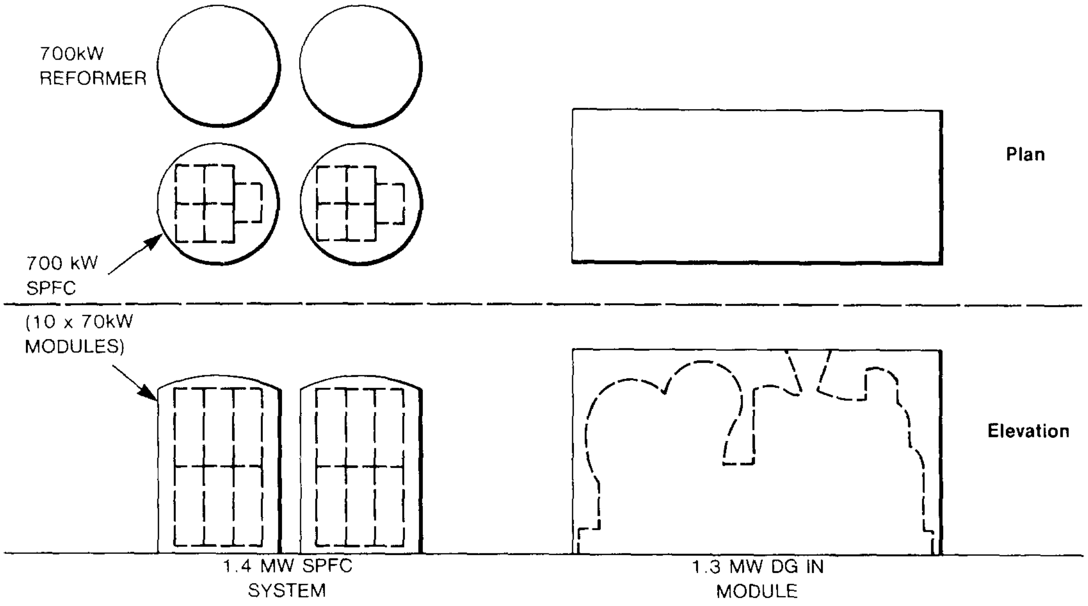

FIG. 5—SCHEMATIC LAYOUTS FOR FUEL CELL SYSTEM COMPARED WITH DIESEL GENERATOR

DG: diesel generator
SPFC: solid polymer fuel cell stack

The potential advantages offered by fuel cell systems, particularly low noise and reduced IR signature, are considered to outweigh the disadvantages. In conjunction with approximate through-life costs it is believed that this merits the start of an exploratory programme on the application of fuel cells to surface ships.

Areas of risk which would need to be addressed early in a programme are:

(*a*) the problems associated with the steam reforming of diesel oil;
(*b*) overall system management;
(*c*) the cost of developing marine fuel cells that can be built into large stacks.

The possibility of fuel cell types with internal fuel reforming, e.g. molten carbonate electrolyte or solid oxide, would also merit examination for longer term development.

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