Auxiliary Power Unit (APU) Application

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1 Introduction

Auxiliary Power Units (APU) are electrical power (and heat) sources for mobile systems operating independently from the main engine responsible for the propulsion. Such mobile systems comprise passenger cars, buses, different types of trucks and ships and also aircraft. The expression APU stems from aircraft auxiliary power units, which presently are mostly turbine-based. The aircraft APU generate on-board electricity for air conditioning or other functions, particularly during the periods on-ground and on the way to take-off.

The independence of an APU from the main engine(s) – in most cases Internal Combustion Engines (ICE) - opens the potential to optimise separately the function of traction or propulsion and the supply of electricity, which promises higher economy at reduced fuel consumption of the system at less noise and exhaust impacting the environment. These are key issues of the future due to the following facts:

The resources of cheap hydrocarbons are limited and mostly located in politically sensitive areas and increasing demand leads to continuously rising costs.

The use of fossil fuels is combined with emissions of gases harmful to environment and climate.

To maintain mobility in future enormous development activities and substantial progress has been achieved and still an intensive activity is under way to improve mobile systems through less consuming engines and peripheral components being more environmentally friendly. In this regard fuel cell systems attract high interest as replacement of present engines due to their inherent substantially higher efficiency for conversion of chemical energy of fuels directly into electricity without an intermediate thermal process step. But, still technical advances are required with respect to reduced production costs and improved power density and lifetime to become attractive for mass production and application.

It is considered that relatively small fuel cell units as Auxiliary Power Units for on-board electricity supply will come on the market earlier compared to big stationary systems and will start to play an important role in reducing the energy consumption. Since the power of such units is relatively small, their allowable specific cost limits can be considerably higher than for the bigger fuel cell engines, while still being attractive if the potentially far-reaching advantages are taken into account. A successful development of APUs will be of high importance for a lot of applications and it will influence considerably the architecture of systems and hence the relevant industry. It can be expected with successful development of this type of APUs that an increasing number of on-board mechanical, pneumatic or hydraulic actuators, operated at present directly or indirectly by the main engine, will be replaced by more efficient and better controllable electrical ones. The ultimate goal will be a system where the main engine is only responsible for the tractionn. Also new aggregates can then be installed on-board improving safety, economy and comfort. The most important feature is the air conditioning in the standing phase. This feature is presently realized mostly by idling the main engine, which is considered more and more critical in most developed countries (for instance the anti-idling legislation in California).

Considering these aspects, cited above, Auxiliary Power Units (APU) are currently seen in U.S. as the most interesting products for the entrance market of fuel cells and the most challenging project is the development of an aircraft APU with the high requirements regarding weight, volume and reliability, whereas cost represents the highest challenge concerning car application. This explains the great political U.S. interest on this technology and the generous funding by the U.S. government in the frame of the SECA program (Solid State Energy Conversion Alliance) of the Department of Energy (DoE) /1/. The SECA program concerns not only aircraft application but also stationary, mobile and other ones where different consortia of industry and research institutions are involved in the development of the fuel cell systems including also the important point of fuel supply.

2 Relevant fuel cell types and fuel aspects

Several fuel cell types with different operating temperatures and fuel quality demands exist and are under development, respectively available with different state of performance. From this variety the low temperature fuel cell types AFC (Alkaline Fuel Cell), PEFC (Polymer Electrolyte Fuel Cell) and the modification of the latter DMFC (Direct Methanol Fuel Cell), and from the high temperature fuel cells the SOFC (Solid Oxide Fuel Cell) and the MCFC (Molten Carbonate Fuel Cell) have to be considered particularly for APU application. An important aspect for the choice of fuel cell types is the fuel available in the system, respectively the possibility to store or to generate it on-board e.g. by reforming of hydrocarbons. For simplicity reasons the fuel base for the fuel cells should preferably be the fuel of the main engine(s), which are typically gasoline, diesel, heavy oil, kerosene or jet fuel, respectively. Therefore, PEFCs and SOFCs seem to have the highest potential and are the first options for application in APUs.

2.1 Polymer Electrolyte Fuel Cell (PEFC)

PEFC, DMFC and AFC have operating temperatures below about 100 °C. Typical for PEFCs (and also of DMFCs) is the use of finely distributed platinum as catalyst for the electrodes, requiring a high gas purity. In particular the CO content in the feed gas has to be as low as only few ppm, otherwise the Pt-catalyst would adsorb CO and lose its activity by passivation. Therefore, PEFCS are ideal, where hydrogen is available on-board for example in hydrogen cars. At this point it should be noted that hydrogen storage for mobile applications is still an open task. Presently existing possibilities are:

At low temperatures (~20 K) as a liquid in highly thermally insulated tanks, where a considerable amount of energy is needed for the liquefying process.

At high pressures (standard 350 bar, recently also up to 700 bar) as gas. In this case, the compression work has to be taken into account.

In metal hydrides, which is simple in principle and means easy and safe handling. However, the weight specific content of stored and available hydrogen amounts only to few percents.

In all these options of hydrogen storage, the stored energy density is considerably lower than that realised with conventional liquid hydrocarbon fuels, therefore, generation of hydrogen on-board by reforming of hydrocarbons is mainly considered at present applying low temperature fuel cells. But, as indicated above, in this case a high effort for reforming and cleaning has to be applied to get a tolerable low CO level. It has to be experienced that even the CO content in the air of heavy traffic can cause negative effects.

The following figure 1 shows the different steps required to get suitable fuels for the different fuel cell types and figure 2 a direct comparison for PEFCs and SOFCs.

Concerning the reforming and cleaning of hydrocarbon fuels for fuel cells MCFCs and SOFCs are much less demanding (figure 1), because in both cases CO can be used as fuel and due to the high operating temperatures and the absence of platinum catalyst material the sensitiveness against impurities is considerably reduced with the exception of sulphur. But, comparing MCFCs and SOFCs the latter have to be preferred because MCFCs are more complex in their system, therefore the APU interest for relatively low power levels is mainly directed to SOFCs.

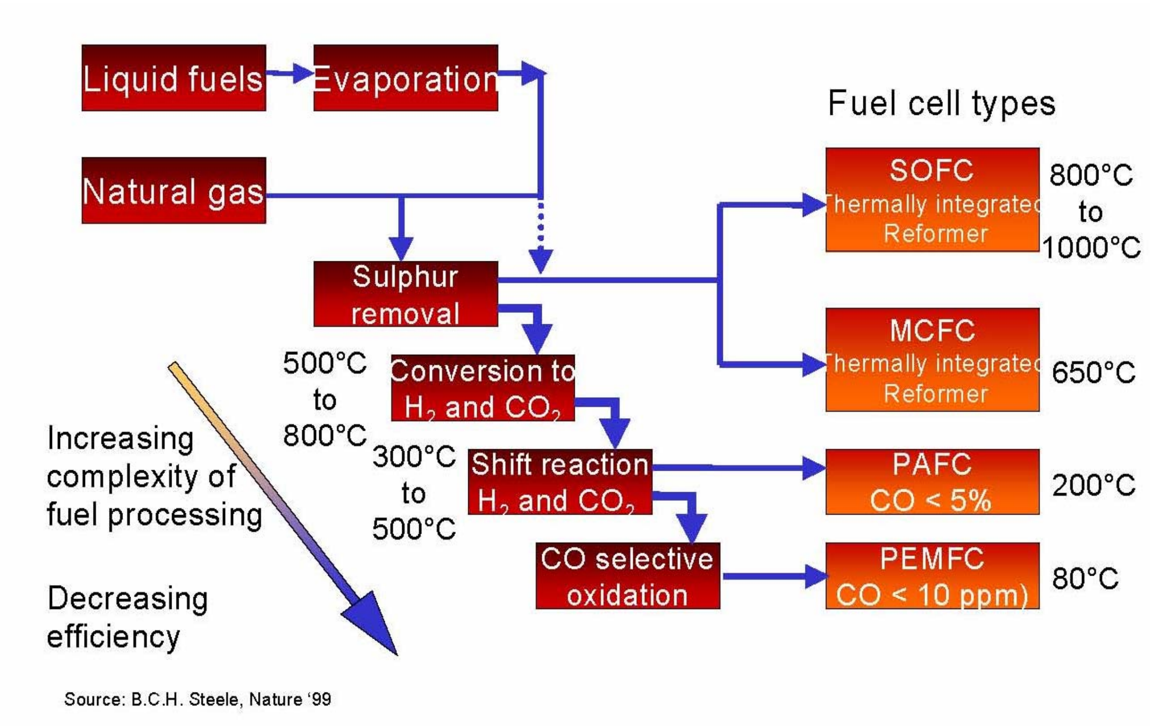

Fig. 1: Required reforming and cleaning steps to get a fuel suited for different fuel cell types

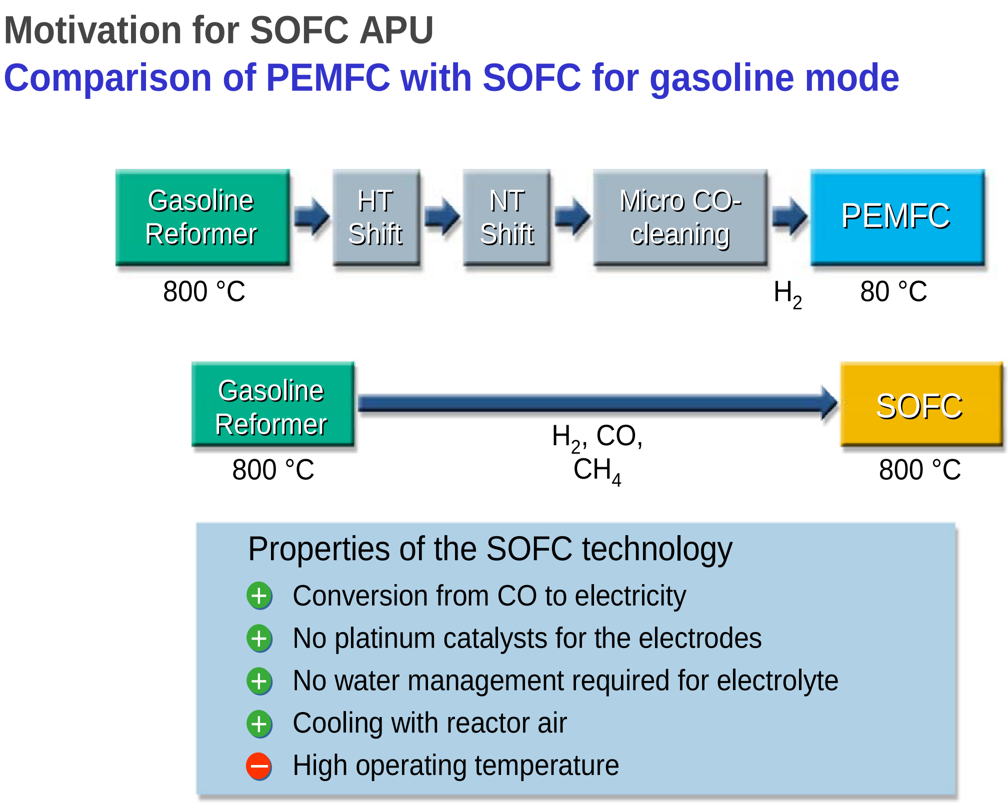

Fig.2: Gasoline reforming for PEFCs and SOFCs (Source BMW) /2/

2.2 Solid Oxide Fuel Cells

Among the high temperature fuel cells SOFCs are of the highest interest for this application. Therefore and due to the high relevance for the SOFCnet, the different SOFC geometries under development will be described in more detail. The basic principle of SOFCs will be explained by means of figure 3 with a planar SOFC of first generation.

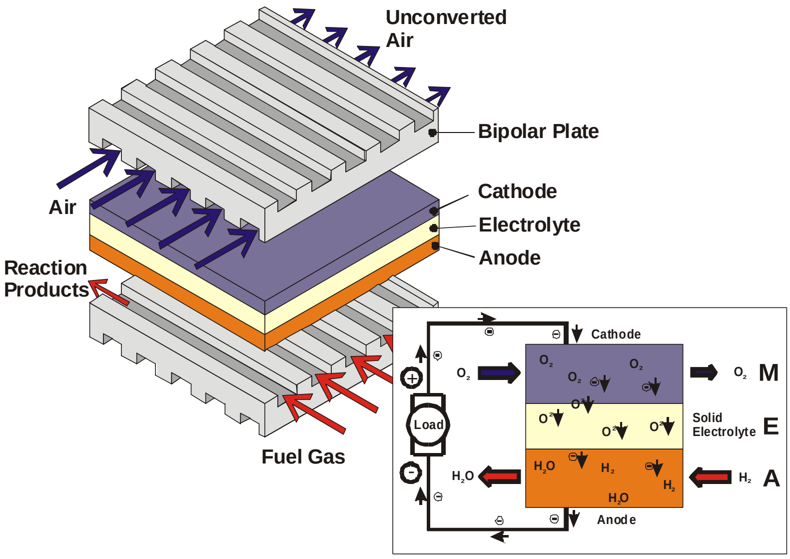

Fig. 3: Planar SOFC cell of first generation

The solid ceramic electrolyte usually consists of zirconia (ZrO_2) doped with yttria or scandia for stabilization of the high temperature phase and to increase the electrical conductivity for oxygen ions, which in the case of SOFCs represent the electrical charge carriers in the electrolyte. These ions are produced by dissociation of the oxygen molecules in the feed air at the cathode side, followed by a reducing process where they take over two electrons per atom. Driven by a concentration gradient, the resulting doubly negatively charged oxygen ions migrate through the electrolyte to the electrolyte/anode interface. There, they react with fuel components while getting rid of the previously gathered electrons, which are returned via an external load to the cathode being then involved again in the ionisation/reduction process of oxygen atoms. The electrodes on both sides of the electrolyte have an open porosity to provide good access of the reacting gases to the active sites and to dispose easily the reaction products together with un-reacted fuel gas. Usually, the anode consists of a mixture of metal and ceramics (a cermet) made from Ni and doped zirconia, whereas mixed conducting oxides such as lantham-strontium-manganate (LSM) form the cathode.

The voltages achieved to-date at suitable operating conditions are between 0.5 and 1.0 V at a current density of about 1 A/cm². To obtain a technically suitable power level several cells have to be stacked together by means of so-called bipolar plates providing the electrical connection between the cells. These plates have also the task to distribute and to separate the reacting gases. To get a high power density the electrical conductivity of the electrolyte has to be sufficiently high. The conductivity depends on the composition of the electrolyte material and its doping, and also considerably on the operating temperatures. One important approach to reducing the internal loss, i.e. to improve the cell performance, is therefore the reduction of the electrolyte thickness. The first generation type of SOFCs with yttria-stabilized zirconia electrolyte needs an electrolyte thickness of about 200 microns as the structural backbone of the cells (Electrolyte Supported Cells (ESC)), to which both electrodes have been fitted by screen-printing and sintering. As a consequence of the relatively high thickness, operating temperatures of about 1000°C are required for an interesting power density. At such temperatures, significant degradation effects may occur and expensive materials have to be used for bipolar plates and peripheral structural components. Therefore, new designs have been developed allowing for lower operating temperatures.

In recent years advanced planar cells opening the potential for higher performance or/and reduced operating temperatures have been under development, where the electrolyte lost the function to represent the mechanical backbone of a cell. Now, one electrode (e.g. Anode Supported Cells (ASC) or another component takes over this function. Depending on the surface quality of such a substrate the electrolyte thickness can be diminished to values as low as some microns and consequently the operating temperature can be reduced below 800 °C with still attractive performance values. In most cases, presently under development, a porous cermet anode of preferably Ni/YSZ with about 0.5 to 1 mm thickness forms the base, on which the thin electrolyte and the cathode are put on by screen printing and subsequent sintering. In some development activities a porous metallic plate represents the substrate and at the same time as fuel gas distributor, where plasma deposition methods are applied for making the electrolyte and the cathode as thin coatings on top of the substrate. In this case the metallic substrate consists of a ferritic steel alloy with almost same coefficient of thermal expansion as the ceramic cell parts and with the quality to form a stable mixed conducting oxide layer. The principle of such a cell design is shown in figure 4 despicting the metal supported DLR Plasma Spray Concept /3/.

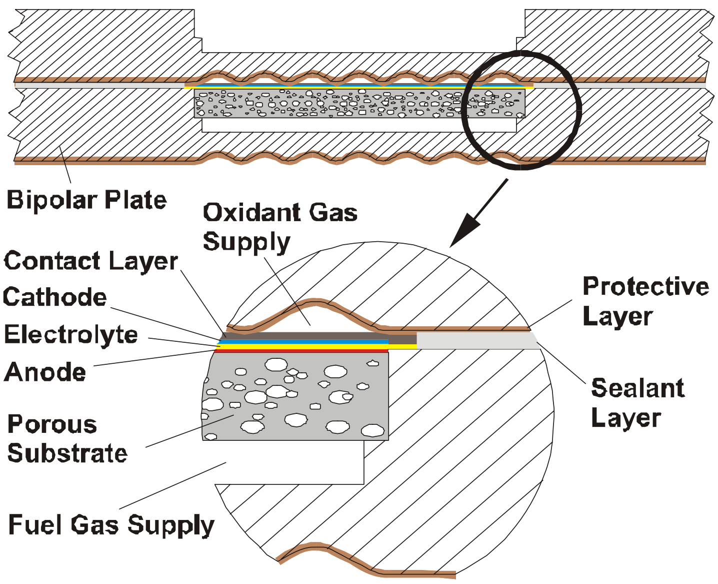

Fig.4: DLR plasma spray design with metal support /3/

Most development effort performed to-date in the field of SOFC has been devoted to systems for combined heat and electrical power generation in utilities operated with natural gas. Originally, the tubular cells of Siemens Power Corporation have a length of about 2 m and the systems with the cathode supported cells (CSC) show a relatively low power density and require a high operating temperature in the 1 000 °C range which are prohibitive qualities for an APU application.

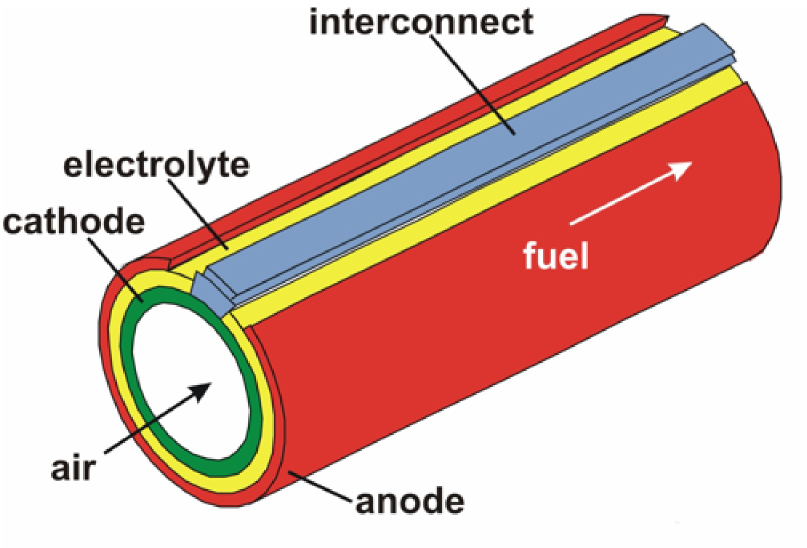

Fig. 5: SiemensWestinghouse tubular cell

Some years ago SWPC started a development with a new cell type showing a considerably higher performance with more compact cells, the so-called High Power Density (HPD) tubes, combining tubular geometry and flatness (figure 6). Several tubes are arranged to flat cells with shorter distances (less internal losses) for the electricity carrier, resulting in higher power density and stability, allowing with much shorter cells a design with improved compactness and lower volume.

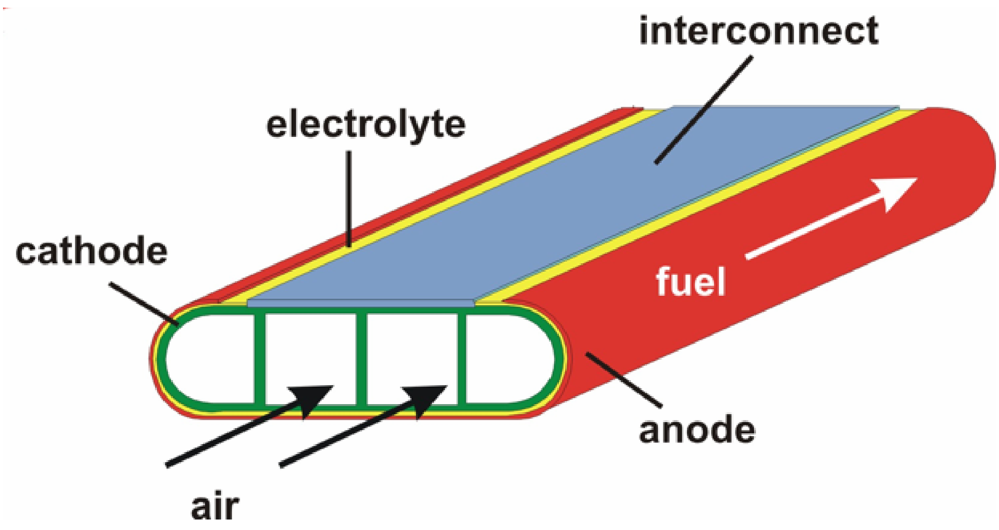

Fig. 6: High Power Density (HPD) tube of Siemens Westinghouse

An interesting design concept, which may find first application with small systems for some hundred W, are micro tubular cells with an outer diameter in the mm-range (figure 7). They have the property of extremely short start-up times at considerably high specific power density. But, a great number of such micro tubes have to be combined to get a power level in the kW-range, this means a manifold problem with a considerable high number of mechanical and electrical connections. Recent progress recommends to observe the relevant development activities with interest.

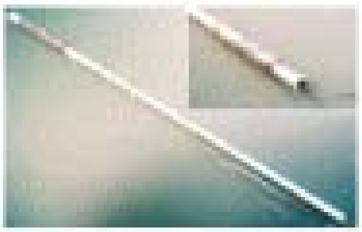

Fig. 7: Micro tubes

A critical consideration regarding APU applications is the present state of the maturity of the technology regarding performance, weight and volume, power level, operating temperature, reliability and lifetime.

3 Preferred APU Application Fields and the Relevant Requirements

As application fields for SOFC-APUs particularly passenger cars, buses, different truck types, boats and ships, different kinds of trains and aircraft have to be considered /4/. A successful APU development will possibly find the greatest distribution with passenger cars, beginning with such of the high prize level. Highest requirements are to be met with aircraft application. Success there will be of importance for a lot of other fields, because fuel cells and in particular fuel cell APUs are considered a key technology.

3.1 APUs for passenger cars

The demand for electrical energy in passenger cars is continuously increasing. Since the installation of the first generators, the electric power consumption of cars has increased by about 500 % and the capacity of the batteries by around 200 % /2/. Many electrically operated functions and components are already installed at present and new ones should be added or are recommended to improve safety and comfort, such as for air conditioning in engine-off operation. Also the replacement of conventional mechanically, hydraulically or pneumatically operated actuators by better controllable and more efficient electrical components is highly desirable. At present, the electric power on board depends directly or indirectly on the Internal Combustion Engine (ICE) and the generator. When this engine is running with reduced efficiency in part-load, economic and technical reasons limit the installation of additive electrical functions in cars.

The goal of the development is a car architecture where the ICE will only provide the power for the traction while all other functions are performed electrically powered by means of a fuel cell system. For the first generation of fuel cell APUs in a "more electric car" the power should amount to about 2 to 6 kW_e, which requires that at least the major power consumers will run with a voltage of 42 V. Such a fuel cell system for cars has to fulfil some specific performance criteria to become an attractive technological component suitable for mass production. Such requirements concern particularly reliability, lifetime, high efficiency and fuel utilisation, low weight and volume, short start-up time, cycling stability, suitability for the on-board available fuel and acceptable costs. As already remarked above, the APU should use for simplicity reasons preferably the same fuel as the main engine.

BMW was successful with the combination of hydrogen fed ICEs and PEFC APUs (UTC) in test cars of the 7series in the frame of the "Clean Energy Project" /2/, where the hydrogen was stored in cool liquefied form in super isolated cryogenic tanks. Since about 5 years this company is under way with the goal of SOFC APUs, fuelled with gasoline reformate. The first technical targets are:

Power level	5 kW_e
Fuel gas	gasoline reformate
Endurance	> 5 000 hrs
Cycles	> 5 000
Fuel utilization	> 60 %
Start-up time	< 10 minutes
Specific weight	< 4 kg/kW_e (Stack)
Specific volume	~ 1 l/kW_e (Stack)
System cost	< 2 000 €

The whole system with all the necessary peripheral components should exhibit a volume of less than 50 l at a weight not over 50 kg. At least a system efficiency of 35 % should be reached. Besides the high lifetime with low degradation the great number of operating cycles accompanied with high temperature gradients and transients with the resulting thermo-mechanical stresses represent to present knowledge the main technological challenges. Also to become economically attractive, the costs for the system should not exceed 350 to 500 €/kW_e. This requires a cell and stack design suited for series production without expensive materials.

3.2 APUs for trucks, buses and heavy mobiles

The main motivation for the development of APUs for such types of mobiles is the reduction of fuel consumption and of environmental impact by avoiding the idle operation of the ICE, for instance at over-night stops of trucks which is particularly necessary in the case of refrigerator trucks. The idling of the engine is restricted by legislation and therefore more efficient ways for electricity supply with less exhaust and noise are of high interest to keep comfort and functionality. In most relevant cases such mobile systems are operated with diesel fuel, which has to be reformed to obtain a fuel cell-suitable fuel. But due to the potentially much higher available volume with such applications the storage of natural gas or even hydrogen may become possible, which would influence reforming and the selection of the fuel cell type and system. Natural gas as fuel, stored in steel bottles, would considerably reduce the reforming and cleaning effort and hydrogen. The development tasks for the SOFCs are similar to those for passenger cars with few differences: the required power level would be higher with a range between 10 and about 30 kW_e, however, low volume and weight are of reduced importance. Also, a higher lifetime of the APUs corresponding to the generally longer operation times of such mobile systems has to be obtained.

3.3 APUs for marine applications

Similar to the fields described in 3.2 a large variety of types, applications and specific requirements exist in the marine field. Also there, the need to reduce noise and exhaust is present. Particularly in harbours the operation of diesel engines to supply electric power is unwanted. Concerning the different types of ships or boats it has to be distinguished, at least roughly, between small ones for short operating distances (low power demands and short activity interval) and such for long distance travelling ones requiring a much higher electrical power level. In the first case daily refuelling of battery changing may be possible.

For the first category, up to about 100 kW_e, PEFC-systems hybridized with electrical batteries can fulfil the task. Hydrogen, natural gas or methane can serve as fuels. For the high-power long distance ships the use of the on-board fuels such as diesel or marine bunker fuel is desired, requiring higher reforming and cleaning effort, particularly concerning the sulphur content. In this case high temperature fuel cell systems are to be preferred. MCFCs and SOFCs are relevant options and combined systems, e.g. combinations of fuel cells with turbines etc., have to be considered. Also, the use of the fuel cell product water may be of interest. In general, corresponding to the usually long lifetime of ships the endurance of the fuel cell should be in the same range. But, as the fuel cell stack represents only about 30 % of the whole system, it may be possible and advantageous to replace and recycle the cells in shorter intervals depending on their degradation behaviour.

3.4 APUs for trains

Since most passenger and transport trains are directly connected with their own electrical grid, fuel cell APUs are not of high interest, at least in developed countries. This may change, when fuel cell systems of high power level have obtained the quality to become the source of power to tract the train by means of electric motors. For long distance trains this may be economically attractive since the ohmic losses of long power lines can be avoided. The situation is different for trains for short distances, for remote areas or for special applications like coal mining etc.. There, aspects of grid or power line independence, safety, fuel supply or reduction of exhaust are strong arguments for the replacement of ICEs by fuel cell systems. Depending on required electric power further developed and adapted MCFCs and SOFCs seem to be the first options for such applications.

3.5 APUs for aircraft

As already mentioned above, the expression APU stems from aircraft. "Current gas-turbine APUs operate at ~15 % load cycle efficiency, contribute up to 20 % of the aircraft ground based emissions, and APU/secondary power systems account for 50 % of the maintenance delays which presents 12 % of the maintenance cost" /1/. This statement explains the high interest for a better and more efficient system for electricity supply on board. This is backed by the wish for "More Electric Aircraft" where more of the present components and actuators in the aircraft shall be replaced by more efficient and better controllable electric ones. Recent progress in fuel cell development attracted the interest of aircraft manufacturers for fuel cell systems to replace the present APU. But, in the variety of potential APU fuel cell applications the one for aircraft represents the highest technical challenge. The main requirements to be fulfilled by such a fuel cell system are as follows:

High reliability and safety,
Long lifetime: > 20 000 operating hours,
Light-weight, high power density, low volume,
Matching the conditions of high cruising height (10 000 m), where
 only ~20 % oxygen partial pressure of sea level value and
 temperature values below -50 °C exist,
Suitability for kerosene or kerosene reformate,
High tolerance against fuel impurities, thermal cycling, shocks and vibrations
Relatively high power requirements (>200 kW)

The problem of reduced oxygen partial pressure at high altitudes can be solved by installation of an air compressor, the temperature problem by insulation and thermal management.

To present knowledge and expectations PEFCs and SOFCs seem to have the highest potential to meet the stringent requirements if further technology development is forced. To keep aircraft systems and logistic problems relatively simple no second fuel is wanted on-board. Kerosene will remain the main fuel for the next decades. SOFCs are attractive because of the simpler overall system, however, their presently lower development state means higher technological challenges compared to PEFCs. As explained already, PEFCs demand more effort for reforming and cleaning to get a sufficiently low CO-content of the fuel.

The PEMFC is the fuel cell type that has the best weight and volumetric power densities and the best transient performance of all types. The PEMFC improvements in the last years were largely created by the efforts of the automotive industry research teams and their partners. The automotive industry primarily uses PEMFC for their research activity applying fuel cells for propulsion. In Table 1 some selected power densities of automotive stacks are given. For comparison the aeronautic (gas turbine) APU power density is approx. 2 kW/kW.

Table 1: Examples of state of the art PEFC stacks for transportation

	Manufacturer	Power kW	Vol. Power Density kW l^{-1}	Grav. Power Density kW kg^{-1}	Conditions and specialty
Mark 902 Fuel Cell Module	Ballard Power Systems	85	1.13	0.88	H_2-air; 1-2 bar; 80 °C
GM 2001 Stack	General Motors	103	1.7	1.24	H_2-air; 1.5 bar; 80 °C
Honda FCX	Honda	85	na	1.0	Aromatic membrane

Presently the short term application of fuel cells for aircraft application focuses on PEMFC because of their higher technological maturity. The SOFC is a promising alternative for the future and has to be kept in mind as strategically important (10-15 years). Especially combinations of SOFCs and micro gas turbines seem to represent an excellent combination for solving the problem of low oxygen partial pressure at high cruising altitude. The exhaust of the cells, consisting of not reacted fuel and steam, can be fed to such a turbine, which is mechanically connected to an air compressor, as shown principally in **figure 8**.

In /8/ experimental results on the altitude testing of PEFC (Ballard NEXA) fuel cell systems for aircraft applications are reported. Mainly, the potential application being investigated is the replacement of a conventional aircraft battery with a fuel cell system. An opened system altitude chamber has been developed to evaluate fuel cell system performance in flight altitudes. Trends in temperature, cooling fan speed, airflow, and fuel flow at various loads and altitudes up to 5000 feet have been reported. Electrical power quality in steady state and transient loading has been determined to be insufficient to meet the aircraft power quality characteristics (the fuel cell system was voltage unregulated). Further development is needed to properly regulate voltage and obtain sufficiently quick responsiveness. Low pressure hydrogen storage using metal hydride canisters have been tested at altitude and for endurance. The tests indicate that fuel cells operate best for aircrafts applications when pressurized and used primary for steady state loads.

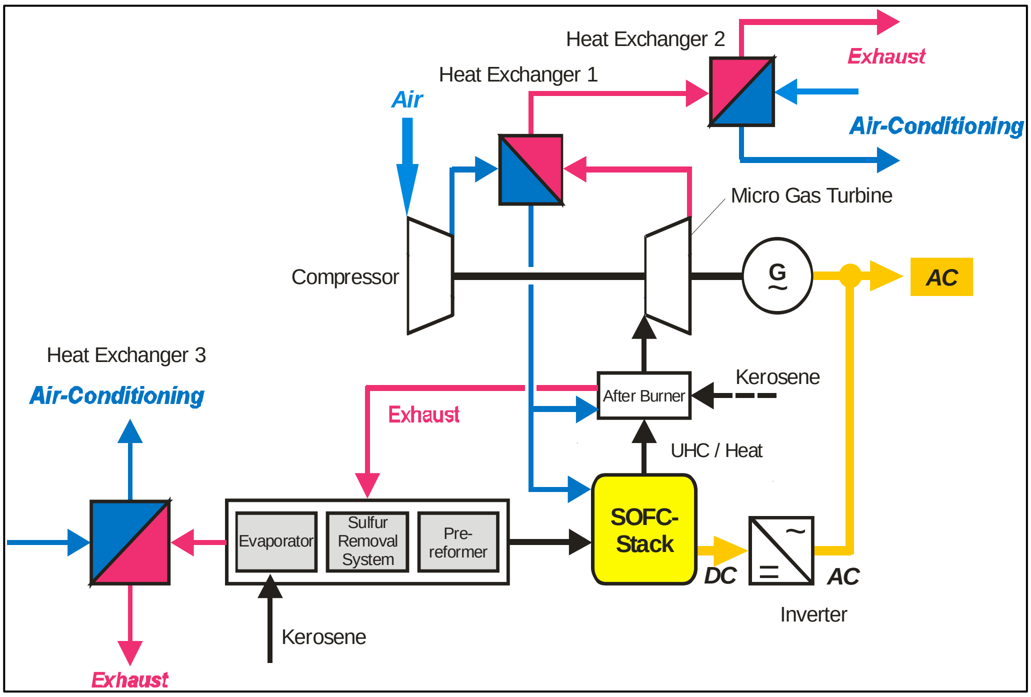

Fig. 8: SOFC and micro gas turbine system

3.6 SOFC APUs for Military Application

Most military vehicles and remote, not grid connected installations have an increasing demand for electricity. This demand is not for traction, but rather for other loads such as air conditioning, heating, lighting, communication and reconnaissance systems, etc. Typical for military applications are so-called "silent watch" situations where the vehicle engine, which is normally driving the alternator for electricity production, has to be switched off to avoid emissions of noise, heat, vibrations and exhaust gases. Under these conditions, batteries are used to supply the electrical energy required to keep the system in operation. However, there are limitations to the amount of power that can be supplied by batteries; hence additive power sources have to be considered for the increasing electricity demand, which also comply with the specifications required for military applications.

Fuel cell APUs show, in principle, some attractive properties. With exception of the air fan they have no rotating, noise and vibration producing parts, and the amount of exhaust is very low. Therefore, it has been suggested to use a combination of PEFC, electrolyser and hydrogen storage unit to build a regenerative system. Water produced by the fuel cell is converted into hydrogen and oxygen by an electrolyser operated through the alternator, and the hydrogen is stored for later use by the fuel cell. However, considering the fuel base which is usually diesel or another hydrocarbon, SOFCs have some advantages over PEFCs: they are less sensitive to fuel impurities and the reforming process to obtain a suitable fuel is much simpler and requires less parts and processing steps, since CO represents also a fuel for SOFCs. The problem of waste heat from the SOFC may be resolved by the fact that a considerable amount of this heat is used internally for reforming and thermal management of fuel and oxidant streams; furthermore, innovative insulation concepts, such as vacuum insulation or phase change materials, can be used to reduce the outside temperature to tolerable levels.

Recently also fuel cell backup power systems with some hundred watts came into consideration with preferable use at remote wireless sites /9/. The successful development of a 75 W portable SOFC system is described with a dry mass of 3 kg and a fuel consumption of ~0.55 kg/day. With 17 cells and 0.7 V/cell an operating point near 12 V and 7.5 A was obtained. For the fuel utilisation a value above 67 % is reported, leading to a stack gross efficiency (stack output power/lower heating value of reformat) of ~ 33 %. For a future 250 W generator with advanced tubular stacks a system weight of ~4 kg, an overall efficiency of 30 % and a start-up time below 15 minutes to full power is expected which will be competitive to hydrogen PEM systems.

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