Application of regenerative fuel cells for space energy storage: a comparison to battery systems

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Abstract

A major advantage of regenerative fuel cells compared with battery systems arises from the decoupling of their rated power and their capacity, which determines the storage system. The mass of battery systems is related to the energy stored, whereas the masses of regenerative fuel cell systems are mainly determined by their rated power. On the other hand, average power and total energy are not independent variables, since they are correlated by the period of discharge of the electrochemical cells. Thus a comparison of the different approaches to storage can be given, by evaluating system masses as a function of power requirement and period of discharge. Since space power applications are considered, the charging and discharging periods can be expressed in terms of orbit altitudes.

Introduction

Recent investigations show that regenerative fuel cell (RFC) systems for space power application may be competitive with battery storage systems (e.g., Ni/H_2 batteries) [1–3]. The advantage of the regenerative storage systems mainly arises from their capability of separating the design requirements for the rated power and the capacity. Whereas the RFC cell stack masses are determined by their rated power, the reactant storage masses are related to the energy which must be stored. In contrast, the battery mass is given by the required energy storage capacity. An additional advantage of the RFC arises from the strong dependence of the depth-of-discharge (DOD) on the number of discharge cycles of the batteries. Hence, the overall operating time is a fundamental parameter in comparing electrochemical energy storage concepts.

For unmanned space missions ranging from low earth orbit (LEO) to geosynchronous earth orbit (GEO), the criterion of success of the regenerative energy storage over conventional battery systems is given by the overall system mass, since synergetic effects from its integration into the environmental control and life support system are negligible. However, the limiting conditions of the space mission considered (e.g., power requirements, orbit altitude and the overall operating time) determine whether the RFC or the battery is the more advantageous.

In this paper H_2/O_2 RFC systems are compared with the Ni/H_2 battery. RFC systems using alkaline (AFC) and solid oxide (SOFC) technology are considered along with state-of-the-art and future requirements for the specific power and energy density of both fuel cells and batteries. The comparison of these systems is made in terms

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of fundamental parameters given above (i.e., power requirement, orbit altitude and mission duration). In addition, the benefits of solid oxide and reversible fuel cells compared with alkaline systems are discussed.

Fundamental considerations

System mass calculations were performed for a RFC system consisting of dedicated electrochemical cell stacks (fuel cell and electrolyzer), fuel storage, a photovoltaic (PV) array as the primary energy supplier, and a radiator rejecting waste heat. In contrast, the battery storage system has only three components (i.e., the Ni/H_2 battery, PV array and radiator).

Evaluation of the component weights was based on data for the specific power and energy density of these components and on the efficiencies of the related electrochemical reactions. The data assumed in the calculations are given in Table 1.

The system mass depends on independent parameters such as rated power, orbit altitude and overall operating time. However, only the rated power appears directly in the equations only. The dependence of the component masses on the orbit altitude is expressed by the ratio of the eclipse period to the sunshine period:

$$\frac{t_d}{t_c} = \frac{\arcsin(R/r)}{\pi - \arcsin(R/r)} \tag{1a}$$

where R and r, respectively, denote the radii of the earth and the orbit considered. The absolute value of the eclipse period is given by:

TABLE 1

Characteristic values of the subsystems as used in the calculations

Component	Symbol	State-of-the-art	Future
Battery energy density, (W h/kg)	ρ_{bat}	45	55
Efficiency	η_{bat}	0.75	0.84
Fuel cell specific weight, (kg/kW)	ρ_{fc}	10.5/3.2[a]	6.9/1.9[a]
Efficiency	η_{fc}	0.62/0.47[a]	0.67/0.55[a]
Electrolyzer specific weight, (kg/kW)	ρ_{el}	10.5/3.2[a]	6.9/1.9[a]
Efficiency	η_{el}	0.96/0.90[a]	0.98/0.95[a]
PV array specific weight, (kg/kW)	ρ_{PV}	30.9 (120 W/m^2) in low earth orbit	
specific weight, (kg/kW)	ρ_{PV}	16.0 (80 W/m^2) in high earth orbit	
Radiator specific weight, (kg/W)	ρ_{rad}	6.6/1.6[a]	

[a]The data taken for the solid oxide regenerative fuel cell components. The data are taken from ref. 4.

$$t_d = \frac{\sqrt{\dfrac{4\pi^2 r^3}{\gamma M}}}{\dfrac{t_c}{t_d} + 1} \tag{1b}$$

where γ and M denote the gravitation constant and the mass of the earth, respectively.

Since the lifetime of RFC systems is assumed to be long compared to the duration of the missions considered, their system mass does not depend on overall operating time. However, the lifetime of the battery systems is limited by relationship between the number of discharge cycles and the depth-of-discharge (DOD). A typical DOD versus cycle time relationship taken from ref. 5 is used in this calculation. This characteristic is approximated by a polynominal of the fifth order. Assuming a certain operating time, the total battery mass is a function of (i) the maximum battery DOD operational used, and (ii) the number of battery exchanges in operation.

System mass calculations were performed assuming that the battery stack is exchanged after at least 30 000 charge/discharge cycles, and the DOD is limited to 90% if a small number of charging cycles is required. Both DOD and the number of battery exchanges were optimized in regard to minimum battery mass for all combinations of the independent parameters (i.e., power requirement, orbit altitude and overall operating time).

The masses of the subsystems can be expressed in terms of the rated power P_r, the charging and discharging periods t_c, t_d, the DOD and the number of battery exchanges n_x. The mass of the PV array for the RFC and for the battery storage, respectively, is given by eqns. (2a) and (2b):

$$m_{PV} = \left(1 + \frac{t_d}{t_c \eta_{fc} \eta_{el}}\right) \rho_{PV} P_r \tag{2a}$$

$$m_{PV} = \left(1 + \frac{t_d}{t_c \eta_{bat}}\right) \rho_{PV} P_r \tag{2b}$$

where the η denotes the efficiencies for the fuel cell, electrolyzer and battery, as indicated by the indices. Since the overall efficiencies for RFCs and batteries generally differ, the system mass comparison does not only depend on the masses of the electrochemical stacks, but also on the specific power of the PV array. Hence two different types of PV cells were considered in the calculations, the first type being optimized for specific mass, in the second type the overall array area being minimized to reduce the aerodynamic drag. Previous estimations have determined, that PV arrays should be optimized in regard to array area for orbits of less than 600 km altitude.

Drag optimization gives a system mass penalty which depends on the size of the PV array, the mission duration and the orbit altitude. This contribution to the overall mass is calculated assuming an excess system mass per unit area and year of $\Delta m = 3.6$ kg/m^{2}a in a 450 km orbit. The dependency of this mass penalty on orbit altitude is calculated from data given in ref. 1.

For both, RFC and batteries, waste heat production rate is highest during discharge of the energy storage [6]. The radiator mass is related to this mode of operation, and is given by:

$$m_{rad} = \left(\frac{1}{\eta_{fc}} - 1\right) \rho_{rad} P_r \tag{3a}$$

for the RFC system, and

$$m_{rad} = \left(\frac{U_{enth} - U_{bat}}{U_{bat}} \right) \rho_{rad} P_r \tag{3b}$$

for battery storage, where U_{enth} denote the thermoneutral potential of the Ni/H_2 battery reaction and U_{bat} the discharge voltage of the battery ($U_{enth} = 1.51$ V, $U_{bat} = 1.25$ V).

Since long-term space missions are considered in this analysis, cell stack exchanges must be taken into account, when necessary. This may be considered by determining the overall transport capacity requirement from sea level into orbit. The lifetime of fuel cells and electrolyzers are assumed to be long compared to duration of the missions. On the other hand, battery operations are limited by limited cycle stability and insufficient DOD as a function of discharge cycles. Thus, cell stack exchanges must contribute to the overall battery mass in long-term missions. As indicated earlier, fuel cell mass is directly related to rated power, whereas battery mass is related to capacity:

$$m_{fc} = \rho_{fc} P_r \tag{4a}$$

and

$$m_{bat} = \frac{t_d}{\text{DOD}} (1 + 0.8 n_x) \rho_{bat} P_r \tag{4b}$$

In eqn. (4b) DOD denotes depth-of-discharge and n_x the number of battery stack exchanges over the entire orbit period.

Finally, the dedicated RFC system requires two additional components, an electrolyzer to charge the energy storage and fuel storage for the reactants:

$$m_{el} = \frac{t_d \rho_{el} P_r}{t_c \eta_{fc}} \tag{5}$$

Recently, calculations of fuel storage masses have been given as a function of the required storage capacity [2, 5]. These relationships may be approximated by linear expressions with good accuracy as is given in eqn. (6):

$$m_{st} = 105 + 1.442 \times 10^{-4} \frac{t_d}{\eta_{fc}} P_r \tag{6}$$

The battery and RFC storage can be compared using eqns. (1–6), although the comparison does not depend only on these relationships. Results may change due to further improvement in the technology of both batteries and fuel cells. In addition, the fuel cell or electrolyzer design may use alkaline, solid polymer (SPE) or solid oxide (SOFC) technologies. Finally, RFC design would be at an additional advantage if the fuel cell could be operated reversibly. The comparison was performed using accepted and advanced specific cell data to take future technological effort into account.

Results

The decision, as to whether the Ni/H_2 battery or the RFC system would be applied as the most favourable energy storage depends on the considered space mission. To determine the energy storage layout, the space mission can be characterized by its

power consumption, orbit altitude and the overall operating time. For general validity in a comparison of different energy storage system, these parameters must be varied over a wide range. Thus, system mass evaluations were performed as a function of:
(i) power requirement from 1 to 100 kW, to cover the full range of power consumption from small satellites to large space stations;
(ii) operating time of the energy storage system t_{OP} from a single orbit to ten years, and
(iii) orbit altitude from LEO to GEO, considering all relevant space missions in earth orbits.

The results are given in Fig. 1 as a contoured surface in three-dimensional space, opened up by a given set of parameter. The surface shown in Fig. 1 is defined by the ratio $m_{RFC}/m_{bat}=1$. The regenerative fuel cells are advantageous compared with the batteries for parametric vectors $v=(P_r, t_{OP}, r)$ directed into the region above the surface shown. For other cases the batteries would be more favourable. From Fig. 1 we can deduce that the application of RFCs for space power requires two mission conditions: (i) high power consumption, and (ii) either high orbit altitude or long duration of the mission. A quantitative discussion can be given by presenting these data in a two-dimensional plot, as in Fig. 2. The plotted curves are related to different

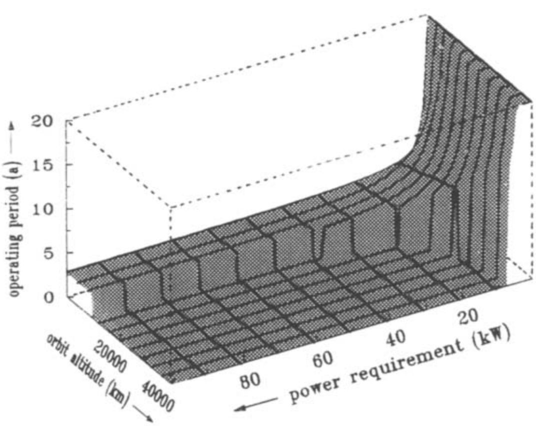

Fig. 1. Boundary layer in the parametric space of the mission properties. The layer indicates parameter combinations leading to equal system masses for both batteries and RFCs.

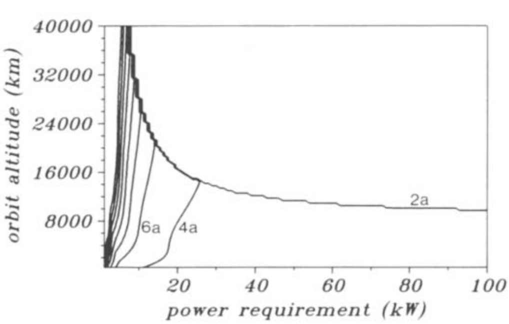

Fig. 2. Two-dimensional plot of data shown in Fig. 1. The curves indicate operating periods for equal system masses for RFCs and batteries.

operating times (t_{OP}=2, 4, 6..18a) and indicate the parameter combinations (P_r, r) which result in equal system masses for the battery and the RFC ($m_{bat}=m_{RFC}$).

For GEO space missions the use of RFCs for space power will result in lower system masses compared with batteries for power requirements higher than 8 kW. This 8 kW limit does not depend significantly on the overall energy storage operating time, although a slight trend to lower power (5 kW) is observed for missions longer than twelve years.

LEO application of RFCs is much less favourable than RFC operation in GEO. Battery operation in the LEO is advantageous for all missions not exceeding two years of operation, but fuel cell operation will have distinct advantages for long-term space missions, depending on power requirement. The applicability of RFCs is restricted to power levels higher than 10–15 kW, assuming a mission duration of four years. The minimum power consumption for efficient fuel cell application decreases with increasing operating time. Energy storage for LEO space missions operating for more than ten years in orbit with power consumptions higher than 2 kW have a better power weight ratio favouring an RFC system over batteries.

If one of the parameters is kept constant, a more detailed quantitative discussion of the results can be obtained by plotting the relative excess mass of the battery in a two-dimensional plot. The relative excess mass of the battery with respect to the RFC system is calculated using eqn. (7):

$$\Delta m = (m_{bat} - m_{RFC})/m_{bat} = 1 - m_{RFC}/m_{bat} \tag{7}$$

Figure 3 shows a quantitative comparison of the Ni/H_2 battery and the alkaline RFC system. The curves indicate data of equal relative mass $\Delta m/m$ versus power requirement and orbit altitude. The data are calculated assuming a long-term space mission operating for ten years in orbit. Benefits for the RFC system are indicated by the solid lines, and parameter combinations leading to competitive battery data are indicated by dashed lines. From Fig. 3 batteries are restricted to low power applications consumption, assuming ten year LEO missions. RFC system benefits increase between P_r=2 kW and P_r=5 kW up to $m_{bat}-m_{RFC}/m_{bat}$=30%. Benefits of more than 40% occur for power requirements higher than 11 kW. Beyond this value, further increase of power consumption will only result in slightly increased benefits.

RFC systems for GEO operation will reduce energy storage mass by 20 to 25%, for power requirements higher than 27 kW. In contrast, RFCs are at a disadvantage for GEO space missions at a power level less than 8 kW. Since current GEO space

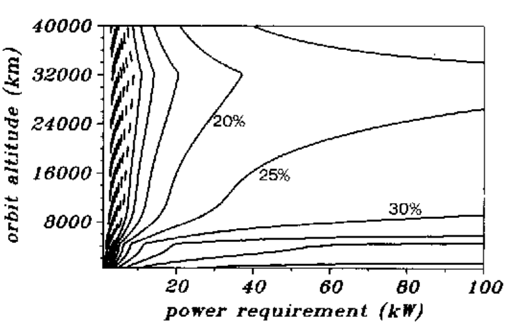

Fig. 3. System mass comparison for battery and RFC systems ($\Delta m/m$ vs. P_r, r). The data are plotted in two dimensions with the curves spaced by 5%, benefits for battery operation are indicated by the dashed lines.

applications (e.g., telecommunication satellites) require only 1.5 to 4.5 kW, RFC operation in GEO will be advantageous compared with the Ni/H_2 battery for only significantly increasing power requirements.

Performance losses of batteries compared with RFC systems for LEO applications result from their unfavourable DOD versus discharge cycle characteristics, resulting in a low DOD operation and cell stack exchange for long-term battery operation.

The influence of the overall operating time on the comparison of RFCs and batteries is examined in Fig. 4. A 25 kW RFC and a battery system are compared as function of orbital altitude and operating time. Curves of equal relative mass $\Delta m/m$ are spaced at 5%, intervals with negative values indicated by the dashed lines. The result of the system mass comparison does not depend on the operating time for a wide range of parameters (t_{OP}, r). For these parameter combinations the number of discharge cycles is very low, and neither battery exchange nor any change in DOD is necessary. One should note that the observed injections in the curves from Fig. 4 correspond to Fig. 3 using the same parameter set.

For a power of 25 kW, the RFC will generally show a lower system mass for orbit altitudes higher than 16 000 km. In LEO, the battery shows lower system mass for an overall operating period of less than three years, whereas the RFC shows better performance, if the system is operated longer than 3.5 years.

The same data are plotted versus the P_r, t_{OP} plane for the 450 km orbit in Fig. 5. For long-term space missions, a large increase in relative system mass is observed, increasing power requirement up to 20 kW. Further power increase shows no significant effect on relative system mass. If the operating period of the mission is decreased, the slope $\partial(\Delta m/m)/\partial P_r$ decreases and the relative system masses become limited to lower values. The RFC system is not advantageous compared with batteries when the operating period is less than three years.

Similar behaviour is shown for the gradient $\partial(\Delta m/m)/\partial t_{op}$. For high-power applications, this shows only smooth variations. However, low-power requirements (2 to 5 kW) generally show the battery system to be superior. From Fig. 5, one may conclude that RFC systems are preferable to batteries, when the power consumption exceeds 5 kW and the operating period exceeds four years, with the exception of a small parametric area within 20 kW and five years on the power-time axis.

The comparison of the Ni_2 battery and the alkaline or SPE regenerative fuel cell concept shows, that batteries used for in space power supply will generally result in better system performance under the following conditions: (i) for missions of less than

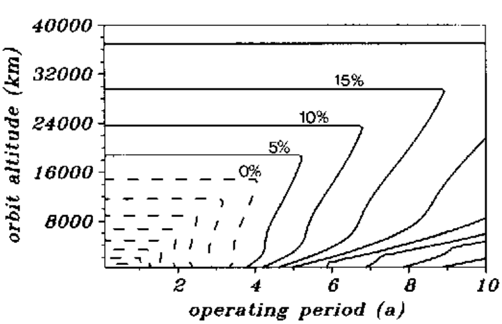

Fig. 4. System mass comparison for battery and RFC systems ($\Delta m/m$ vs. t_{OP}, r). The data are plotted in two dimensions with the curves spaced by 5%, benefits for battery operation are indicated by the dashed lines.

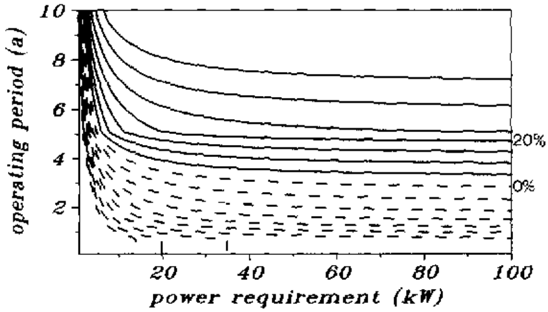

Fig. 5. System mass comparison for battery and RFC systems ($\Delta m/m$ vs. t_{OP}, P_r). The data are plotted in two dimensions with the curves spaced by 5%, benefits for battery operation are indicated by the dashed lines.

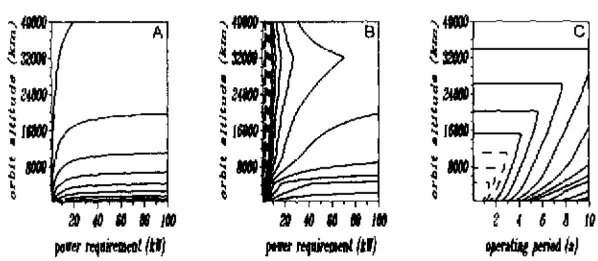

Fig. 6. System mass comparison of regenerative and reversible FC systems ($\Delta m/m$ vs. P_r, r); (A) the data are plotted in two dimensions with the curves spaced by 2%, (B) and (C) comparison of the reversible fuel cell with respect to the battery. The indicated levels are spaced by 5%.

3.5 years in low earth orbit, and (ii) for missions requiring less than 2 to 9 kW, depending on orbit altitude. RFC systems will have the advantage for: (i) long-term missions ($t_{OP} > 4.5$ years) with power requirements higher than 10 kW, and (ii) orbit altitudes higher than 20 000 km and power requirements higher than 10 kW. For missions beyond these requirements, a detailed comparison depending on all parameters must be performed. Recommendations are restricted to the assumption that aerodynamic drag affects both the battery and the RFC systems in the same manner.

However comparison of RFCs and batteries does not only depend on the independent parameters describing the space mission considered. Further energy storage techniques such as reversible fuel cells or the SOFC may improve on RFC performance, as well as improvements in component specific mass.

The application of reversible fuel cells may be a promising method to improve system performance. As charge and discharge reactions then take place in the same electrochemical cell, the electrolyzer mass is eliminated. However, the problem of finding a stable bifunctional oxygen electrode catalyst has yet to be solved. A comparison of RFCs and reversible fuel cells based on the assumption that a stable bifunctional oxygen catalyst is available with an efficiency comparable to current separate catalysts, is given in Fig. 6.

The performance gain for systems operating in GEO is negligible. This is reasonable, since the GEO t_d/t_c ratio is small and only, a small electrolyzer is required which does not change efficiencies and the specific masses. For LEO operation, the use of the reversible fuel cell system would result in overall system mass benefits of 16%. This value includes the PV array, radiator and storage. For the electrochemical cells alone, the system mass saving would be significantly higher. Beyond the saving in mass by eliminating the electrolyzer, fuel processing is simplified, which should result in a higher energy density for the reversible fuel cell system.

The above results are uncertain, since they are based on variable assumptions, e.g., the efficiency of the reversible fuel cell. Slightly decreasing efficiency may cause a significant overall performance loss using this technology.

Ambiguity in the technical data may be avoided by considering SOFCs, which are well understood on a laboratory scale. Performance data are reported in Table 1. Due to the high operating temperature of the SOFC, polarization losses are negligible, and the cell can be operated in a reversible mode.

A direct comparison of alkaline RFCs and SOFC systems is given in Fig. 7. For LEO, slight improvements in performance using the SOFC are only seen for orbits less than 600 km altitude. Since, for this parametric range, PV cells with higher specific weight are considered, system improvements result from the lower specific weights of the SOFCs, but are nearly compensated by slightly less efficiencies (see Table 1). Beyond this limiting orbit altitude, SOFCs show system mass savings up to 22% compared with AFCs, depending on power requirements. System mass savings of 20% can be achieved for power ratings higher than 15 kW. Operating the SOFC in GEO results in a 24% lower system mass compared with alkaline technology, assuming power requirements higher than 20 kW. This implies a significant improvement of RFC performance compared with batteries. A power consumption higher than 10 kW will result in mass savings greater than 30% a value, which is not obtainable within the 100 kW range, using alkaline RFC.

The SOFC is advantageous compared with batteries for operating periods less than three years in LEO. This value is slightly lower than the corresponding time limit for AFCs.

Finally, we compared the battery excess mass based on state-of-the-art cell performance data to results which assume future cell performance improvements. Future cell performance data, are given in Table 1, assuming:

(i) the potential for a 40% mass reduction for the RFC cell stacks;

(ii) battery energy density improvements greater than 20%, and

(iii) slight efficiency improvements.

The data presented in Fig. 8 are calculated from the relative excess mass of the battery (eqn. (7)), using eqn. (8):

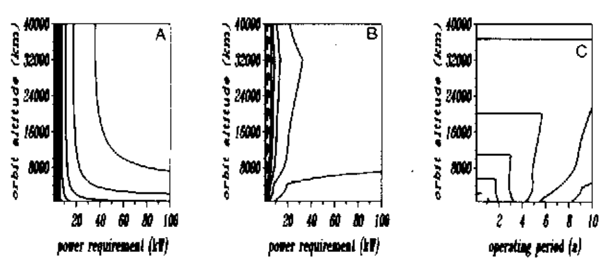

Fig. 7. System mass comparison of SOFC and alkaline RFC systems ($\Delta m/m$ vs. P_r, r); (A) the data are plotted in two dimensions with the curves spaced by 2%, (B) and (C) comparison of the SOFC with respect to the battery. The indicated levels are spaced by 10%.

$$\frac{\Delta m_f - \Delta m_a}{1 - \Delta m_a} = 1 - \frac{m_{RFC,f} m_{bat,a}}{m_{RFC,a} m_{bat,f}} \tag{8}$$

where the subscripts a and f refer to present and future performance data respectively.

Figure 8 shows that a future effort in technology will increase the system mass benefit of the RFC for high orbit mission whose power demands are higher than 15 kW. For LEO missions and GEO space application requiring less than 15 kW, the system mass disadvantage of the battery will diminish.

Development in both RFC and Ni/H_2 technology will not significantly change the present relationship of their system masses, but the parametric area of fuel cell operation will be slightly narrower.

Although improvements in the specific masses of both the PV array and the radiator may affect the overall system comparison, these are not considered. However, the effect of a small improvement of the RFC efficiency compared with the battery has been estimated.

Again results are restricted to the assumption that the aerodynamic drag contributes to both systems. Since the battery system efficiency ($\eta_{bat} = 0.75$ W h) is considerably higher than the overall RFC efficiency ($\eta_{RFC} = 0.59$), battery storage requires smaller PV arrays compared with the RFC. This will cause an additional mass penalty for the RFC system in regard to the aerodynamic drag. This mass penalty presents the increase in required transport capacity to supply propellant for drag compensation. A system mass comparison including drag contributions is shown in Fig. 9 for the LEO applications. It clearly shows, that drag considerations lead to a strongly increasing system mass for space missions operating in 600 km orbital altitude. In a 450 km

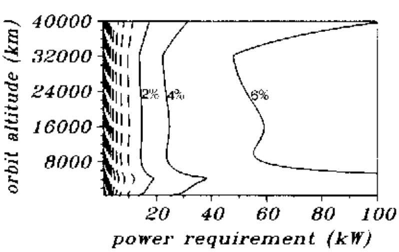

Fig. 8. Variations of the system mass saving due to further development. The data are plotted in two dimensions with the curves spaced by 5%. In the parametric range of the dashed curves, battery development will be more successful than RFC development.

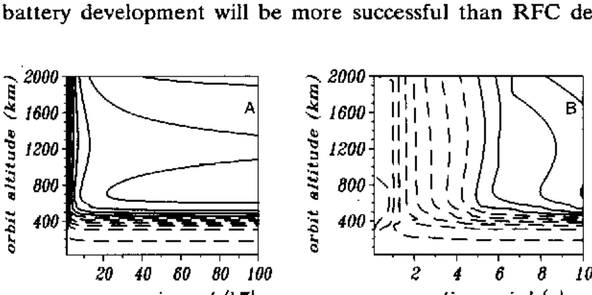

Fig. 9. System mass comparison for battery and RFC for LEO missions considering of the aerodynamic drag. The data are plotted in two dimensions with the curves spaced by 5%. The data are given depending on both, orbit altitude and (A) power requirement or (B) operating period.

orbit, the system mass benefits of RFC systems are completely annulled by the aerodynamic drag. In orbits beyond this limit, the applicability of RFC systems is shifted to higher power requirements, thus RFC application in LEO space missions will not be worth while for power levels less than 20 kW.

Discussion

In the previous section, a comparison of system masses of Ni/H_2 batteries and RFCs has been given. The parametric areas for fuel cell and battery operation were evaluated based on data representing the system additional mass when a battery is used for energy storage. The Ni/H_2 battery is a qualified system, operating LEO and GEO missions, whereas RFC systems are under development, although fuel cells and electrolyzers are qualified components. Thus, the application of RFCs to future space missions requires a demonstration of distinct advantage compared with the battery system to make the development effort worthwhile. If this is justified, further RFC development will result in a system mass advantage of 20% compared with batteries.

The parametric area of valuable RFC applications must also cover a reasonable range of space missions, including:

• Satellites in the GEO which require typically 1.5 to 5 kW over more than five years. In future applications, significantly increased power is not anticipated. Since GEO applications normally serve worldwide telecommunication networks, large satellite structures with a common energy supply may be excluded, reasonable due to mutual interferences of their emissions.

• For future LEO applications, several manned and unmanned space missions (e.g., Man Tended Free Flyer (MTFF) and the European Space Station (ESS) have been proposed. These missions will orbit at less than 1000 km altitude with power requirements from 7 to 40 kW in the near future (i.e. in 2000–2006).

After having considered both the predicted mass benefits of the regenerative energy storage and the system mass saving required if RFC developments are to be emphasized, we found no necessity to develop the RFC for GEO applications. The power requirements of GEO are predicted to be kept within the 5 kW range. Even if power should increase to 7 kW, it still would not be sufficiently high to encourage the use of alkaline RFC systems in GEO missions. The SOFC technique will result in a better GEO performance but a system mass gain of more than 20% will be necessary for power requirements higher than 7 kW. Reasonable future GEO power demands can be supplied by batteries, which will be competitive with SOFC systems. Thus RFC technology is not required for this application.

As long as the influence of drag is neglected, the parametric range for RFC applicability covers a reasonable field of future space missions in LEO. The RFC systems would reach the performance limit justifying extended development effort if power demands were higher than 4 kW and orbit altitudes were less than 1000 km. However, battery application in orbits of less than 450 km altitude will be favoured when the extra mass caused by aerodynamic drag is considered. System mass savings, when RFC are used, will not significantly exceed 20% for missions operating over ten years in orbits ranging from 600 km to 2000 km altitude (see Fig. 9). The principle advantage of RFC application for space missions requiring high cycle stability will be negated by its less favourable overall efficiency compared with that of batteries. RFC potential to reduce system mass is restricted to a power greater than 20 kW, operating periods longer than seven years and orbit altitudes greater than 600 km. Thus, there are few applications for RFC systems for LEO missions.

Since the increased mass due to drag compensation results from the efficiency of the RFC system, a definite improvement in the fuel cell efficiency is required to make it suitable for LEO. In Fig. 10 the fuel cell development goals are shown which will make RFC operation favourable in LEO. From these results, one may estimate a required fuel cell efficiency of $\eta_{fc}=0.78$ for LEO operation. However, this performance cannot simply be achieved by reducing the operating current density.

Improvement of the catalytic properties of both, the fuel cell and the electrolyzer, is the most important task in RFC development for future space applications.

However, it is questionable, whether the development goal may be achievable by improvement in catalytic properties, since nearly 17% of the reaction enthalpy is converted into heat due to the entropy changes of the H_2/O_2 reaction. Ideally both, an improvement of electrocatalytic properties and the substitution of heat for electricity is required. The latter may be achieved by operating the electrolyzer below the thermoneutral voltage $u_0=1.48$ V with integration of thermal storage into the RFC system.

Additional competition for both RFC and battery systems for future LEO space missions will be given by solar dynamic energy supply combined with thermal energy storage. This concept should show the advantages in regard to overall system mass, since it shows less performance loss due to aerodynamic drag in LEO than PV energy supply. On the other hand, these systems only become applicable for high power requirements ($P_r>25$ kW), so there would always be a wide range of application for LEO electrochemical energy storage.

Further improvement in the characteristic performance data of both RFCs and Ni/H_2 batteries will not significantly effect the results of the presented comparison. Hence the parametric range for RFC operation will not be significantly enlarged. However, any improvement of the DOD versus discharge cycle characteristics of the battery will move the parametric range of reasonable RFC application to higher power requirements. In LEO from 200 to 1000 km altitude, batteries will show better performance than RFCs if their power is less than 4 kW. The system excess mass of the batteries will be within 20% for power requirements up to 8–10 kW, depending on orbit altitude. Thus, improvement of both, DOD characteristics and cycling stability should receive priority in further battery development.

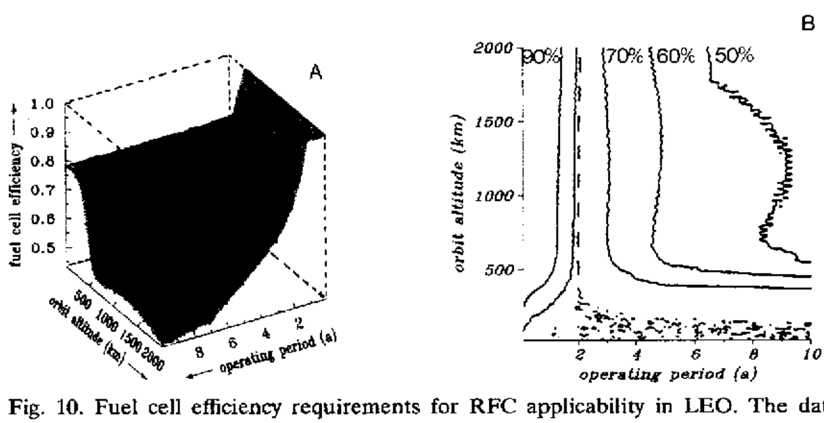

Fig. 10. Fuel cell efficiency requirements for RFC applicability in LEO. The data are plotted both, as (A) three-dimensional plot and (B) as level chart; the solid curves are spaced by 10%, the dashed curve indicates the area of $\eta_{fc}=78\%$.

Development of high power regenerative fuel cells for long term LEO applications may be also desirable. Although solar dynamic (SD) will be a competitor for high power LEO missions, RFCs are still applicable, since SD generators will only supply the base load.

Since long-term operation of RFCs is required if their use in space energy systems is useful, their long-term stability ($t > 7a$) and reliability must be demonstrated.

The limiting conditions for RFC application require stability of both, the fuel cell and the electrolyzer for at least 42 000 discharge cycles. For LEO missions this means accumulated fuel cell operation of more than 20 000 h, and electrolyzer operation of more than 42 000 h. Both, alkaline and SPE fuel cell performance have been tested for more than 20 000 h [7–9], with only small voltage losses. Electrolyzers have been rated for 40 000 operating h [8]. Thus RFCs should be applicable for low-orbit missions.

Recent RFC reliability considerations [10], based on the failure rate of individual fuel cells obtained from a field test program conducted by International Fuels Cell (IFC), show that their operating period must be on the order of seven years to ensure space mission reliability goals. Thus the parametric range for the RFC may be very narrow, unless their stability is improved.

Application of RFC systems in manned space missions will be more advantageous, if the energy supply can be integrated into the environmental control and life support systems, e.g. for water purification. The electrolyzer may for example supply subsystems which require hydrogen for carbon dioxide reduction (e.g. Sabatier reactor) or which supply oxygen to the crew. Additionally, redundancy may be increased by the use of appropriate fuel processing.

Thus, the RFC for manned space missions is not comparable to a conventional energy supply, which would not be integrable into more complex fuel processing systems. However, the life support system is not within the scope of this paper, so these conclusions are restricted to unmanned space missions.

Summary

By comparing the H_2/O_2 RFC to rated battery systems, we found only a few application ranges of H_2/O_2 RFCs for energy supply in space missions. Although the RFCs show better performance in regard to the overall system mass for the widest parametric range of applications, this does not embrace those which are most practical.

For long-term LEO the RFCs may have an advantage over batteries whose cycle life and low DOD may be questioned. However, the low efficiency of the RFC requires a high excess system mass due to aerodynamic drag, thus the battery show better performance for orbit altitudes less than 500 km.

Due to increasing orbit period, high orbit space missions do not require high cycle stability but high energy capacity. Thus, the performance advantage of the RFC system results from decoupling the system requirements for power and energy storage capacity. Even so, it remains within the $\Delta m = 20\%$ range for typical space missions.

An increased effort to develop RFCs cannot be justified by the excess mass of battery systems in GEO applications. This is because the parametric range for mass savings, if RFCs are used, differs significantly from the expected GEO mission range. Similarly, reduced mass should not be expected, if RFCs are used, in LEO missions beyond 500 km orbit altitude.

Extended RFC development may be justified if long-term manned high power LEO missions are required. The strongest argument to increase RFC development effort results from the possible integration of their subsystems into the tasks required in manned space missions.

Thus, the Ni/H_2 battery is still strongly in the competition, particularly if improvements in DOD and cycle life can be maintained. In contrast, fuel cell stability and reliability must be improved if RFC systems are to be successfully applied in space energy.

Further improvement in the specific weight of both batteries and fuel cells is unlikely to change significantly the conclusions concerning the RFC in space power supply. The development of reversible fuel cells seems is even less favourable, since only small system mass savings ($\Delta m/m < 16\%$) are predicted. However, the development of a stable oxygen catalyst may cause performance losses concerning his efficiency. Successfully application of the RFC systems in space applications will require:
(i) improvement in specific weights of both PV arrays and radiators;
(ii) increase in the power per unit area of PV arrays;
(iii) improvement in electrocatalytic properties of electrochemical RCF components;
(iv) substitution of thermal energy for electricity.

In particular, a fundamental research effort on electrocatalytic properties and on the improvement of overall RFC efficiency is required if this technology is expected to succeed as a space power supply.

List of symbols

DOD	depth-of-discharge of the battery
M	mass of the earth, kg
m_{bat}	mass of the battery, kg
m_{el}	mass of the electrolyzer, kg
m_{fc}	mass of the fuel cell, kg
m_{PV}	mass of the photovoltaic array, kg
m_{rad}	mass of the radiator, kg
m_{st}	mass of the reactant storage, kg
n_x	number battery stack exchanges
P_r	output power of the fuel cell, kW
R	radius of the earth (6378 km), m
r	radius of the orbit, m
t_d	discharge period of the eclipse phase, s
t_c	charge period, s
t_{OP}	operating time of the energy storage, s
U_{bat}	discharge voltage of the battery, V
U_{enth}	enthalpy voltage of the battery, V
γ	gravitational constant, $m^3/kg\ s^2$
η_{fc}	efficiency of the fuel cell
η_{el}	efficiency of the electrolyzer
η_{bat}	current efficiency of battery
ρ_{bat}	specific mass of the battery, kg/kW
ρ_{fc}	specific mass of the fuel cell, kg/kW
ρ_{el}	specific mass of the electrolyzer, kg/kW
ρ_{PV}	specific mass of the photovoltaic array, kg/kW
ρ_{rad}	specific mass of the radiator, kg/kW

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