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Selection of Batteries and Fuel Cells for Yucca Mountain Robots

R. S. Upadhye

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Ravindra S. Upadhye

Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA, 94551
925-423-1299; upadhye1@llnl.gov

INTRODUCTION

The Performance Confirmation program of the Yucca Mountain Repository Development Project needs to employ remotely operated robots to work inside the emplacement drifts which will have an environment unsuitable for humans (radiation environment of up to 200 rad/hour (mostly gamma rays, some neutrons) and maximum temperatures of 180°C. The robots will be required to operate inside the drifts for up to 8 hours per mission. Based on available functional requirements, we have developed the following specifications for the power needed by the robots:

Each robot will need a sustained power of 100 W for 8 hours. During that time, for a combined period of 60 minutes, the robots may need 1000 W power. Thus the total energy required by the robots is 1700 W-hr at nominal sustained load of 100 W and peak load of 1000 W.

There are currently no commercially available batteries that meet the specifications of temperature and radiation flux. Most commercial batteries are designed to operate at ambient temperature. Some batteries, such as zinc/air or aluminum/air, designed for ambient temperature, are theoretically capable of being operated at higher temperatures, however, significant R&D will be required to realize their high temperature potential. In any case, their radiation tolerance remains unknown. We have investigated a number of batteries, and downselected four of them as potential candidates for the Yucca Mountain Project. We describe them under the section on batteries.

We have compared a number of fuel cells for the required service at Yucca Mountain. Out of the seven fuel cells we considered, we have downselected three as potential candidates for service in Yucca Mountain. The details of these considerations are given under the section on fuel cells.

We will investigate the radiation tolerance of Phosphoric Acid Fuel Cells (PAFCs) by subjecting them to increasing levels of gamma-ray radiation, and characterizing their performance after each radiation treatment using a proprietary micro-fuel-cell developed at Lawrence Livermore National Laboratory (LLNL). We will describe the construction of the PAFC, followed by the description of the process used to characterize them under the section on radiation resistant fuel cells.

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BATTERIES

A large number of batteries, both primary (single use) and secondary (rechargeable) are on the market. We decided to limit our attention to the secondary types for two main reasons: First, at 1700 W-hr demand per shift, a large number of batteries will be consumed every day, making such a power source uneconomical. Second, no material subjected to neutron flux can be just discarded as waste without proper characterization for activation, thus making the discard operation rather expensive.

The batteries we considered are listed below. Even though this list does not include "every type of battery" ever made, it does include all the battery types mentioned in References 2 and 3.

Table 1
List of batteries considered for the Yucca Mountain Robots

Type	Consider further?	Reason / Comment
Alkaline Batteries		
Aluminum-Air	No	Cannot be recharged electrically
Iron-Air	No	Development discontinued
Manganese-Zinc	No	Rechargeable limited to size D
Nickel-Cadmium	Yes	
Nickel-Iron	No	Development discontinued
Nickel-Metal-Hydride	Yes	
Nickel-Zinc	No	Still under development; limited life
Silver-Oxide-Zinc	No	Not rechargeable type; short cycle life
Zinc-Air	No	Cannot be recharged electrically
Conventional Batteries		
Lead-Acid	Yes	
Lithium Batteries		
Li Liquid-Electrolyte	No	Safety issues in recharging
Lithium-Ion	Yes	
Lithium Iron Disulfide	No	Not developed for rechargeable type
Lithium-Polymer	Yes	
Sodium Batteries		
Sodium-Sulfur	No	Safety issues
Sodium-Metal Chloride	No	Use restricted to large units
Zinc-Halide Batteries		
Zinc-Bromine	No	Safety issues
Zinc-Chlorine	No	Safety issues
Other Types		
Carbon-Air	No	Still experimental

Safety was our number one consideration. A number of batteries were eliminated from further consideration because of safety concerns. The entire class of Zinc-Halogen batteries was eliminated, since these batteries need to store bromine or chlorine externally under pressure. Both chemicals are corrosive and toxic gases, and any leakage of them will lead to severe corrosion problems in the waste packages. Also eliminated was the Sodium-Sulfur battery, the development of which was discontinued due to safety concerns. Finally, the Liquid-Electrolyte Cell was eliminated because it exhibited safety problems while recharging. The details of the specific safety concerns can be found in Reference 2.

Even though the Lead-Acid battery contains sulfuric acid, its widespread use has led to a number of advancements that render leakage of the acid extremely improbable. It is for this reason that we include it for further investigation.

We eliminated the batteries that are mainly primary batteries. For example, Manganese-Zinc, Silver-Oxide-Zinc, and Zinc-air were eliminated because their rechargeable version is not commercially available.

A number of batteries were eliminated from further consideration because they are not commercially available. Among them are Aluminum-Air, Iron-Air, Nickel-Iron, Nickel-Zinc, High Temperature Lithium, Sodium-Metal-Chloride and Carbon-Air.

This leaves us with five batteries: Lead-Acid, Lithium-Ion, Lithium-Polymer, Nickel-Cadmium and Nickel-Metal-Hydride. The typical energy and power densities of them, along with the estimated weight to provide the required service defined earlier, are given in Table 2.

Table 2
Comparison of the four selected battery types

	Lead-Acid (PbA)	Lithium-Ion (LiI)	Lithium-Polymer LiPo	Nickel-Cadmium (NiCd)	Nickel-Metal-Hydride (NiMH)
100 W regime					
Specific energy, W-hr/kg	28	150	160	30	75
Specific power, W/kg	4	45	107	4	160
Required Weight, kg	25	5	4	25	9
1000 W regime					
Specific energy, W-hr/kg	18	75	160	30	55
Specific power, W/kg	18	1350	107	30	300
Required Weight, kg	56	13	9	33	18
Required Total Weight, kg	81	18	14	58	28

It can be seen from this table that the LiPo battery is the lightest, followed by LiI, NiMH, NiCd and PbA. We have decided to investigate these five types in the following order: LiPo, LiI, PbA, NiMH and NiCd. The selection of LiPo/LiI is obvious, because they are the lightest. Nickel tends to get activated by neutrons, so at the end of their useful lives, batteries containing Nickel will need to be handled with care, and it would be desirable to avoid them completely if we can. This places them at the bottom of the list, making PbA battery the second choice.

FUEL CELLS

Compared to batteries, the numbers of different types of fuel cells are rather limited. We considered the following fuel cells for use in Yucca Mountain:

Table 3
List of fuel cells considered for the Yucca Mountain Robots

Type	Consider further?	Reason / Comment
Alkaline	No	Radiation damage; CO_2 poisoning
Direct Carbon	No	Under development
Direct Methanol	No	Under development
Molten Carbonate	Yes	
Proton Exchange Membrane	No	Radiation damage; CO poisoning
Phosphoric Acid	Yes	
Solid Oxide	Yes	

Of the seven types listed above, two (Direct Carbon and Direct Methanol) can be immediately eliminated because they are not commercially available. Both the Proton Exchange Membrane (PEM) fuel cell and the alkaline fuel cell are commercially available, however, both use polymeric membranes, which is likely to degrade due to gamma radiation. In addition, atmospheric CO2 poisons the alkaline fuel cell electrolyte, and CO poisons the electrodes in the PEM fuel cell, unless pure hydrogen is used as a fuel. The PEM suffers from the additional requirement that the polymeric membrane needs to be kept hydrated at all times, limiting its temperature of operation to about 80 C. This leaves us with the remaining three fuel cells: Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC).

All these fuel cells operate at or above the temperatures expected in the Emplacement Drifts and Thermally Accelerated Emplacement Drifts (up to 180 C). PAFCs operate at about 200 C; MCFCs operate at about 650 C; and SOFCs operate between 550 C and about 800 C. Therefore, there would be no need to insulate or cool them, as for batteries. PAFCs have the advantage that they operate at temperatures closer to the expected ambient temperature than the other fuel cells, which will minimize any insulation requirement. It is for this reason that we have chosen to investigate PAFCs first, followed by the other two fuel-cell alternatives.

TEST PLAN FOR FURTHER DOWNSELECTION OF BATTERIES AND FUEL CELLS

We consider the development of batteries that can withstand the high ambient temperatures unnecessary, because insulating them or cooling them is relatively straightforward. Similarly, the MCFC and SOFC can be insulated to limit heat losses.

We plan to characterize the performance of the five battery types at various temperatures above ambient. Once the performance vs. temperature relationship is obtained, we can then select the optimum temperature of operation based on performance and the amount of insulation and/or cooling needed. Similarly, the desired amount of insulation can be estimated for each one of the three fuel cell types.

Unfortunately, a similar simple solution is not available for radiation. Since most of the radiation flux is from gamma rays, there is no practical method of shielding the batteries and/or fuel cells from radiation. Therefore, we need to test the radiation tolerance of candidate battery and fuel cell types. For example, we will examine the dependence of both the specific energy and specific power on Total Integrated Dose (TID) of radiation. Similar measures can be used for fuel cells as well. Once statistically significant estimates of the useful lives of the selected batteries and fuel cells are obtained, we can perform a further evaluation for each specific application.

CONCLUSIONS AND FUTURE WORK

The methodology of selecting the optimal power source(s) for the Yucca Mountain Robots is now in place. We have narrowed our search down to five types of batteries, and three types of fuel cells. In the coming years, we will be conducting a number of tests on the selected batteries and fuel cells to determine their tolerance to temperature and radiation. Based on the performance of these under various conditions of temperature and radiation, we will optimize the power source(s) for each application.

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