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POTENTIAL POWER SOURCES FOR HIGH-TEMPERATURE GEOTHERMAL APPLICATIONS

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Abstract

The thermal response under geothermal-borehole conditions of a conventional thermal battery was evaluated for various designs by numerical simulations using a finite-element thermal model. This technology, which is based on molten salts, may be suitable as a power source for geothermal borehole applications for data logging. Several promising candidate electrolytes were identified for further study.

INTRODUCTION

Modified lithium/thionyl chloride cells are currently used to power instrumentation for data logging in deep geothermal boreholes. The temperature limitation of the cells of ~180°C requires that they be insulated from their immediate thermal environment in the borehole where temperatures can be >300°C. Consequently, this requires incorporating a very expensive vacuum dewar into the system.

The technology used in thermally activated batteries–so-called "thermal batteries"–may have applications for geothermal power sources. This technology uses an internal heat source to bring the battery to operating temperature. Current technology uses lithium alloys (for example, Li-Si) as the anode and metal sulfides (for example, FeS_2) as the cathode. The separator is an ionically conducting molten salt immobilized by capillary action by a ceramic powder (for example, MgO). The melting point of the salt determines the lower temperature of operation of the battery. The battery is active only when the salt phase is liquid and reaches its end of life once the electrolyte freezes.

There are halide mixes and non-halide salts that have melting points less than 300°C. This opens the possibility of using the heat in the surrounding geothermal borehole to maintain the electrolyte salt in the battery separator above its melting point. If enough heat can reach the battery from the surrounding hot geothermal borehole, the battery can continue to function until its electrochemical reserves are consumed. Initial melting of the separator salt before lowering the data logger into the borehole would be required for this scenario. This could be accomplished by using an internal pyrotechnic heat source or possibly an internal resistance heater. Conventional thermal batteries use $Fe/KClO_4$ mixtures to melt the electrolyte and bring the battery stack to operating temperature. This is a mature and well-understood technology.

In this paper, we describe how the use of conventional thermal-battery pyrotechnics technology, in conjunction with improved thermal-management schemes and design changes, can be incorporated into a possible geothermal battery. The thermal response of a typical thermal battery under geothermal-borehole conditions was evaluated for various designs by numerical simulations using a finite-element thermal model. Battery technology based on molten salts was evaluated in the study to determine its suitability as a power source for geothermal borehole applications. Several promising electrolytes were identified for further study.

COMPUTER MODELLING

The model used for calculation of the thermal profiles of a thermal battery was based on a finite-element approach. Several hundred nodes were used in the modelling. The primary temperatures of interest were those of the battery stack and case at each end and in the middle. The modelling work was an extension of earlier work started at Sandia (Bush and Hughes, 1979) using a finite-difference code. The FORTRAN code was further

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developed by the Royal Aerospace Establishment (Knight and McKirdy, 1990) to run on a CRAY computer. The model was later refined at Sandia to incorporate measured thermal-properties. The latest version is based on a finite-element approach and runs on a 486 PC under Lahey FORTRAN. A Visual BASIC interface was incorporated for ease of data entry.

RESULTS AND DISCUSSION

First Simulation Series

The initial series of modelling tests were conducted with the conditions listed in Table 1. The battery parameters were derived by modifying a design used for a long-life (>1 h) thermal battery (Neiswander and Baldwin, 1988).

TABLE 1. Conditions Used for Modelling Purposes for First Simulation Series.

- Seventeen cells, 50.8 mm in diameter; battery diameter of 76.2 mm.
- Separator of LiCl-KCl eutectic (m.p.= 352°C) with 35% MgO.
- Anode of 44% Li/55% Si and cathode of 73.5%FeS_2/25% separator/1.5% Li_2O.
- Battery is activated on surface at top of borehole at t=0.
- Borehole depth is 1,800 m with the depth-temperature profile by Lysne and Henfling (1994).
- Battery is lowered at rate of 0.102 m/s to 1,800 m and is held there for one hour and is then raised at 1.016 m/s.
- Battery is enclosed inside of a 0.508-mm-thick steel case with a 3-mm air gap between the stack and case.
- Stack is insulated with 8.6-mm-thick Min-K TE1400 sleeve.
- Heat transfer coefficient for all surfaces exposed to the borehole air is based on a correlation for laminar flow over a flat plate:

  $$h = (k/L)0.664(Re_L)^{1/2}(Pr)^{1/3} \tag{1}$$

  where k is the thermal conductivity, L is the characteristic length of the battery, Re_L is the Reynolds number, and Pr is the Prandl number. Re_L is defined as

  $$Re_L = \rho vL/\mu \tag{2}$$

  where ρ is the density of air, v is the velocity, and μ is the viscosity. Pr is the ratio of the kinematic viscosity (μ/ρ) over the diffusion coefficient.

The modelling results for the first simulation are shown in Figure 1. Only the temperatures for the center and top cells are shown, as the temperature of the bottom cell (next to the header) was very close to that of the top cell. The presence of extra heat pellets outside of the active stack results in the high initial temperature for the end cells relative to the center cell. After ~1,000 s, the stack temperature becomes fairly uniform.

As can be seen, the electrolyte reaches its freezing point near 5,000 s. (Note the inflection in the temperature-time curve where the salt begins to freeze at 352°C.) At this point, the battery would no longer be able to supply power. At the time of freezing of the electrolyte, the borehole temperature is only 160°C. The borehole temperature during the hold period (starting at 17,712 s) is ~277°C which means that for this design to function properly, the melting point of the electrolyte would have to be less than 277°C. This battery design would not function long enough to be of any value for the envisioned application.

The simulation was repeated but the descent rate was doubled to 0.203 m/s. The onset of electrolyte freezing remains the same but at the faster rate of descent, the onset of the hold period is now 8,856 s instead of 17,712 s. The borehole temperature is 230°C at the time of electrolyte freezing. This is substantially higher than the value of 160°C found in the first simulation at a descent rate of 0.102 m/s. However, the melting point of the LiCl-KCl eutectic of 352°C is still too high to be useable for this application.

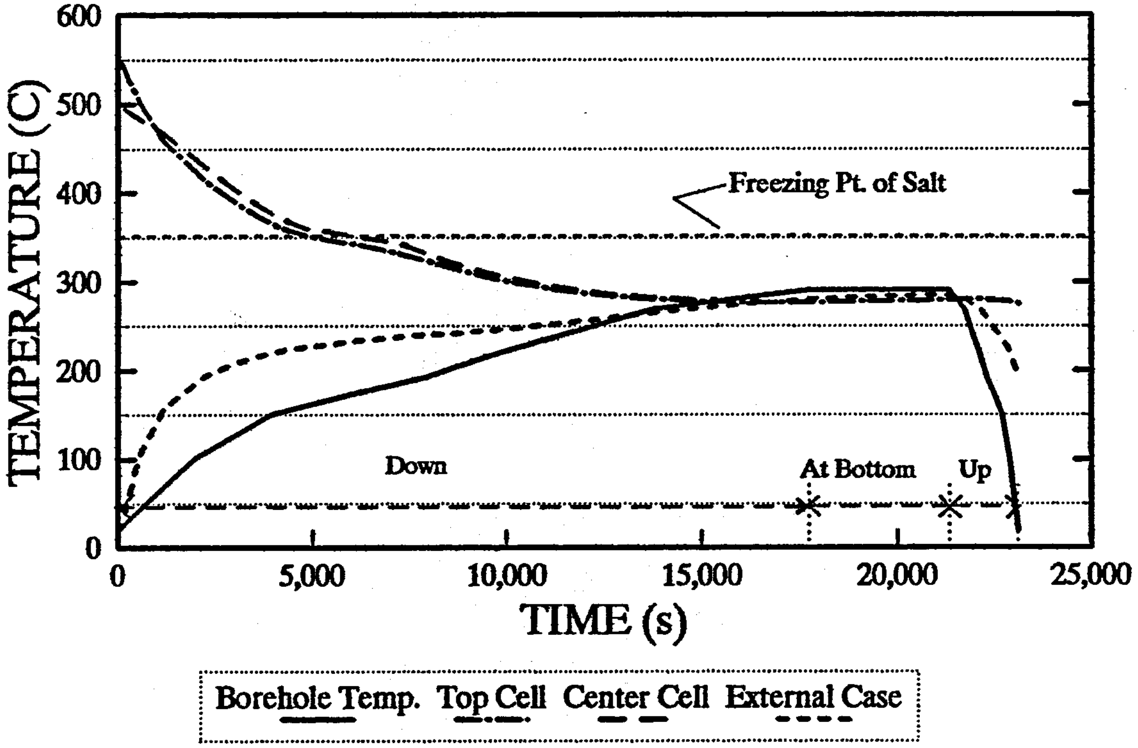

FIGURE 1. Thermal Profile as a Function of Time of Thermal Battery Using LiCl-KCl Eutectic in Borehole.

Second Simulation Series

In the second series of simulations, a LiBr-KBr-LiF eutectic was used in the place of the LiCl-KCl eutectic. This electrolyte has a melting point of 313°C and thermal-property data for it are available in the thermal model for simulation purposes. Table 2 lists six scenarios that were evaluated using the lower-melting electrolyte. A rate of descent of 0.203 m/s was used for this series of simulations, with a one-hour hold at the bottom of the borehole and the same ascent rate as before. The effects of the design changes of Table 2 on the thermal profile of the bottom cell of a battery stack are summarized in Figure 2.

TABLE 2. Changes in Design Parameters for Second Series of Thermal-Modelling Tests.

Case	Description
1	Seventeen cells as for battery of Table 1, except with LiBr-KBr-LiF eut.
2	Repeat Case 1 but reduce stack diameter to 38.1 mm from 50.8 mm.
3	Repeat Case 2 but with 34 cells (two 17-cell stacks electrically wired in parallel or series).
4	Repeat Case 2 but with 50% reduction in thickness of Min-K insulation.
5	Repeat Case 2 but with 50% increase in thickness of Min-K insulation.
6	Repeat Case 2 but with 1.4 cal/s (5.86 W_e) of power supplied by internal heater powered directly from battery.

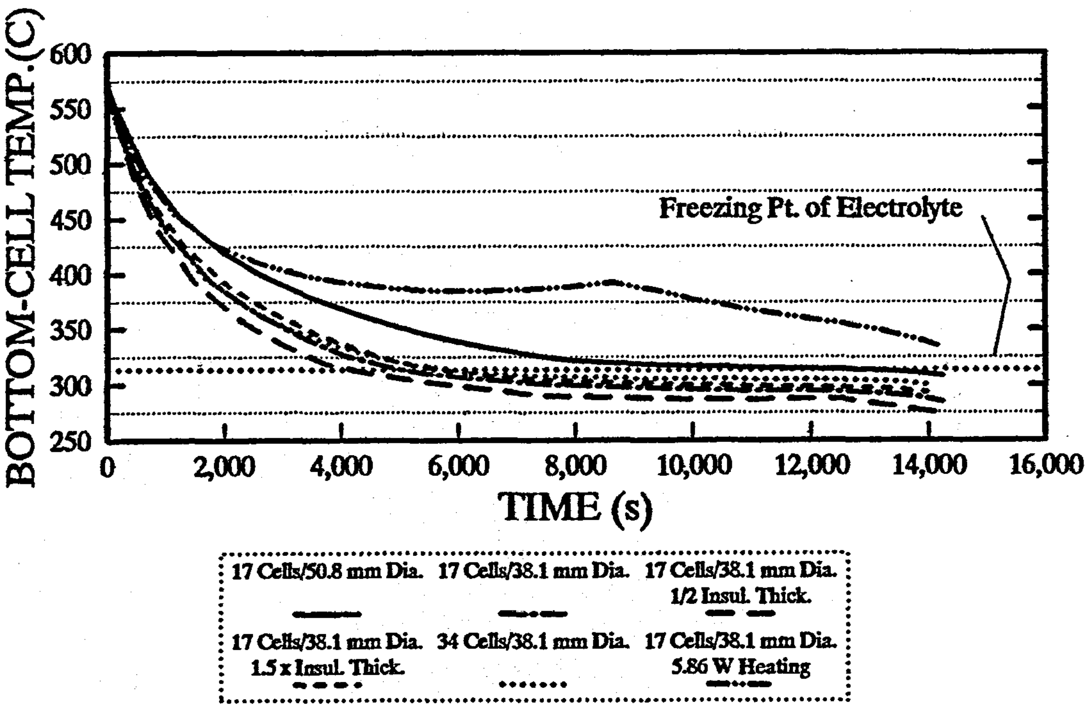

FIGURE 2. Effect of Design Changes to Thermal Profile of Thermal Battery Using Low-Melting LiBr-KBr-LiF Eutectic.

The temperature of the lower-melting electrolyte for the 50.8-mm-dia. stack (Case 1) does not reach the freezing point until almost 12,000 s, compared to 5,000 s for the LiCl-KCl eutectic. This is still insufficient time for the battery to function for the entire data-logging mission.

Typically, the diameter of the case used to contain the data logger used in boreholes is 50.8 mm. Thus, the diameter of the power supply used in this package must be less than that. The data in the first simulation series were for a *stack* diameter of 50.8 mm, with the fully insulated battery being 76.2 mm in diameter. The simulations performed using a battery stack that is 38.1 mm in diameter (Case 2) are more reasonable. As expected, reducing the diameter of the battery stack significantly increases the rate of heat loss from the stack due to the lower mass. The time for freezing of the electrolyte to occur is reduced by more than half–from 12,000 s to 5,000 s.

There is very little difference in the thermal performance when the number of cells (stack height) in the battery is doubled for a 38.1-mm-dia. stack (Case 3). The initial portions of the temperature-time curves are almost identical, with the stack of 34 cells having a slightly higher temperature after ~3,500 s. The small effect over this range of cells suggests that there is some flexibility in meeting the power needs by appropriate electrical configuring of the cell stack. The two stacks can be connected in series for higher voltage output or in parallel for a higher current output. In addition, taps in the stack can be used to provide other voltages that may be needed for geothermal applications

Cutting the insulation thickness in half for a 17-cell, 38.1-mm-dia. stack (Case 4) increases the rate of heat loss, as expected. The melting point of the electrolyte is reached after ~4,000 s, compared to 5,000 s for the standard thickness of insulation. However, when the thickness of the insulation is increased by 50% (Case 5), the degree of improvement that is realized is less than expected. The cell temperature was only slightly higher than that for the standard thickness.

In the last scenario (Case 6), the output of the battery is used to power an internal heater. This could be simply a wrap of resistance wire around the battery stack. The thermal response using a power input of 5.86 W_e of electrical energy in this mode provides the best results. The simulation indicates that it should be possible to keep the temperature of the stack well above the melting point of the LiBr-KBr-LiF eutectic during the entire borehole mission. Of course, extra capacity would be necessary to provide the electrical power and this would have to be built into the original battery design. The input energy corresponds to a heating current of 170 mA with a 17-cell design and a 2-V electrochemical couple. This is reduced to 85 mA if a 34-cell stack is used. Using a cathode with a higher emf will reduce the number of cells and provide higher power.

With a 38.1-mm-dia. stack, the corresponding current densities are 150 A/m^2 and 75 A/m^2, respectively, which are relatively low for this technology. Superimposed on this background load would be the data logger's load that is estimated to be 500 mW or less. Thus, the bulk of the power output from the battery would be used to keep it hot. The final size of the battery will depend upon the total mission time and final power requirements. By adjusting the masses of the active anode and cathode in each cell, it should be possible to design enough capacity into the battery to carry out the intended mission.

Future Work

The computer simulations were conducted using two of the molten salts currently being used in thermal batteries. There are other lower-melting halides that may be equally suitable. Salt mixes based on chlorides and bromides of Rb and Cs, for example, have melting points between 238°C and 278°C. The corresponding iodide mixes have melting points even lower (<190°C). These materials are much more expensive than the corresponding Li, K, and Na counterparts, however.

The viability of such mixes has not yet been tested in the environment expected in geothermal boreholes. Typically, the lower-melting materials have much lower ionic conductivities than the higher-melting halide eutectics. In addition, the electrode reaction kinetics are much slower at the lower temperatures which will limit the maximum current densities possible. Some tradeoffs will have to be made in the various attributes of the different electrolytes.

CONCLUSIONS

By numerical simulations using a finite-element model, the thermal response of both the battery stack and external case of a thermal battery was readily modeled for various design modifications. The simulations indicate that the LiBr-KBr-LiF eutectic shows promise as the separator electrolyte in a high-temperature battery for geothermal borehole applications because of its low melting point. The parameter that has the most significant impact on the thermal response of the battery is the use of internal heating. Only 5.86 W_e is necessary to keep the battery above the melting point of the low-melting electrolyte for the entire duration of the borehole mission. All of the other design options are ineffective in comparison. Reducing the stack diameter from 50.8 mm to 38.1 mm has the next biggest impact on the thermal response, causing a significant loss in heat. Additional heat loss occurs when the thickness of the stack insulation is reduced by half to 4.3 mm. Doubling of the cell stack to 34 cells reduces the heat loss slightly, as does increasing the insulation thickness by 50%. It should be possible to design a geothermal battery using the existing thermal-battery technology based on the LiBr-KBr-LiF eutectic or comparable molten-salt system. Other lower-melting molten salts based on Cs or Rb may be equally suitable.

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