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13. ABSTRACT (Maximum 200 words) The prospects of significantly enhancing antisubmarine warfare (ASW) sonobuoys require a six-hour life in thermal battery capability. The fused-salt primary battery LiSi/CoS ₂ has shown progress in meeting the advanced performance requirements, but is limited to 3-h life using Microtherm insulation. This Phase I project provided a cost-effective prototype development for fully meeting size 'A' sonobuoy performance objectives. An innovative vacuum/multifoil (V/M) insulated container, which was demonstrated in Phase I, can extend operating times to at least 6 hours. Pyro-initiated battery mockup tests with spreadsheet calculation reduced trial and error development of the advance thermal management package. Thin cross-section (0.175 inch thick) V/M Insert accomplishes six-hours and can also be deployed within the standard battery case. It demonstrates the relative independence of V/M insulation thickness and heat retention. The header component accounts for 75% of heat loss. Reduced thickness of insulation may allow increased battery stack diameter and capacity (by 25%) to exceed 200 ping-seconds or power at greater than 10 kW. Thinner (by 50%) ceramic fiber-separator, CFS, and FeS ₂ -CuFeS ₂ cathodes with 25% higher capacity density and lower-melting electrolyte have shown proof-of-concept for further increasing 'A' size sonobuoy battery performance and life. In Phase II based on 30 ten-cell tests, we expect to increase both battery life and performance by at least 50%. Phase II would demonstrate the requirements for the improved, 6-h sonobuoy battery and aid in commercialization of the rechargeable thermal battery. A "dual-use" objective enables cost-effective deployment of the long life thermal battery for the 'A' size sonobuoy.				
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Final Report of Option (March 30, 2000)
for Navy SBIR "Long Life Thermal Battery for Sonobuoy"
Contract #N00167-98-C-0038, (option)
Total Contract Amount-\$99,245
Award: Competitive

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In our Phase I SBIR, a vacuum/multifoil (V/M) insulated case for an A-size sonobuoy battery gave proof of concept to extending thermal battery life to 6 h. We also identified the header end of the insulating system as an area of design to improve overall heat retention. Design changes and anticipated tradeoffs can lead to cost reduction for prototype development. The Phase I option enables design, development and parts procurement for prototype testing in FY00. V/M design verification tests using pyro-ignited battery mockups is an advanced feature of this work.. The option period is divided into 3 tasks.

Task 1, Design/Development of prototype V/M insulating packages for Phase II deployment

Task 2, Design/Fabrication of pyro-ignited battery mockups.

Task 3, V/M design verification tests using pyro-ignited battery mockups

Results of the Phase I primary effort is detailed in the paper "Component Development for Six Hour Thermal Battery " by Thomas Kaun that was presented at the 6th Workshop for Battery Exploratory Development held June 21-24, 1999 at Williamsburg VA. This report is attached. Advanced separator, CFS, and lower-temperature battery chemistry are pursued at a subsistence-level in anticipation of Phase II and Phase II option fundings.

Task 1, Prototype V/M insulating package design/development

Substantial design effort was expended on two viable designs, which address heat loss from the header end. One integrates the V/M with the existing battery can, Fig. 1; the other uses a V/M insert at the proximity of the cell stack OD. Both use a much thinner cross section, 75 mil vacuum annulus, with 35 mil SS walls. Both have individual strong points to permit tradeoffs in design and fabrication to extend battery life to six hours and reduce fabrication costs. For example, without a direct path for heat conduction to the header, both designs can tolerate heavier wall thickness. Our calculations indicate that the overall heat loss is reduced by 35 W, or a third of the calculated heat loss of the Phase I V/M case design. This design can also exceed the 6-h goal by substituting lower cost Fiberfrax at the header-end. That is also because end insulation thickness can be transferred from the bottom to the top with the V/M case.

Unlike the Phase I V/M case that was constructed with machined parts, the objectives of the Phase II designs are to minimize machining and welding. The goal of the Phase II V/M insulating system is to produce by batch (e.g. furnace-brazed construction). Prospective producers for the deep-drawn stainless steel components have been identified. But at this stage of development, soft-tooling (spin-forming) is the more economical approach for a small number of pieces (50-100) at about \$2500. Spin-forming also permits design change at lower cost. None-the-less with a restricted option budget, the initial prototypes of the new design used machined parts from pipe stock. The agreed-upon battery length for the FY99 demonstration is 12". A 12" battery can is not

available. So for the interim, an extension has been welded to the standard 10" can. InvenTek has ten of the extended cans. Unfortunately, the original deep-draw tooling used to produce the 9" tall battery cans is no longer available. A change in length to 12" tall is not a trivial matter, as deep-drawn battery-can longer than 9" must be double drawn. The project may need to purchase new tooling for about \$20K.

**Crosssection of Thermal Battery inside V/M-Insulated Battery Case
having a Spun Inner Wall and the Standard Battery Can**

(Microtherm added at header-end, that is, 0.5 " moved from bottom end)

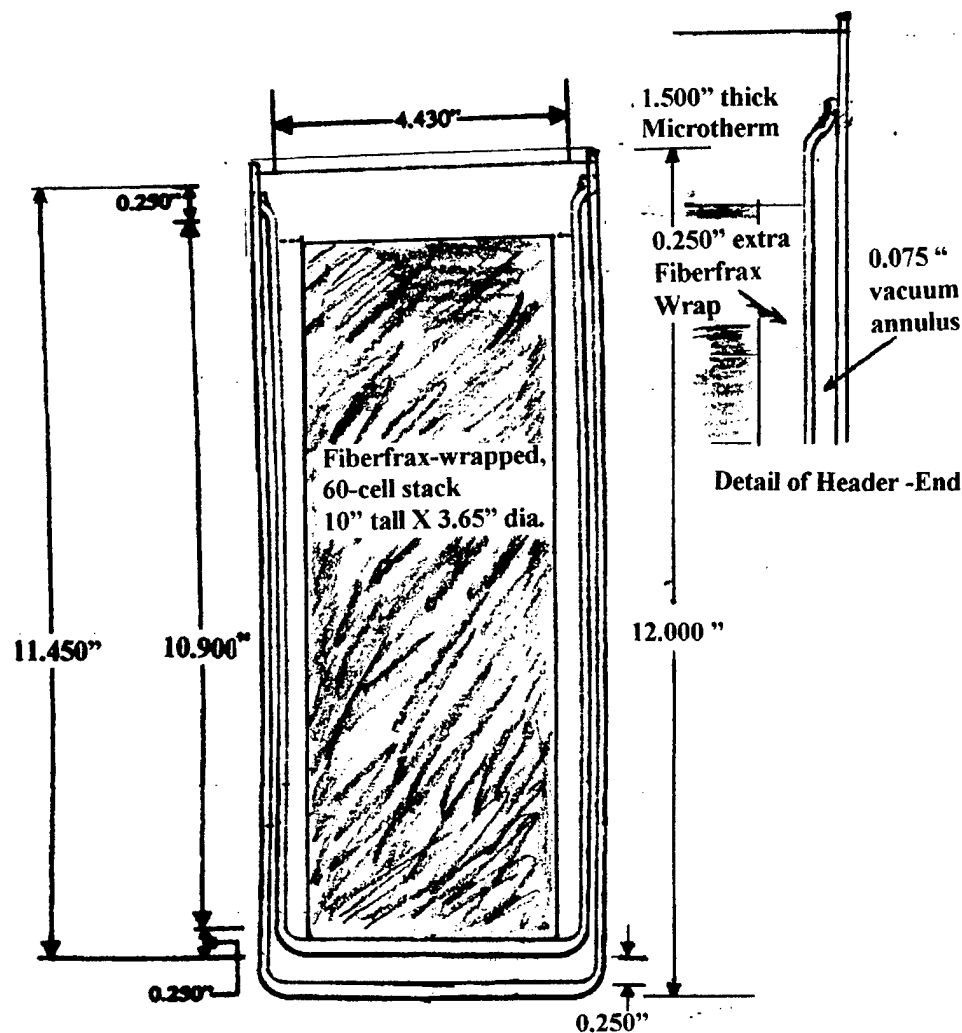


Fig.1, Drawing of a Prototype Vacuum / Multifoil Insulated Case with a Thermal Battery inside

The first V/M cases for the size 'A' sonobuoy battery were fabricated with custom parts, which approximates the critical dimensions of the actual battery case, i.e. its ID is such that comparisons to other types of insulation can be made. It is a double-walled vessel; within its vacuum annulus are 12 layers of Al foil and glass paper. Its outside wall is heavier than desired, due to available stock; the inner wall is dimensioned to readily accept the sonobuoy battery. The inner sleeve is cantilevered from a substantial welding ring at the mouth of the case. The V/M case is insulated on the bottom, as well as the sidewalls. To minimize heat loss along the inner sleeve at the header, its cross-section is reduced. Future battery cases would use a thin, deep-drawn inner sleeve to accomplish this feature.

The V/M Insert is a second generation version of V/M for thermal batteries. Its thin cross-section (0.175 in.) allows it to be inserted into the standard battery can (Fig. 2) with annular space for a two layer wrapping of fiberfrax. The fiberfrax wrap centers the V/M Insert snugly within the battery can. The vacuum annulus of 0.075" contains wrappings of Al foil and glass paper. The V/M Insert provides insulation on the bottom, and is sized to come within 0.4" from the header; again to accommodate standard battery assembly. As in the earlier V/M cases, the cross-section of its walls are reduced at the header to minimize heat loss. These design details were supported by a finite-element model for the V/M-insulated battery case.

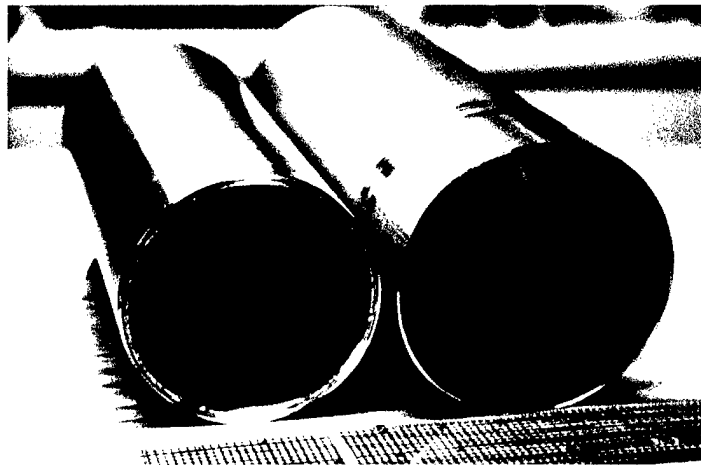


Fig. 2, the V/M Insert is laying beside a standard battery case.

Task 2. Design/Fabrication of Pyro-ignited battery mockup

In our study, a pyro-initiated mockup of the standard battery consists of aluminum slugs, steel current-collectors, and heat pellets, that are stacked with initiator strips, Fig. 3. This combination of components approximates the thermal mass of the actual battery. The aluminum slugs were hogged out to give the appropriate stack height along with the weight (thermal mass). The ENSER heat model assisted in specifying thermal mass and heat input requirements. Following a typical assembly procedure, the stack was compressed, wrapped with fiberfrax and wound with glass tape, also Fig. 3. It was

critical to duplicate the end insulation treatments by copying the sequence of heat pellets and Microtherm disks as used in the actual battery. Internal temperature was monitored by K-type thermocouples, which were inserted into holes in some of the aluminum slugs. The battery mockup assembly was slid into the insulated battery can and was finished off with the standard header plate. The header had a slit cut into it to bring out the thermocouple leads.

These 12" long mockups are intended to give real life evaluation of insulation systems without the expenditure of a full battery test. The first pyro-ignited battery mockup will examine the standard Microtherm insulating package with an initial temperature of 475°C. The following tests will again examine a modification of the header assembly with Phase I cases will be evaluated. The required heat pellet (caloric input) must be established for the full battery test in Phase II. Nick Shuster calculated the heat required for the mockup. Heat pellet requirements for actual batteries was also considered. This mockup test will provide increased confidence in the full battery test

Greg Gabert at ENSER produced Al slugs and heat pellet parts and later assembled the pyro-ignited battery mockups. Preparation in the option period should enable general use during the shortened Phase II FY00 period. These mockups will assess the design details of the prototype V/M insulating-package, and again set the heat requirement to obtain full battery performance and 6 h life.

Task 3, V/M Case Testing

Due to a facility move at ENSER, Task 3 was delayed until March 2000. For the Phase I option a group of four pyro-initiated thermal tests examined a 12" long battery, instead of the 10" battery. Along with the standard Microtherm insulating package, two versions of V/M insulation are tested. These are the Phase I V/M version (from heavy pipe stock) and a deployable V/M Insert. Additionally, these pyro-initiated mockups provide an improved level of simulated thermal battery operation. Both heat input via pyrotechnic and associated "thermal shock" are simulated. This Phase I V/M version case was originally produced almost 2 years ago. It was gratifying to find that there had been negligible degradation of insulating quality in 2 years. Also, the insulating quality is unchanged from the very first heat up.

The pyro-ignited battery mockups are designed to attain two initiation temperatures, 475°C and 525°C. This is the checkout before full battery testing to establish heat pellet requirement. A 12.0" battery length was anticipated for 60 cells. Multiple thermocouples will be used to verify design detail and support design models, especially at the header-end. Both mockups and batteries are will be stacked and wrapped (using notes from Nick Papadakis) with Microtherm disk insulation at the stack ends. The V/M insulation is also at the bottom, and requires battery less length. Extra Microtherm insulation and outboard heat pellets will be brought from the bottom to the top to increase performance and life.

The first pyro-initiated mockups with a Microtherm-insulated battery-can verified the thermal mass. The thermal mass of the battery is simulated with about 2.75 kg of Al plus heat pellets and steel sheets, (see Fig.3). Calorimetric evaluations of V/M insulation relative to the conventional Microtherm insulation use actual battery cans and Microtherm parts that were obtained from ENSER. The heat pellet content targeted peak temperatures of between 475-525 °C. These targets were attained with the aid of the ENSER thermal model. The cooling curve for the pyro-initiated mockup of the thermal battery using the standard Microtherm insulated case, Fig. 4, shows a period of stable temperature and then has a steady temperature drop. The steady temperature drop of 62 °C/h had also been determined in the resistance-heated mockup using Microtherm.

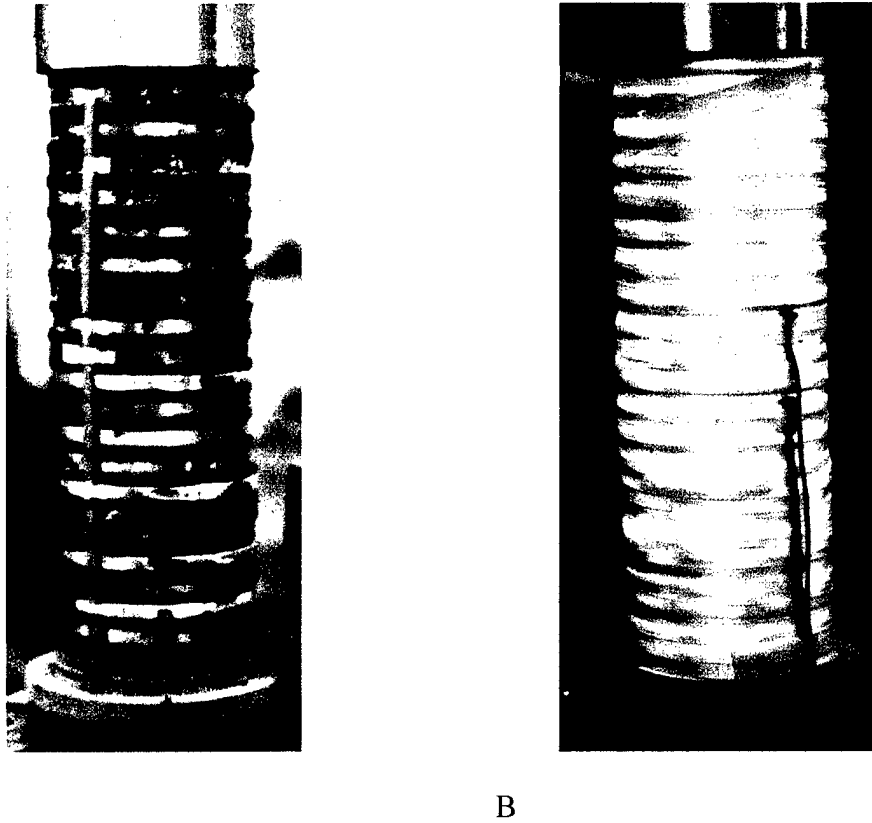


Fig.3, (A) The thermal mass of the thermal battery is simulated with 2.75 kg of Al plus heating pellets. (B) Thermocouples inserted into the wrapped stack assess battery temperature.

The cooling curves for the pyro-initiated mockups of the thermal battery using the V/M-insulated cases and the standard Microtherm-insulated case are presented in Fig. 4. The same header assembly is used in all three tests. After initiation, the thermal mass reaches peak temperature in 15 minutes. Temperature is usually quite stable in the V/M-insulated cases for the next 30 minutes. In these tests the Microtherm-insulated battery attained 455 °C, and lost temperature at an overall rate of 40 °C/h. With a 40 °C increase in initiation temperature, the Microtherm would attain a 3-h life as has been independently determined. These independent studies give further validation to the results obtained here. The temperature for the Phase I V/M version and "deployable" V/M Insert drops at 17 °C/h, and at 20 °C/h, respectively. Both of these pyro-initiated battery mockups with the V/M-insulated battery case exhibit over 6-h life, that is time at operating temperature above 370°C.

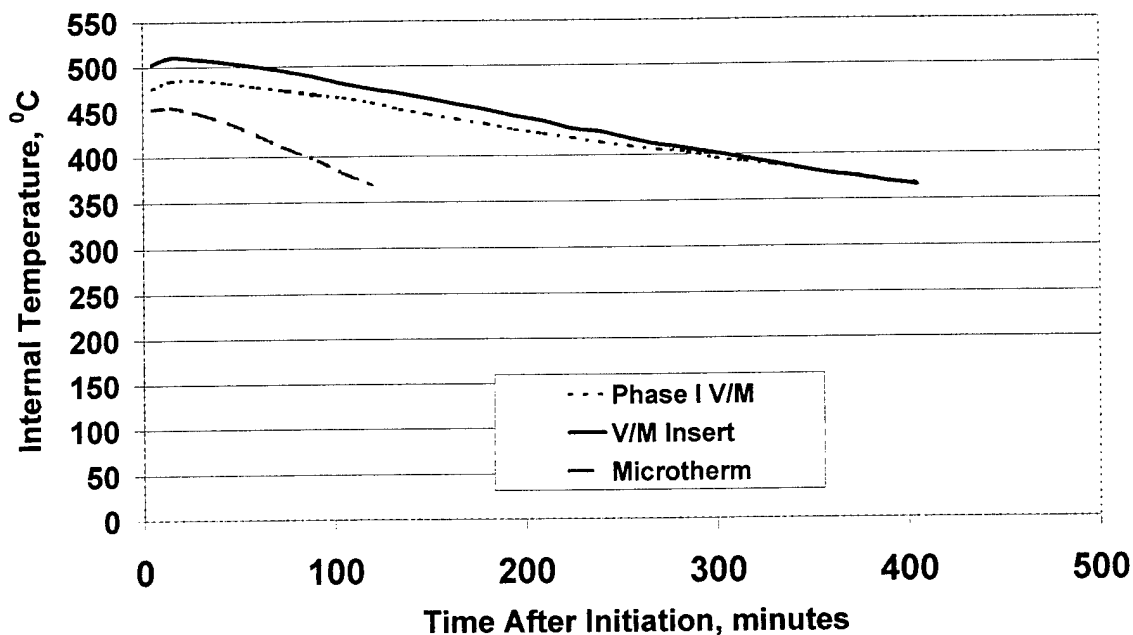


Fig. 4, Comparison of the internal temperature of pyro-mockups using three battery case insulations: one with standard Microtherm and two with vacuum/multifoil, V/M.

In addition to the internal temperature, external temperatures; header, side, and bottom are recorded, Fig. 5. External temperature for the V/M case was generally 45-60 °C cooler than Microtherm to indicate the improved quality of heat retention., The heat losses from the sides and bottom were dramatically reduced. For the V/M cases, external temperature is 40-60°C The temperature at the header end was affected by the nearby out-board heat pellet as noted by the abrupt rise, Fig. 6. None-the-less, heat loss for the mockups with V/M-insulated cans is dominated by the header. For the Microtherm, external temperature is 105 °C at battery temperature of 455 °C, Fig.7, and is dominated

by the side wall. Our spreadsheet calculations of heat loss also indicate that the header end of the battery with V/M insulation is responsible for at least 75% of the battery's heat loss. Our method of battery mockup operation followed by heat loss calculation can avoid trial and error in developing heat management design for increased battery life.

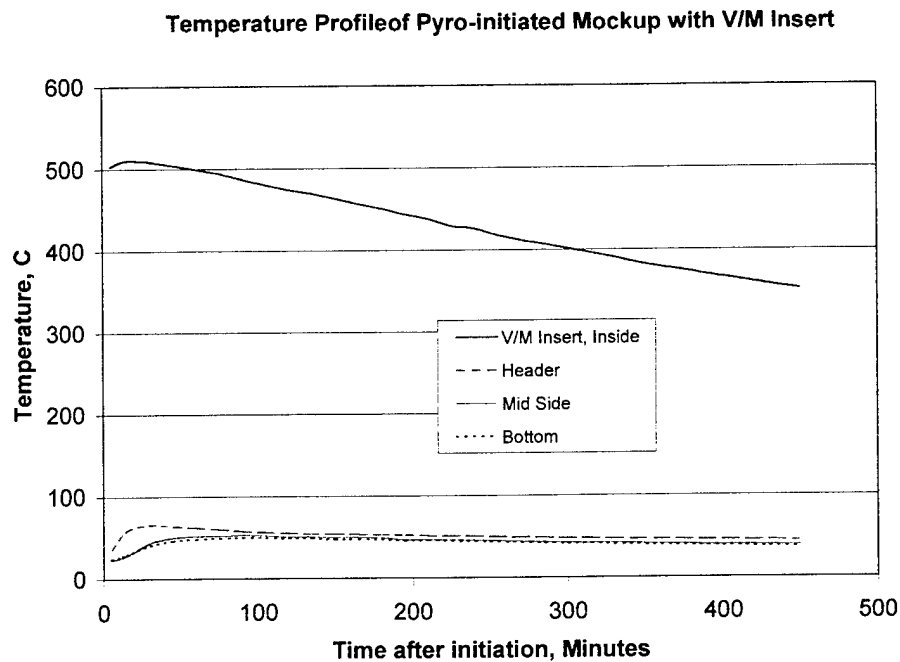


Fig. 5, Temperature profiles for pyro-initiated mockup with V/M Insert. including external temperatures: header, side, and bottom

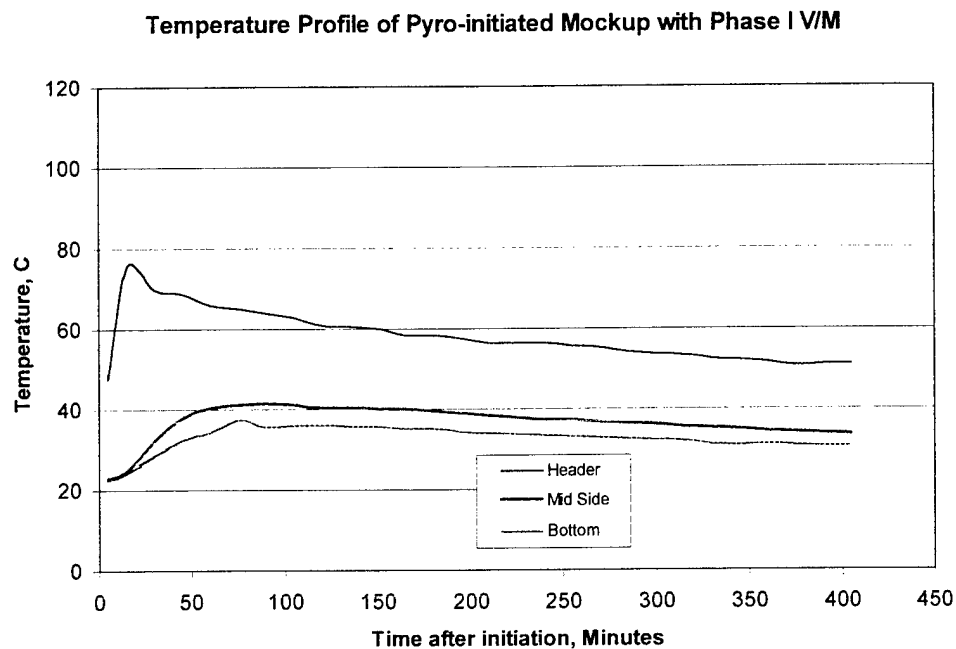


Fig. 6 External temperature profiles for pyro-initiated mockup with Phase I V/M

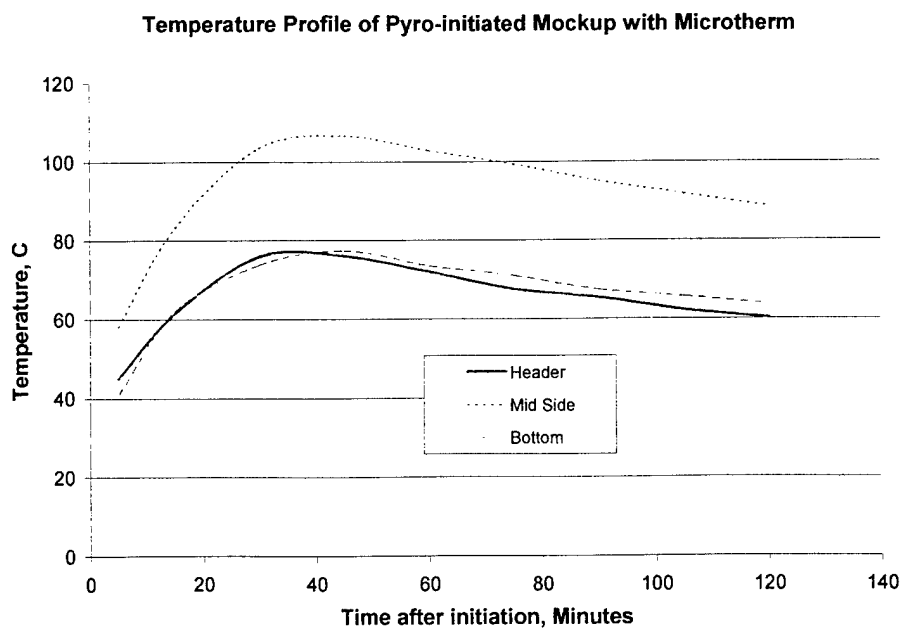


Fig. 7, Temperature profiles for pyro-initiated mockup with Microtherm, including external header, side, and bottom temperatures:

CONCLUSION

Pyro-initated battery mockups provided a proof-of-concept for a six-hour thermal battery using V/M-insulated battery cases. Long life is in reference to extending life of the state-of-the-art thermal battery for sonobuoy application with Microtherm insulation from 3.0 h to 6.0 h using V/M-insulated battery cases. Pyro-initated mockup established heat pellet requirements and associated battery cooling profiles to attain the goals.

The thin cross-section V/M Insert accomplishes over six-hours and can also be deployed within the standard battery case. It demonstrates the relative independence of V/M insulation thickness and heat retention. As proposed, long life is accomplished by a significantly improved heat retention using vacuum/multifoil (V/M) insulation rather than Microtherm insulation. Its cooling profile extended more than two fold; temperature-decrease/hour for the V/M insulation was about 40% of the conventional insulation to enable a 6-h operating life.

The pyro-initated battery mockups give confidence to proceed with the Phase II designs for a V/M insulated battery.

Phase I Travel: A paper "Component Development for Six Hour Thermal Battery " was presented at the 6th Workshop for Battery Exploratory Development held June 21-24, 1999 at Williamsburg VA.

Phase I Option expenditures are on track and include POs for the support of Tasks 1-3 activities. Task 3 was delayed to March 2000 as a result of the ENSER facility move.

Component Development for a Six-Hour Thermal Battery

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ABSTRACT

The focus of advanced thermal battery development is extension of life to six hours. Improved heat retention with vacuum/multifoil (V/M) insulation is examined. A proof of concept is demonstrated using a mockup which exhibits a greater than two fold life extension with the substitution of V/M insulation for the Microtherm that is currently used. A fibrous ceramic separator and a positive electrode chemistry of $\text{FeS}_2\text{-CuFeS}_2$ also show prospects for improving performance and life.

INTRODUCTION

The Navy has identified the need for a substantial increase in thermal battery performance. In the recent past, the Navy has worked with thermal battery developer Northrop Grumman (NG), Cleveland, OH (now ENSER). The NG chemistry, LiSi/CoS_2 with pressed MgO -powder separator, has demonstrated a thermal battery having performance capability of 4.2kW for 10 sec. The Navy has set "long life" as a primary goal for advanced thermal battery. The ENSER/NG thermal battery, uses Microtherm, a mineral insulation, which limits life to about 2.5-h.

In this Phase I SBIR, we saw an opportunity to apply our rechargeable thermal battery (RTB) technology (1) to bring about increased performance, along with extension of operating life to the desired 6-h life. The Phase I SBIR evaluated InvenTek component technologies, e.g. vacuum/multifoil (V/M) insulation, thin ceramic fiber separator (CFS), and positive electrode chemistry of $\text{FeS}_2\text{-CuFeS}_2$ with electrolyte having LiI addition. We chose to collect data which closely simulated test conditions at NG to enable system optimization with the NG/ ENSER Model. Extra effort was taken to use the actual thermal battery components in our project. Primarily through improved heat retention with V/M insulation, the objective of this work is to extend operation time to about 6 h.

Additionally, we see excellent prospects to concurrently increase thermal battery pulse power/energy by 50%.

Vacuum/Multifoil, V/M, Insulation Applied To Thermal Battery

Proof-of concept for a 6h life for the thermal battery was provided with a Vacuum/Multifoil (V/M) insulated case. Using a battery mock up test having an Al block thermal mass and standard header, thermal-loss tests were initially conducted with the standard Microtherm insulation, 0.4 inch thick. This standard battery mockup simulates the 2.65-h battery life that is generally obtained. The same battery mockup was then inserted into the InvenTek-designed, V/M-insulated battery case. For comparison, the dimensions closely followed those of the Microtherm insulation. Then, cooling profiles from 525°C for the V/M case show time at operating temperature extended to 6 hours.

V/M Case Design

Based on the available information, the first V/M case for the battery was fabricated with custom parts. This V/M case is considered a test vehicle, which approximates the critical dimensions of the actual battery case, i.e. its ID is such that comparisons to other types of insulation can be made. Fig. 1 is a drawing of the V/M case that has been produced; it is a double-walled vessel. Within its vacuum annulus are 12 layers of Al foil and glass paper. Its outside wall is heavier than desired, due to available stock; the inner wall is dimensioned to readily accept the thermal battery and retrofit to the current battery. The inner sleeve is cantilevered from a substantial welding ring at the mouth of the case. Although overdesigned, the inner sleeve can accept the 250 lb/in^2 compressive load; whereas, the total load to assemble the battery is only about 250 lbs. The V/M case is insulated on the bottom, as well as the side walls. To minimize heat loss along the inner sleeve at the header, its cross-section is reduced (see detail on

[illegible]

V/M Case Testing

This battery mockup was then applied to the V/M battery case. The cooling curves for the mockup of the thermal battery using the V/M case and the standard Microtherm-insulated case are presented in Fig. 3. The same header assembly is used in both tests. Again, the thermal mass is heated to 525°C and held 15 minutes before being allowed to cool. Temperature drops at 27 °C/h, or 165 °C in 6-h. This battery mockup with the V/M battery case exhibits about a 6-h, that is time at operating temperature above 360°C.



Figure 10 is a line graph titled "Cooling of Battery Mockup in two types of insulated cans". The y-axis is labeled "Temperature, C" and ranges from 0 to 700 in increments of 100. The x-axis is labeled "Time, h" and ranges from 0 to 12 in increments of 2. There are two data series: "Microtherm" represented by a solid line and "V'M" represented by a dashed line. Both series start at approximately 520°C at 0 hours. The "Microtherm" series decreases steadily to about 240°C at 6 hours. The "V'M" series decreases more slowly, reaching about 380°C at 4 hours, then drops sharply to about 350°C at 6 hours, and continues to decrease slowly towards 280°C at 12 hours. A horizontal line at approximately 370°C is labeled "Lower temperature limit".

Time (h)	Microtherm (C)	V'M (C)
0	520	520
2	400	480
4	320	380
6	240	350
8	-	320
10	-	300
12	-	280

Steady-state heat loss measurements provided data relating heat loss as function of temperature, ie. higher heat loss rates at higher temperature. External temperature for the V/M case was generally 75 °C cooler, that is 50°C vs. 125 °C at 525 °C battery temperature. Heat loss for the V/M case mockup is dominated by the header. The heat losses from the sides and bottom were

dramatically reduced in the case of the vacuum/multifoil container, but the heat losses were greater from the header end. The steady-state temperatures for the vacuum/multifoil case showed more hysteresis than did those for the case with Microtherm insulation, because of the slower rate of heat loss. This resulted in much longer equilibration times to reach a pseudo steady-state temperature. Heat is transferred along the skin of the container rather than through the wall. Most of the data was taken after two hours of equilibration. Details of these tests are seen in Fig. 4. These values will be used in design calculations for the phase I option effort.

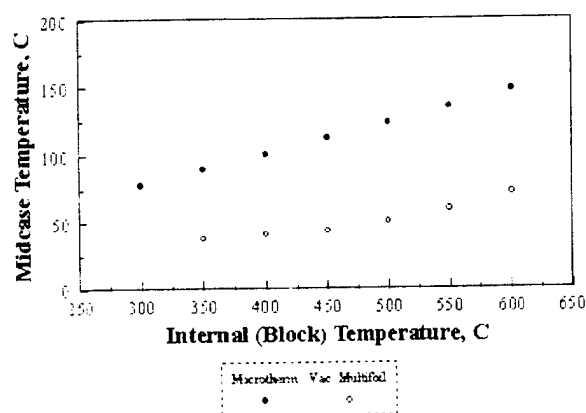


Fig. 4. Steady-state temperature at external sidewall, mid-case, as a function of internal temperature

Our spreadsheet calculations of heat loss also indicate that the header end of the battery with V/M insulation is responsible for at least 75% of the battery's heat loss. Our method of battery mockup operation followed by heat loss calculation can avoid trial and error in developing heat management design for increased battery life. Design improvement of the header component is likely to further increase battery life. We may compromise the quality of the V/M insulation to reduce cost, but through design of the overall heat-management package further improve time at operating temperature.

Our success in increasing time at operating temperature for the battery was also supported by a live battery test. This battery with

insulated case was a smaller OD, 2.5" vs. 5.0". A V/M case of the same 2.5" OD with 0.2 in thick wall was used in the live thermal battery test at ENSER. It also demonstrated 2.5 times increased battery operating life. Heat loss was reduced to 25°C /h. By comparison, a mockup using 0.2 in. thick Min K insulation indicated the same proportional increased time at operating temperature for the V/M insulation, as identified earlier.

Ceramic Fiber Separator, CFS

Our innovative ceramic fiber separator, CFS, has shown proof-of-concept to substitute for MgO powder separator in a thermal battery. At 12 mil thickness, or 50% of the MgO, it wets readily, has a fine pore structure for particle retention, and has 85% porosity for high ionic conductivity. Two types of CFS were tested; both exhibit improved handling characteristics. Unlike pressed MgO powder separator, full -size, 3.66" dia. separators of 12 mil or 25 mil thickness pass the "drop test", and display some physical flexibility. These fiber separators were compared to the MgO powder separator in tests with 90A, 10 sec pulses, and exhibit comparable cell impedance. The CFS has the prospect of reducing cell thickness and weight, while improving cell power and production cost (due to a lowered piece-loss rate). Approximately 15% more cells may be added to the battery by substituting CFS for pressed, MgO powder separator.

FeS₂-CuFeS₂ Positive Electrode Chemistry

The SBIR tested the reduced-temperature cell chemistry of FeS₂-CuFeS₂ positive electrode with electrolyte having LiI addition. It has shown prospects for significantly increasing peak power by 70% under the pulse battery test conditions. Specifically, cell impedance of 0.45-0.56 ohm/cm² for the CoS₂ chemistry was reduced to 0.28 to 0.38 ohm/cm² for the FeS₂-CuFeS₂ chemistry. The lower cell impedance can be translated into increased peak power of 2.75W/cm² compared to 1.63W/cm² for the typical CoS₂ cell. The higher peak power could also allow a tradeoff of higher cell capacity for longer life and greater ping-sec operation. Although the Phase II SBIR will emphasize increased life with the V/M insulation,

the improved performance, that is anticipated with this reduced-temperature battery chemistry, is also likely to permit lower materials cost. Cost remains a key feature to thermal battery deployment, which is to be addressed in the Phase II project. Considerable development remains before qualification.

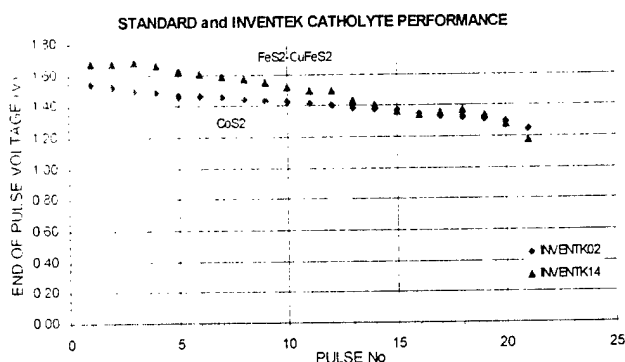


Fig. 5. Final voltage from power pulses ($0.9\text{A}/\text{cm}^2$ current density) is higher with the $\text{LiAl}/\text{FeS}_2\text{-CuFeS}_2$ chemistry (Inventek14) than the baseline LiSi/CoS_2 (Inventek02).

SUMMARY

The Phase I SBIR provided a proof-of-concept for a long life thermal battery. Long life is in reference to extending life of the state-of-the-art thermal battery for sonobuoy application from 2.5 to 6.0 hours. As proposed, long life is accomplished by a significant improvement of heat retention using vacuum/multifoil insulation rather than Microtherm insulation. A battery mockup, using the same header, was placed into the vacuum/multifoil (V/M) insulated battery case. Its cooling profile extended more than two fold (temperature-decrease/hour for the V/M insulation was about 40% of the conventional insulation) to enable a 6-h operating life.

ACKNOWLEDGEMENT

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This project was also subsidized by a grant program, SBI #3303 with Sandia National Lab.. We are grateful for the independent evaluation of our insulation that was conducted at Sandia by Ron Guidotti.

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- (1) T. D. Kaun and P. A. Nelsen, "A LiAl/FeS_2 Battery for Portable 250W Applications", Proc. of the 38th Power Sources Conference, p 244 (1998)