# COMPONENT AND SUBSCALE TESTING IN SUPPORT OF THE DESIGN OF A BATTERY POWER SUPPLY FOR THE ELECTROMAGNETIC GUN RESEARCH FACILITY

M. R. Palmer, E. C. Kirkland
Science Applications International Corporation,
Shalimar, Florida

J. B. Cornette
Air Force Armament Laboratory, AFATL/SAH,
Eglin Air Force Base, Florida

L. E. Thurmond
Computer Science and Applications, Incorporated,
Fort Walton Beach, Florida

## ABSTRACT

A high power and high energy battery system is currently being designed to support electromagnetic (EM) gun research requirements of the Air Force Armament Laboratory, Eglin Air Force Base, Florida. This battery system will be constructed at Eglin in 1987. Design goals are for a battery power supply which uses current technology to provide megawatts of power. Test data on the pulsed power performance of the batteries, switches, and other components to be utilized in this system are presented here along with details of plans for subscale system testing to validate the system design.

## INTRODUCTION

A high power and high energy battery system is currently being designed[1] to support electromagnetic (EM) gun research at the Air Force Armament Laboratory, Eglin Air Force Base, Florida. This battery system will be constructed at the EM Gun Experimental Research Facility (EMGERF) at Eglin in 1987.

Design objectives are to provide megawatts of DC power for several seconds. Maximizing system reliability and maintainability while minimizing cost, developmental risk and construction time are primary design goals. These goals dictate the use of off-the-shelf components almost entirely.

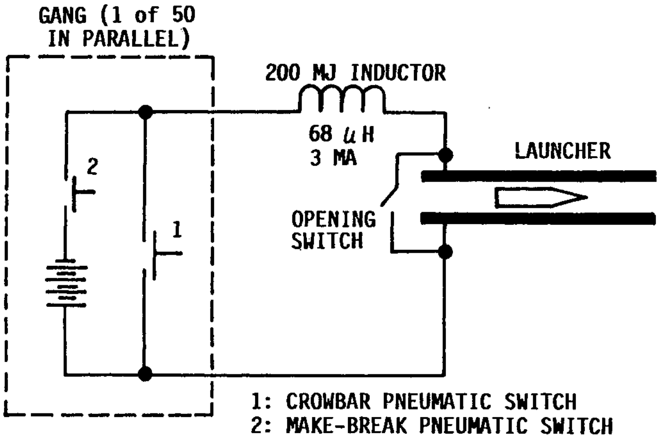

Figure 1. Battery System Circuit (1 Gang only)

The system design will be treated in a separate paper at this meeting[1], but a short synopsis here will clarify this presentation. Figure 1 shows the basic circuit in which the batteries will be used to power the EM launcher system. The basic unit shown is termed a gang. Forty-two such gangs will be installed in parallel to charge an inductor. The single battery shown in Figure 1 will actually consist of 24 parallel strings of batteries. Each string will consist of 16 automotive batteries in series with a heavy duty contactor.

The switches shown in Figure 1 will be heavy duty pneumatic switches capable of opening and closing against 50 kiloamps and 250 volts a minimum of 20 times before refurbishment. These switches are currently being designed and no test data have yet been obtained. Testing will be carried out as part of a subscale test program which will be briefly described.

Electrical contactors will be used to switch each string individually. These contactors will provide a backup capability to interrupt current flow in the event of failure of any gang level pneumatic switch to open. They will also increase the flexibility of the system in both discharge and charging modes. Due to the very large number of string level contactors (approximately 1600), maximum lifetime and minimum maintenance is desired. This is provided by using the gang level pneumatic switches for the routine current make and break operations.

Utilizing two levels of switching, one at the gang level and one at the string level, should provide the necessary high reliability for routine current interruption. Extraordinary faults will be interrupted with fuses in each string and with explosive disconnects in the main inductor buss.

Clearly the components most critical to the operation of the system are the batteries and switches. The performance, cost, and reliability of these components are crucial. Extensive component screening and testing are occurring to select the best components to meet the design goals.

System interaction effects are very important in a system as complex as this battery power supply. Testing is therefore occurring in three areas: individual component testing, string level testing, and subscale system testing.

## INDIVIDUAL COMPONENT SELECTION AND TESTING

Preliminary analyses showed that standard high rate automotive batteries offered the highest power per unit volume and per unit cost of presently available batteries. Power per unit volume is important due to the very high cost of busswork to transmit megaamps of current. Low power density implies a large battery system volume, which entails long buss runs. The cost and volume of submarine batteries and nickel cadmium batteries are compared to automotive lead acid batteries in Table 1.

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14. ABSTRACT
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Table 1. Battery Power Density Comparisons

| BATTERY TYPE | WATTS/KG | WATTS/LITER |
|---|---|---|
| AUTOMOTIVE LEAD-ACID$^1$ | 500 | 1000 |
| SUBMARINE LEAD-ACID$^2$ | 20 | 30 |
| NICKEL-CADMIUM$^3$ | 500 | 1000 |

A survey of costs and performance of all high production volume, high rate automotive batteries was undertaken. Some of the performance results are shown in Table 2. Numerous factors were taken into account in selecting a battery to be used in subscale system testing. These factors included power density, cost, battery chemistry, production volumes, and quality control.

Table 2. High Rate Automotive Battery Performance

| Maker | CCA | mOhms* | mOhms** | Volume | Mass | W/L |
|---|---|---|---|---|---|---|
| A | 530 | 8.0 | - | 10.7 | 17.9 | 460 |
| A | 875 | 3.8 | 4.2 | 11.1 | 22.7 | 860 |
| A | 925 | 4.0 | 4.3 | 13.7 | 28.8 | 670 |
| A | 1050 | 3.1 | 3.6 | 14.0 | 28.1 | 790 |
| B | 650 | 5.6 | - | 8.8 | 15.8 | 800 |
| B | 900 | - | 4.9 | 13.7 | 25.4 | 590 |
| B | 925 | 4.2 | 4.4 | 13.3 | 27.0 | 680 |
| C | 850 | 4.1 | 4.0 | 10.0 | 22.6 | 900 |
| C | 1050 | 4.0 | 3.9 | 13.8 | 28.7 | 740 |
| E | 725 | 3.9 | 4.6 | 14.0 | 26.5 | 610 |
| E | 840 | 4.5 | 5.7 | 12.5 | 20.6 | 560 |
| D | 1000 | 2.8 | 3.5 | 13.1 | 29.4 | 860 |

* Measured after 0.1 sec at 1000 amps
** Measured after 5 sec at 2000 amps
All at 20$^{o}$ C.

An 875 cold cranking amp[*] (CCA) battery produced by manufacturer A (Hereafter A,875) was chosen for further consideration based on the aforementioned factors. It incorporates lead-calcium grids which greatly reduce hydrogen evolution and self discharge compared to more conventional lead-antimony grid alloys.

Lead-acid batteries have quite complex electrical behavior based on a variety of variables. Table 3, for example, shows the strong variation of internal resistance with temperature. The building housing the batteries has been designed to maintain a temperature up to 55$^{o}$ C. in order to produce maximum system power. Such temperatures would be sustained for only a few hours due to battery life deterioration at high temperatures.

Table 3. Internal Resistance vs Temperature

| Temperature $^{o}$C. | Internal Resistance Milliohms |
|---|---|
| -40 | 15.9 |
| -20 | 12.3 |
| 0 | 5.1 |
| 20 | 4.2 |
| 30 | 3.4 |
| 40 | 3.5 |
| 50 | 4.0 |

Resistance calculated after 5 sec discharge with 4.2 milliohm load.

Internal resistances also vary as functions of state of charge, discharge current, and discharge time. Figures 2 through 6 illustrate the performance of an A,875 battery. All five figures refer to a single 15 second discharge with a constant 4.2 milliohm load. Total energy deposited in the load was 173 KJ. The initial battery temperature was 28$^{o}$ C. and the battery equilibrium temperature rose approximately 10$^{o}$ C.

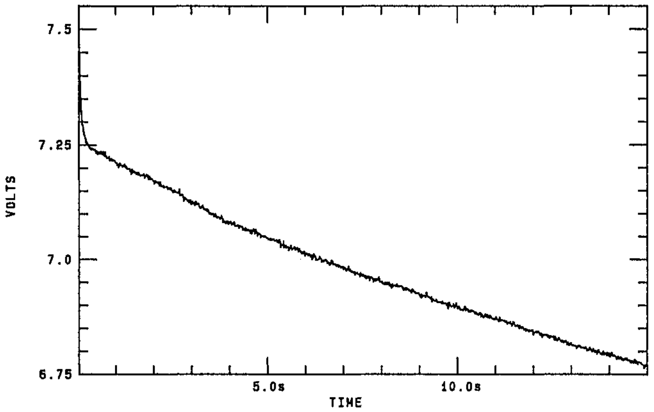

Figure 2. Battery Discharge Voltage

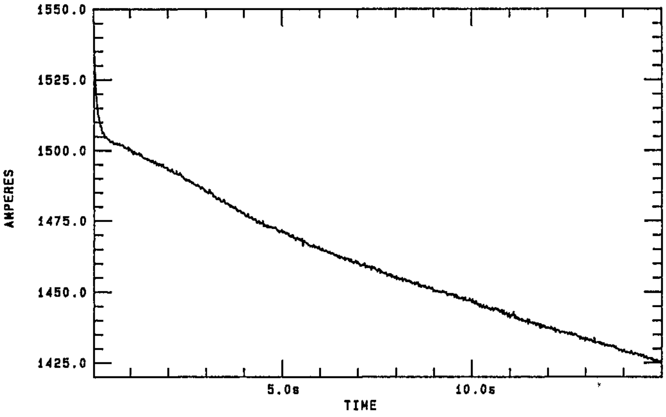

Figure 3. Battery Discharge Current

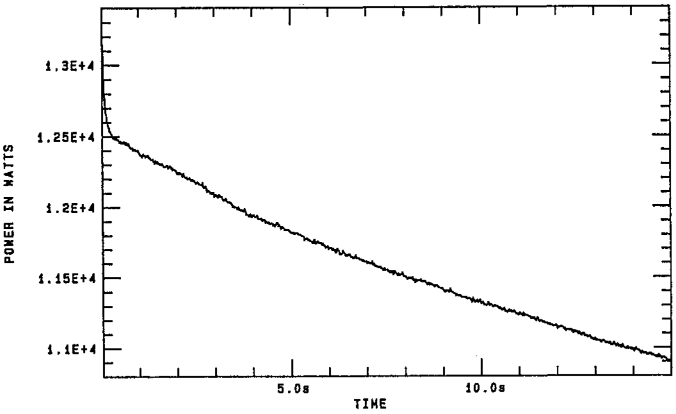

Figure 4. Battery Discharge Power

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[*] The CCA rating is the constant current which yields a 7.2 V battery voltage after 30 seconds at -18$^{o}$ C.

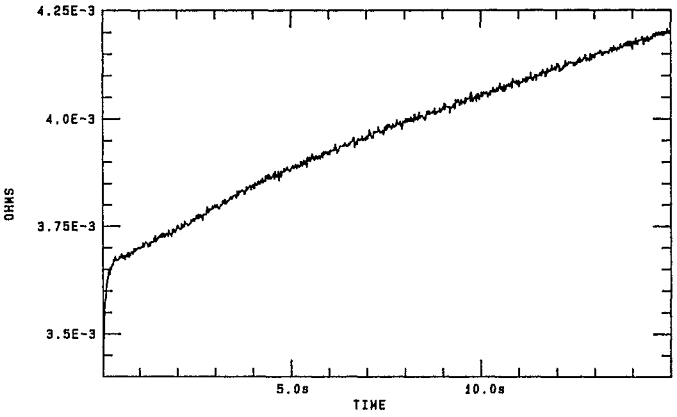

Figure 5. Battery Internal Resistance

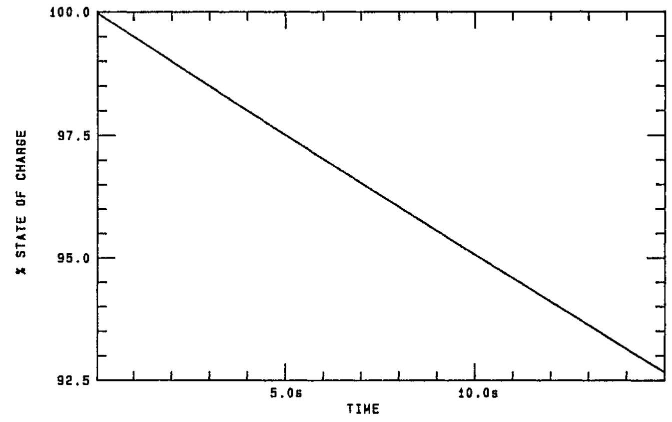

Figure 6. Battery State of Charge

Short circuit currents can be maintained for only about 10-15 seconds before failure due to melt down of lead conductors inside the battery or battery post failure. This melt down typically occurs in 10-15 seconds with 3000-3500 ampere short circuit currents in the A,875 battery. This type of failure does not occur below about 2400 amps of discharge current due to depletion of active electrode materials and greater thermal conduction at the longer discharge times.

These melt down failures are completely uneventful unless high rate overcharging has been performed within the previous 10 hour period. The arc produced on fusing then ignites the hydrogen/oxygen mixture in the battery case. The top caps are forcibly expelled, with resultant splattering of electrolyte. The battery is not damaged, however, and can be refilled and reused. Present test results on over 300 discharge/charge cycles show that peak power discharges of 5 seconds do not adversely affect battery performance as long as the state of charge remains over 90%.

At low discharge rates, the high rate 23-30 kilogram batteries tested have a total stored energy of approximately 4 megajoules, or 170 kilojoules per kilogram (350 KJ per liter). At peak power only 50% of this energy appears in the load. In addition, as the state of charge declines, the battery internal resistance increases. Figures 5 and 6 and Table 4 illustrate this effect for the A,875 battery.

Maximum battery lifetime for an automotive battery design is assured only if the battery state of charge is kept high. Limiting the charge depletion to 10% allows only 5% or 200 KJ of the battery energy to be utilized. This still corresponds to 3200 MJ in a 16,000 battery system. Energy extracted in a single discharge will probably be limited to about 1000 MJ in the EMGERF system due to system reliability and lifetime considerations.

Table 4. Internal Resistance vs State of Charge

| State of Charge % | Internal Resistance Milliohms |
|---|---|
| 100 | 3.4 |
| 90 | 3.5 |
| 80 | 3.8 |
| 70 | 4.0 |
| 50 | 5.2 |
| 37 | 7.9 |
| 28 | 10.5 |

Resistance calculated after 1 sec discharge with 4.2 milliohm load. Temperature 30$^{\circ}$ C.
State of charge calculated based on coulombs removed.

Advanced lead-acid batteries use calcium-lead instead of antimony-lead alloys. This greatly reduces self discharge reactions and hydrogen evolution upon charging. Water loss upon charging is being measured by weight loss. After 100 cycles of 5 second, 2000 amp discharges, 10-20 grams of water is lost per A,875 battery. This information is being used for lifetime estimation, charging system design, and safety analyses of hydrogen evolution rates.

Battery charging protocols will be designed to obtain maximum battery lifetime with minimum water loss due to hydrogen evolution. The design charge time for the full system after a 5 second, 2000 amp discharge is planned to be 24 hours.

Switching was recognized early on to be one of the most challenging problems in designing a minimum cost, high reliability system. Initial plans and testing were directed towards using automotive starter relays at the string level for the entire switching function. This would have replaced the string level contactors and gang level pneumatic switches previously discussed.

Extensive testing showed that standard automotive starter relays were individually capable of conducting 2000 amps for 7 seconds before thermal damage. These relays interrupted with minimal damage a 2000 amp current flow into a 10 microhenry load with open circuit voltages to 36 volts. Such switches remained functional with moderate damage after 100 cycles and maintained contact resistances below 300 microohms. Higher open circuit voltages (48 volts and higher) led to several millisecond opening arcs which caused considerable damage per cycle.

Seven such starter relays in series were tested using 16 batteries in a series string with a 10 microhenry load at 2000 amps for five seconds. After 100 cycles, moderate damage was sustained.

Tests in which one relay was purposely opened under these conditions produced an immediate and very intense fire. Reliability and fire safety considerations therefore dictated that 3 strings of relays be used in parallel to suitably reduce the probability of such a failure.

A seven by three series-parallel array of automotive relays was deemed affordable at a probable cost of approximately $200 assembled. Reliability arguments dictated that a single heavy duty contactor be chosen instead due to the reduced parts count even though the estimated cost for such a contactor is $400.

A survey of industrial contactors suitable for interruption of 2000 amp, 250 volt DC circuits indicated typical prices of $2000-$6000. Such contactors are designed for very high reliability over hundreds of thousands of operations. Since the string contactors will interrupt current flow only when a gang switch failure occurs, the interruption lifetime required for the string level contactors is only a few tens of operations. Given this fact, smaller less expensive contactors with lower ratings are being tested.

## STRING LEVEL TESTING

More than 200 discharge tests have thus far been carried out on strings of 16 batteries. Typical discharges are into a 60 milliohm constant load. Discharges are for 5 seconds at 1700 amps. No battery failures have occurred, although one battery post failed due to a loose connection.

Single string testing with an industrial contactor rated to 4000 amps interruption at 250 VDC and 500 amps continuous current has shown minimal damage to the contactor. Further testing is planned, and elimination of the aforementioned pneumatic gang switches may be possible if this contactor proves highly reliable.

## SUBSCALE TESTING

Manufacturers perform extensive tests on both automotive batteries and contactors, but these tests are in a much different performance regime than that of interest here. Due to the unique and stressful planned use of these components in the EMGERF system, detailed testing of integrated systems is necessary to provide basic design and reliability information.

A subscale test program is being planned based on failure modes and effects analyses and failure rate results from the string level testing. This analysis and Monte Carlo simulations of the battery system will be used to derive component reliability budgets from system reliability requirements. Subscale testing will verify that each component will meet its individual reliability requirements.

Subscale testing will be carried out with two gangs in parallel. Each gang will be half populated with strings and will utilize half scale pneumatic switches. The subscale system will thus contain 480 batteries. It will be a full mechanical mockup with use of hardware and geometries as close to the full scale system as possible. Testing will be performed with all system components in place: battery racks, battery trays, batteries, switches, current limiting resistors, fuses, inductive loads, and charging and control circuits. Loop and load inductive effects, lifetime, reliability, and maintainability will be investigated.

The load for subscale testing will consist of a resistive and an inductive element in series. Figure 7 shows a drawing of the design. The resistive element can be varied from 50 to 9,000 microohms, while the inductor can be varied from 1 to 100 microhenries independently. This flexibility will allow all the planned system discharge configurations to be explored in the subscale system.

## CONCLUSIONS

Test results thus far indicate that a high power and energy battery system can be designed which can function reliably and safely. Further testing of a subscale system will validate the final system design.

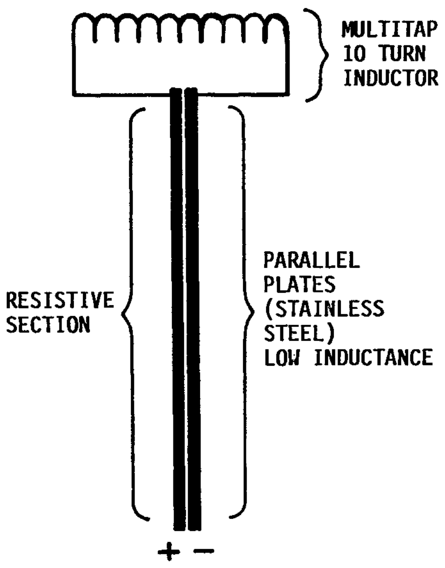

Figure 7. Subscale System Load Design

The EMGERF battery power supply should provide a unique and very cost effective power source for EM launcher research.

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2. Personal communications with GNB Corporation.

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