AIRCRAFT MAIN BATTERY DEVELOPMENT PROGRAM FOR THE F/A-18E/F SUPER HORNET AIRCRAFT

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Abstract

Batteries have been and are still an important component of the aircraft direct current (DC) power system. Batteries can be used for various functions aboard the aircraft, such as auxiliary power unit starting, canopy operation, refueling, lighting, emergency power, fight control backup or a combination of functions. It is not uncommon, in modem aircraft that the battery requirements have to be tailored to meet the unique operational size, weight and shape requirements of the aircraft. The specific requirements of the F/A-18E/F Super Hornet aircraft and related battery issues will be discussed.

Introduction

The F/A-18E/F Super Hornet is an upgraded variant of the current F/A-18C/D aircraft and has an extended range, better performance, improved DC power system and avionics, increased payload and is a fly-by-wire aircraft. A F/A-18C/D aircraft has a DC power system consisting of seven major components. Two 150-ampere (amp) transformer-rectifiers (TRs), one 50-amp TR, two 7.5 ampere-hour (AH) sealed, lead-acid (SLA) batteries, one battery relay control unit and one analog battery voltmeter. The number of major components in the DC power system of the F/A-18E/F aircraft has been reduced to four units: two 150-amp TRs, one 50-amp battery charger and one 15.0 AH SLA aircraft battery. The battery relay control unit and the battery voltmeter were replaced with a timer and voltage sensing relays integrated into the F/A-18E/F electrical wiring system. The F/A-18E/F DC power system improvements represent a weight savings and improved supportability.

Discussion

During the development of the F/A-18E/F aircraft main battery (battery) the following initial factors were considered:

Ž Aircraft Electrical Requirements
Ž Aircraft Mechanical Requirements
Ž Available Batteries (Standardization)
Ž Cost

Aircraft Electrical Requirements

McDonnell Douglas Aerospace (MDA), the manufacturer supplied the Crane Division, Naval Surface Warfare Center (NAVSURFWARCENDIV Crane) with the projected normalized battery load profile for the F/A-18F model aircraft. The normalized profile was used as a basis for the battery discharge profile Figure 1, herein.

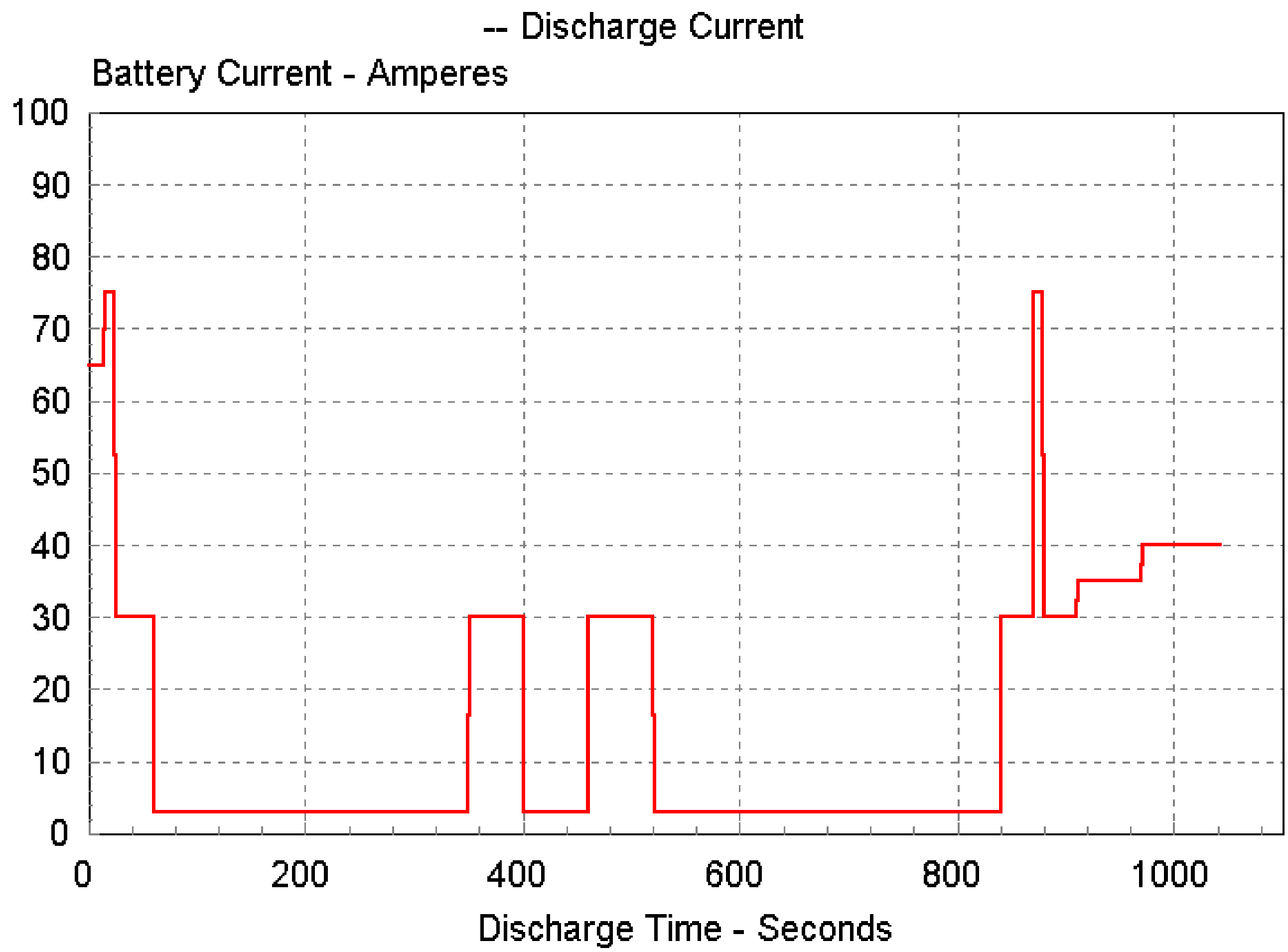

Figure 1. F/A-18E/F Aircraft Battery Load Profile

Figure I denotes the aircraft battery loads from the time the aircraft returns from a flight until it is launched for the next sortie. Examples of the turnaround loads are: engine deceleration, crew station checks, canopy opening, canopy closing, aircraft maintenance indicator, brake check and engine starting. Since the aircraft main alternating current (AC) generators are equipped with permanent magnet generators (PMGs) MDA did not require the main battery to support any emergency loads. However, the battery is a secondary emergency power source and does provide keep alive power for critical systems. NAVSURFWARCENDIV Crane did specify an emergency load test to provide MDA and the Government with an estimate of battery performance under a constant load of 71.0 amps. The 71 -amp level was based on the emergency load requirement for the F/A-18C/D aircraft.

Based on the peak loads for the aircraft NAVSURFWARCENDIV Crane determined that a battery with a rating of at least 15.0 AHs would be best suited for the F/A-18E/F aircraft application. The specified high rate capability of the 15-AH battery (97.5 amps) exceeds the maximum aircraft current load by 20 percent (6.5 x 15 / 80 = 1.2).

Aircraft Mechanical Requirements

The F/A-18C/D aircraft is equipped with two shock mounted SLA batteries with a total volume and weight of ~10.13 liters (618 cubic inches) and 23.64 kilograms (52.0 pounds), respectively. Whereas, the available volume for the one battery in the F/A-18E/F aircraft is ~8.6 liters (525 cubic inches) and a maximum allowable weight of 20.45 kilograms (45.0 pounds). This posed an interesting task of designing a battery that is required to support higher aircraft electrical loads with 15.0 percent less available volume and 13.0 percent less available weight and a requirement for a non-shock mounted battery with a unique shape to be compatible with aircraft Bay 1R.

NAVSURFWARCENDIV Crane received the projected mechanical shock and vibration requirements for the aircraft from the manufacturer. The mechanical shock information reflected a requirement for the battery to be able to withstand half-sine shock pulses with an amplitude of up to 40.0

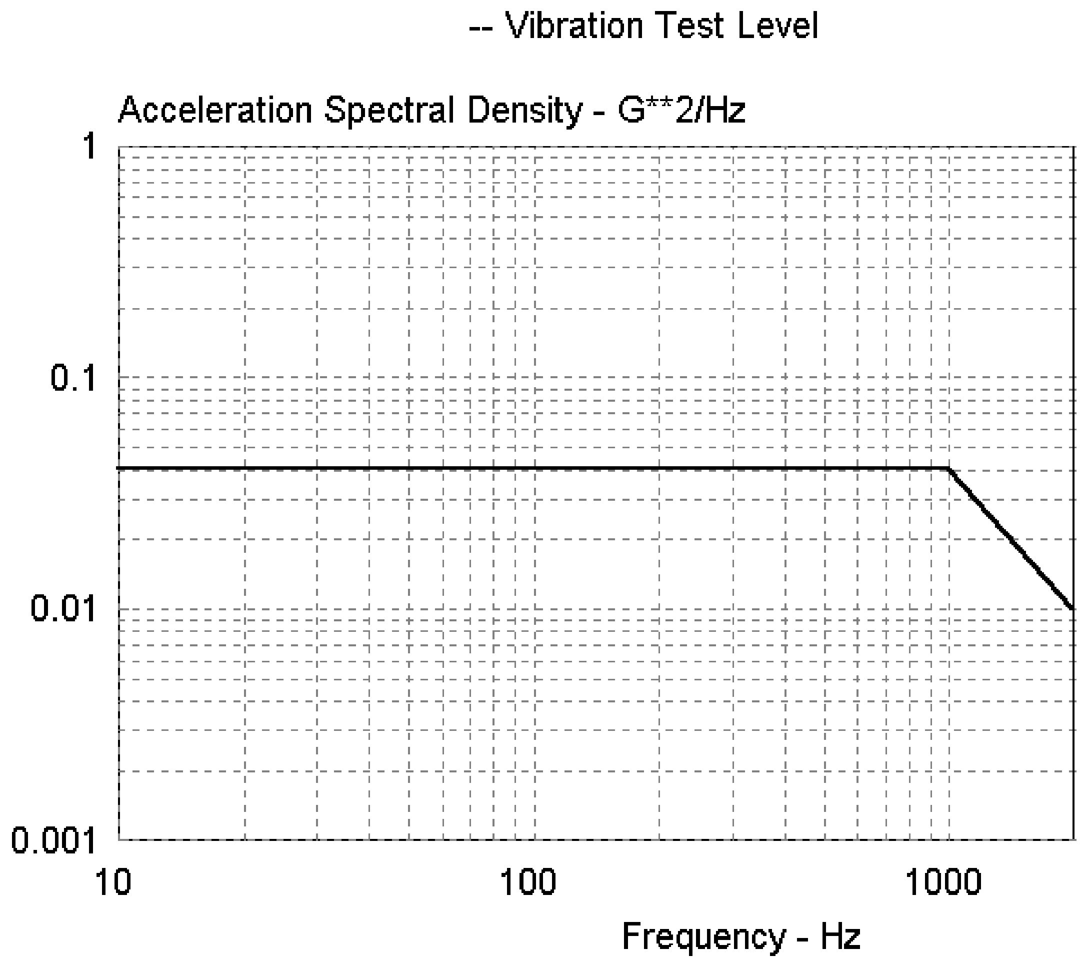

Figure 2. F/A-18E/F Aircraft Random Vibration Level (7.7Grms).

G's. MDA supplied vibration data indicating that the battery would have to survive a random vibration level of 7.7 Grms over a frequency range of 10 - 2000 Hz and sinusoidal vibration levels of up to 10.0 Gs over a frequency range of 50 - 2000 Hz as shown on Figure 2 and Figure 3, respectively. With the advancements made in the construction and packaging of modern aircraft batteries the Government did not anticipate any problems with batteries meeting the mechanical shock and vibration projections for the aircraft.

Available Batteries (Standardization)

At the Government's direction MDA conducted a market survey to determine if any existing aircraft batteries would meet the electrical and mechanical requirements of the aircraft. The survey was not limited to any one battery chemistry, however the three most prevalent technologies were examined: low-maintenance flooded, nickel-cadmium (LMF); sealed, fiber nickel-cadmium (SFNC); and sealed, lead-acid (SLA). The results of the market survey indicated that several existing batteries would meet the aircraft's electrical requirements, but none of the batteries were compatible with the aircraft's space requirements and the required battery shape.

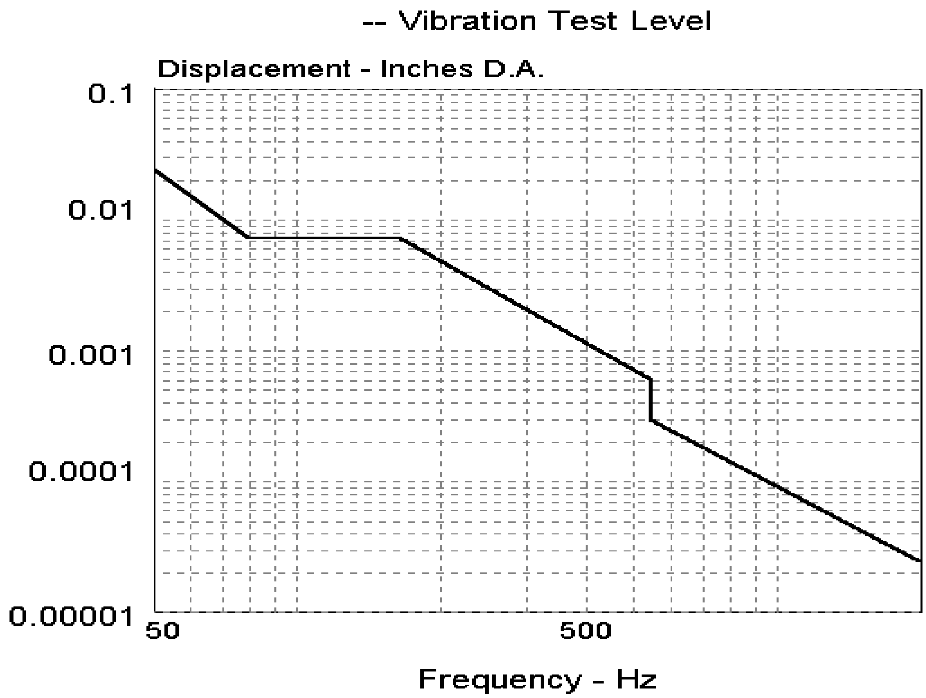

Figure 3. F/A-18E/F Aircraft Sinusoidal Vibration Level (10.0 Gs MAX).

Further investigations revealed that existing LMF cells were available and being used in a US Army helicopter battery application and could possibly be repackaged for the F/A-18E/F aircraft. Also, SLA monoblocs were being utilized in a US Air Force and US Navy inertial navigation system (INS) indicating that SLA technology could be readily reconfigured for the F/A-18E/F application. Even though a SFNC system was being used in an US Army advanced helicopter, a foreign fighter aircraft, and was being tested by the US Air Force no cell or container configuration could be readily adapted to the F/A-18E/F aircraft battery shape and volume.

Battery supportability in the field was another area of concern when evaluating available aircraft batteries. Batteries using nickel-cadmium and lead-acid technology have been in the US Navy inventory for years and so has nickel-cadmium and lead-acid battery ground support equipment and battery maintenance manuals. However, since, SFNC battery technology is new and currently being used in very limited military applications and requires a specialized charger no ground support equipment is available in the US Navy inventory to support the SFNC technology.

Cost

In these times of downsizing and shrinking defense budgets cost is an important driver when developing any component for a new or existing weapons system. The F/A-18E/F aircraft main battery is no exception.

For comparison purposes the cost was based on the total price of the respective battery and its charger. Since LMF batteries and SLA batteries can be safely and adequately charged using the constant potential method on the aircraft, these batteries can be charged using the same 50-amp airborne charger. However, the SFNC battery has to have its own dedicated charger because of its unique charging profile based on battery temperature rise, timed topping charge and battery voltage clamp circuitry. Cost and pricing information received by the Government indicated that the cost of the LMF battery with charger and SLA battery with charger were almost equal. On the other hand, the cost of the SFNC battery with charger exceeded the cost of the other two systems by approximately 58.0 percent.

Initial Battery Selection

The initial battery selection was based on the following criteria: Availability of hardware to meet aircraft electrical requirements;availability of hardware to meet aircraft mechanical requirements;Battery volume and weight limitations; ability of manufacturer to develop new hardware or adapt existing hardware to meet program schedules and funding constraints;availability of ground support equipment and hardware cost.

The Government chose to proceed with the development of two competing batteries based on LW and SLA technologies. These technologies were chosen because existing hardware could be readily modified and adapted to be compatible with the aircraft's mechanical, weight, space and shape requirements, and program schedules and funding levels. Also, the LMF and SLA batteries could be maintained in the field with existing common ground support equipment, exhibited a high probability of meeting the aircraft's electrical requirements, and were equally cost competitive.

A battery utilizing SFNC technology was not developed for the F/A-18E/F aircraft because of the following: Hardware did not exist or could be readily adapted to meet the aircraft's space and shape requirements within the program schedule and cost constraints; No common ground support equipment was available in the field to maintain the battery; The SFNC battery charger is unique and could not be used with any other battery: The cost of the SFNC system exceeded that of the other systems by an estimate 58.0 percent.

The following areas were addressed after the initial decision was made to develop and evaluate aircraft batteries utilizing LMF and SLA technologies:

- Safety-of-Flight Evaluation
- Final Battery Selection
- Award Contract for EMD Batteries
- Qualification Tests

Award Contracts for LMF and SLA Batteries

NAVSURFWARCENDIV Crane awarded one contract for the design, development, manufacture, and delivery of LMF batteries and one contract for the design, development, manufacture, and delivery of SLA batteries for safety-of-flight testing. The batteries were designed and manufactured pursuant to the requirements of military specification MIL-B-8565J and a procurement performance specification, which reflected the aircraft's mechanical, electrical and operational requirements.

Safely-of-Flight Evaluation

The LMF battery was comprised of 19 nickel-cadmium cells connected in series and housed in a steel container equipped with a circular connector receptacle. On the other hand, the SLA battery was made up of two monoblocs connected in series and housed in an aluminum container. The SLA battery was equipped with a circular connector receptacle and internal battery heaters. Both the LMF battery and SLA battery were rated at 24.0-Volts, 15.0 AH/1-HR/24°C/20.0V.

The following test descriptions and tables describe test methods used and show direct comparisons of the two battery technologies evaluated. In instances where the battery capacity is derated the derating results from the normal electrochemical properties of batteries at temperature extremes. Test failures are marked in the data tables with an asterisk.

Table 1
Battery Weights

Battery Type	Measured (Avg. Lbs.)	Required (Lbs.)
LMF	33.37	45.1 MAX
SLA	39.1	45.1 MAX

Each battery was subjected to a conditioning charge and subsequent constant-potential charge and the battery capacities were measured during a 15-amp discharge to a cutoff voltage of 20.0 volts. The battery performance is shown in Tables 2 and 3.

Table 2
Battery Capacities After Conditioning Charge

Battery Type	Measured (Avg. AHs)	Required (AHs)
LMF	16.38	15.O MIN
SLA	18.15	15.0 MIN

Table 3
Battery Capacities After Constant-Potential Charge

Battery Type	Measured (Avg. AHs)	Required (AHs)
LMF	15.21	15.0 MIN
SLA	17.88	15.0 MIN

The batteries were subjected to the load profile as shown on Figure 1 at test temperatures of -26°C, 24°C, and 68°C. The batteries were discharged while at the test temperature after being soaked for a period of 20 - 24 hours. A listing of the battery performances is contained in Table 4.

<u>Table 4</u>
<u>Battery Performance During</u>
<u>Simulated Aircraft Turnaround Loads</u>

Battery Type	Test Temp (°C)	AH Out	Measured (Avg Volts)	Required (Volts)
LMF	-26	4.35	19.99	18.0 MIN
SLA	-26	4.35	21.00	18.0 MIN
LMF	24	4.35	21.92	18.0 MIN
SLA	24	4.35	23.41	18.0 MIN
LMF	68	4.35	21.40	18.0 MIN
SLA	68	4.35	23.50	18.0 MIN

Both types of batteries were subjected to an aircraft start-up load test at a temperature of -30 0 C after a 20 - 24 hour soak period. Table 5 contains a listing of the test results and Figure 4 shows the aircraft start-up load profile.

Table 5
Battery Performance During
<u>Simulated Aircraft Start-Up Load Profile</u>

Battery Type	Test Temp (°C)	AH Out	Measured (Avg. Volts)	Required (Volts)
LMF	-30	4.02	17.78*	18.0 MIN
SLA	-30	4.02	20.18	18.0 MIN

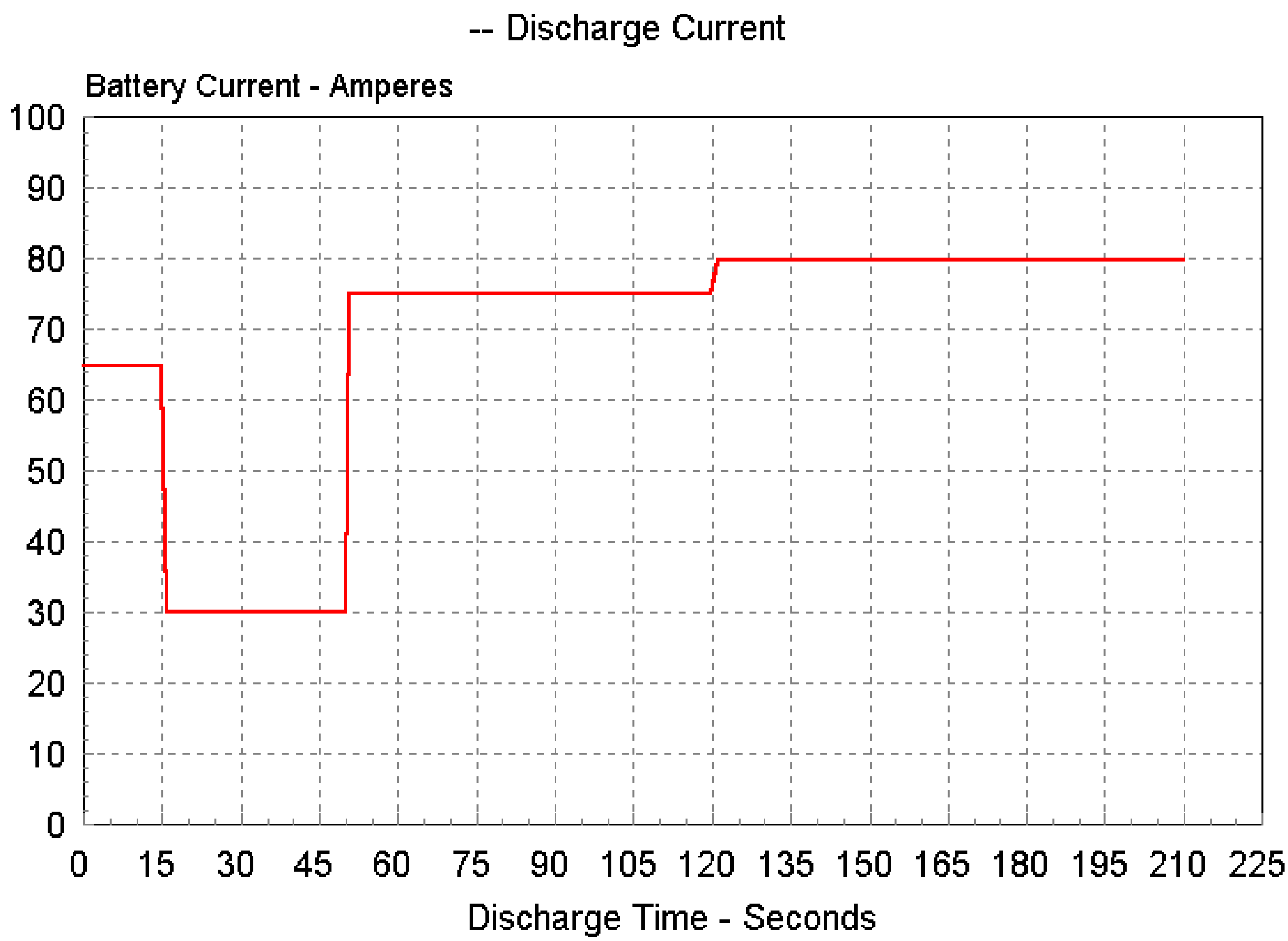

Figure 4. F/A-18E/F Aircraft Start-up Load Profile.

The LMF and SLA batteries were tested to determine the battery performance under an emergency condition. A 7 1 -amp load was applied to the batteries for 4.0 minutes at test temperatures of -18°C, 24°C and 50 °C. A summary of the test results is contained in Table 6.

Table 6
Battery Performance During
Aircraft Emergency Load

Battery Type	Test Temp (°C)	AH Out	Measured (Avg. Volts)	Required (Volts)
LMF	-18	4.73	18.6	18.0 MIN
SLA	-18	4.73	20.86	18.0 MIN
LMF	24	4.73	20.85	18.0 MIN
SLA	24	4.73	22.9	18.0 MIN
LMF	50	4.73	20.53	18.0 MIN
SLA	50	4.73	23.25	18.0 MIN

Each type of battery was subjected to a hot temperature-charging test at 50°C and 68°C to determine the battery's high temperature charging characteristics. The batteries were fully charged and placed in a temperature chamber adjusted for 50°C and allowed to soak for 20 -24 hours. At the conclusion of the soak period, the batteries were discharged at a rate of 15.0 amps to a cutoff voltage of 20.0 volts and the test results were recorded. The batteries were allowed to stabilize at laboratory conditions and then fully charged using a constant-potential method with a voltage level of 28.25 vdc. The batteries were then placed in a temperature chamber adjusted to 50°C and allowed to soak for 20 -24 hours and were discharged per Figure 1, and the lowest allowable battery terminal voltage during the discharge was 18.0 volts. Immediately following the step discharge and while still at 50°C the batteries were charged using the constant potential method with a charging voltage of 28.25 vdc for a period of two hours. At the conclusion of the 2 hour charging period, the batteries were removed from the temperature chamber and immediately discharged at a rate of 15.0 amps to a cutoff voltage of 20.0 volts and the test results were recorded. The test was repeated using a second sample, but at a test temperature of 68°C. The 1C-rate capacity of the batteries after hot temperature charging was derated due to increased battery inefficiency at high temperatures. Table 7 contains a complete listing of the batteries' performance.

Table 7
Battery Performance During
Hot Temperature Charging

Battery SN	TestTemp (°C)	Discharge	Measured	Required
LMF-1B	50	15.0 Amps to 20.0 Volts	11.31 Ahs*	15.0 AHs MIN
LMF-1B	50	Aircraft Profile	21.53 Volts	18.0 Volts M IN
LMF-1B	24	15.0 Amps to 20.0 Volts	11.51 AHs	10.0 AHs MIN
LMF-2B	68	15.0 Amps to 20.0 Volts	10.83 AHs*	13.5 AHs MIN
LMF-2B	68	Aircraft Profile	21.33 Volts	18.0 Volts MIN
LMF-2B	24	15.0 Amps to 20.0 Volts	10.20 AHs	7.5 AHs MIN
SLA-1	50	15.0 Amps to 20.0 Volts	15.88 AHs	15.0 AHs MIN
SLA-1	50	Aircraft Profile	23.4 Volts	18.0 Volts MIN
SLA-1	24	15.0 Amps to 20.0 Volts	16.94 AHs	10.0 AHs MIN
SLA-2	68	15.0 Amps to 20.0 Volts	15.17 AHs	13.5 AHs MIN
SLA-2	24	15.0 Amps to 20.0 Volts	16.88 AHs	7.5 AHs MIN

Each type of battery was subjected to a cold temperature-charging test at -40°C to determine the respective battery's low temperature charging characteristics. The batteries were fully charged and placed in a temperature chamber adjusted for -40°C and allowed to soak for 20-24 hours. At the conclusion of the soak period, the batteries were discharged at a rate of 15.0 amps to a cutoff voltage of 20.0 volts while still at the low temperature condition. The batteries were allowed to stabilize at -40°C and were charged using a constant-potential method with a voltage level of 28.25 vdc. At the conclusion of the 2-hour charging period, the batteries were removed from the temperature chamber and immediately discharged at a rate of 15.0 amps to a cutoff voltage of 20.0 volts. During the low temperature evaluation the internal heaters in the SLA battery were only activated during charging, however the LMF battery was not equipped with internal heaters. The IC-rate capacity of the batteries after cold temperature charging was derated due to increased inefficiency of the batteries during low temperature operation. A complete listing of the test results is contained in Table 8.

Table 8
Battery Performance During
Ultra-Cold Temperature Charging

Battery SN	Test Temp (°C)	Discharge	Measured	Required
LMF458	-40	15.0 Amps to 20.0 Volts	0.01 AH	No Requirement
LMF-OB	24	15.0 Amps to 20.0 Volts	4.0 AHs*	13.5 AHs MIN
SLA-3	40	15.0 Amps to 20.0 Volts	5.94 AHs	No Requirement
SLA-3	24	15.0 Amps to 20.0 Volts	16.26 AHs	13.5 AHs MIN

A temperature rise and float test was performed using both types of batteries. Each battery was fully charged and soaked in a temperature chamber adjusted to 49°C for a period of 12 hours. At the end of the 12-hour period the batteries were discharged at a 97.5 amp rate for 5 minutes or to 14.0 volts, whichever occurred first. Immediately following this discharge and while still in the temperature chamber the batteries were subjected to 28.6 vdc constant-potential charge for 16 hours. During the 16-hour charging period the batteries were monitored to ensure that the battery current did not increase by more than 1.5 amps from its lowest value. The batteries were removed from the temperature chamber and allowed to stabilize at laboratory ambient conditions and then discharged at a rate of 15.0 amps to a cutoff voltage of 20.0 volts. Table 9 lists the test results noted during the temperature rise and float test.

Table 9
Battery Performance During
Temperature Rise and Float

Battery SN	Test Temp (°C)	Discharge Rate	Measured	Required
LMF-2B	50	97.5 Amps	4.89 Minutes*	5.0 Minutes or 14.0 Volts MIN
LMF-2B	24	15.0 Amps to 20.0 Volts	9.28 AHs*	I5.0 AHs MIN
SLA-2	50	97.5 Amps	21.7 Volts After 5.0 Minutes	5.0 Minutes or 14.0 Volts MIN
SLA-2	24	15.0 Amps to 20 0 Volts	17.69 AHs	15.0 AHs MIN

Each battery type was subjected to a 30-day storage test at temperatures of 50°C and -26°C. The batteries were fully charge prior to being placed in the temperature chambers for a 30-day storage period. At the conclusion of the 30 days the batteries were removed from the chambers and subjected to a discharge at a rate of 15.0 amps to a cutoff voltage of 20.0 volts. The 1C-rate capacity of the batteries was derated to allow for the natural self discharge of batteries in a storage environment. Table 10 lists the test results noted after the storage test.

Table 10
Battery Performance After 30-Day Storage

Battery SN	StorageTemp (°C)	Test Temp (°C)	Measured (AHs)	Required (AHs)
LMF-4B	50	24	9.57	7.5 MIN
LMF48	-26	24	11.16	7.5 MIN
SLA-4	-26	24	12.74	7.5 MIN
SLA-4	50	24	6.25*	7.5 MIN
SLA-2	50	24	7.56	7.5 MIN

Each type of battery was subjected to vibration tests that simulated the predicted aircraft random and sinusoidal vibration levels. The batteries were subjected to the random vibration levels as shown on Figure 2, for 1-hour in each of the batteries' three mutually perpendicular axes. Additionally, the batteries were evaluated to determine their resistance to sinusoidal vibration inputs per the requirements shown on Figure 3, for 30 minutes in each of the batteries three mutually perpendicular axes. The batteries did not appear to exhibit any significant mechanical degradation due to vibration, but post vibration tests indicated that the LMF batteries did not meet the battery capacity requirement. A listing of the post- vibration capacity test results is contained in Table 11.

Table 11
Battery Performance After Vibration

Battery SN	Type of Vibration	Measured (AHs)	Required (AHs)
LMF-2B	Random	10.43	15.0 MIN
LMF-6B	Sinusoidal	12.01*	15.0 MIN
SLA-2	Random	17.25	15.0 MIN
SLA-3	Sinusoidal	15.63	15.0 MIN

The Government's goal was to utilize a battery in the F/A-18E/F aircraft that could be installed in the aircraft and not require any scheduled maintenance for 3 years. Both battery technologies were tested to determine if they could complete a minimum of 400 successful life cycles.

Each battery type was placed in a temperature chamber and connected to a DC power source adjusted to 28.25 vdc and current limited to 50.0 amps. However, the SLA battery was also connected to an AC power source adjusted to II 5.0 vac 400 Hz, which supplied power to the battery's internal heater circuit. Power was only applied to the SLA battery's internal heater circuit during the charge portion of each life cycle. Each life cycle consisted of an 18.0-minute discharge, 2-hour constant-potential charge and a 102.0-minute rest period (open circuit). Additionally, the test temperature was varied every 25 life cycles from 24 0 C to 43 0 C to - 18°C and back to 24 0 C throughout the test. Table

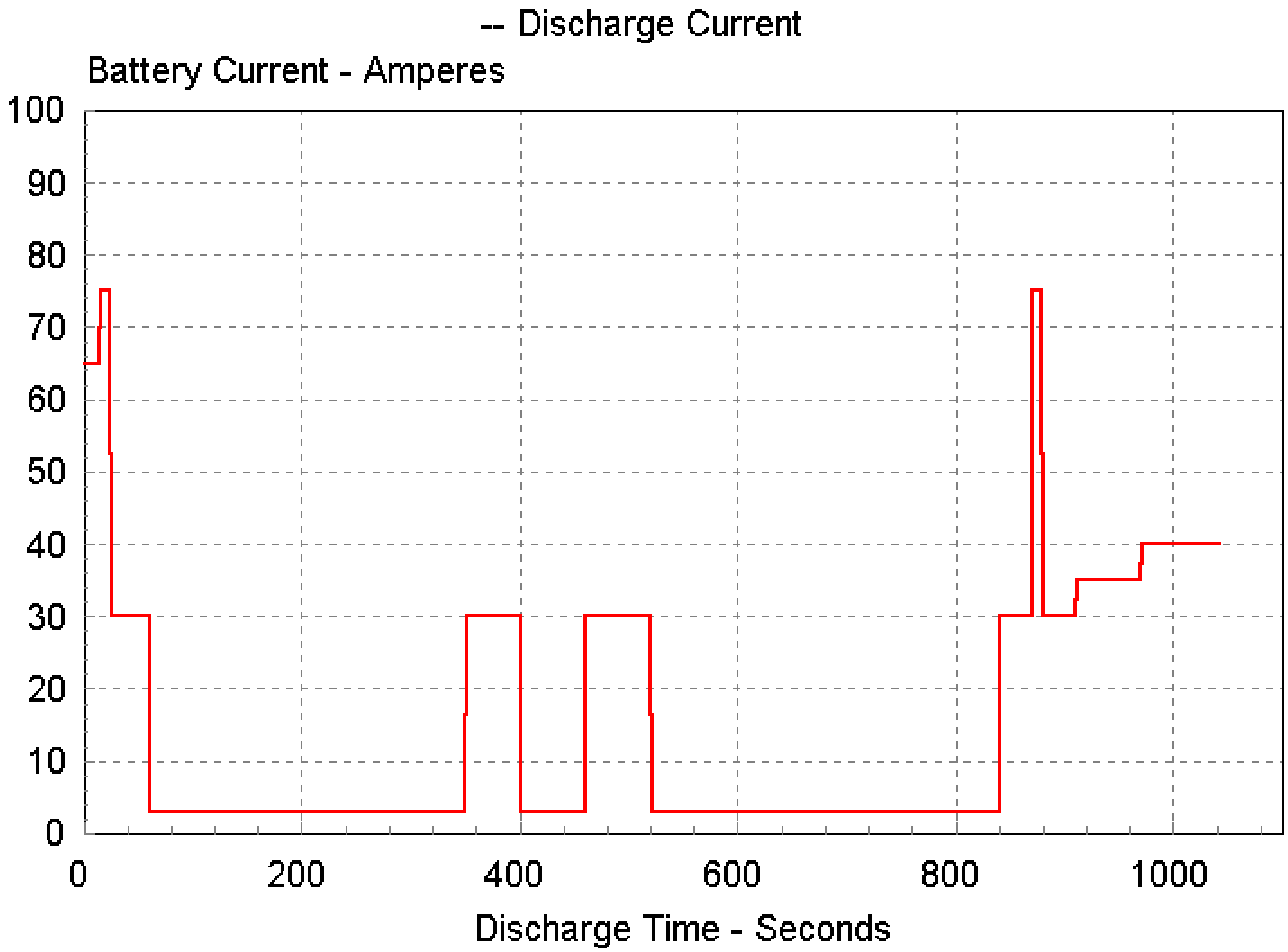

Figure 5. F/A-18E/F Aircraft Battery Life Cycle Profile

12 contains a @g of the batteries performance during and after the life cycling test.

Figure 5 and Figure 6 show the life cycle load profile and the batteries' performance lively.

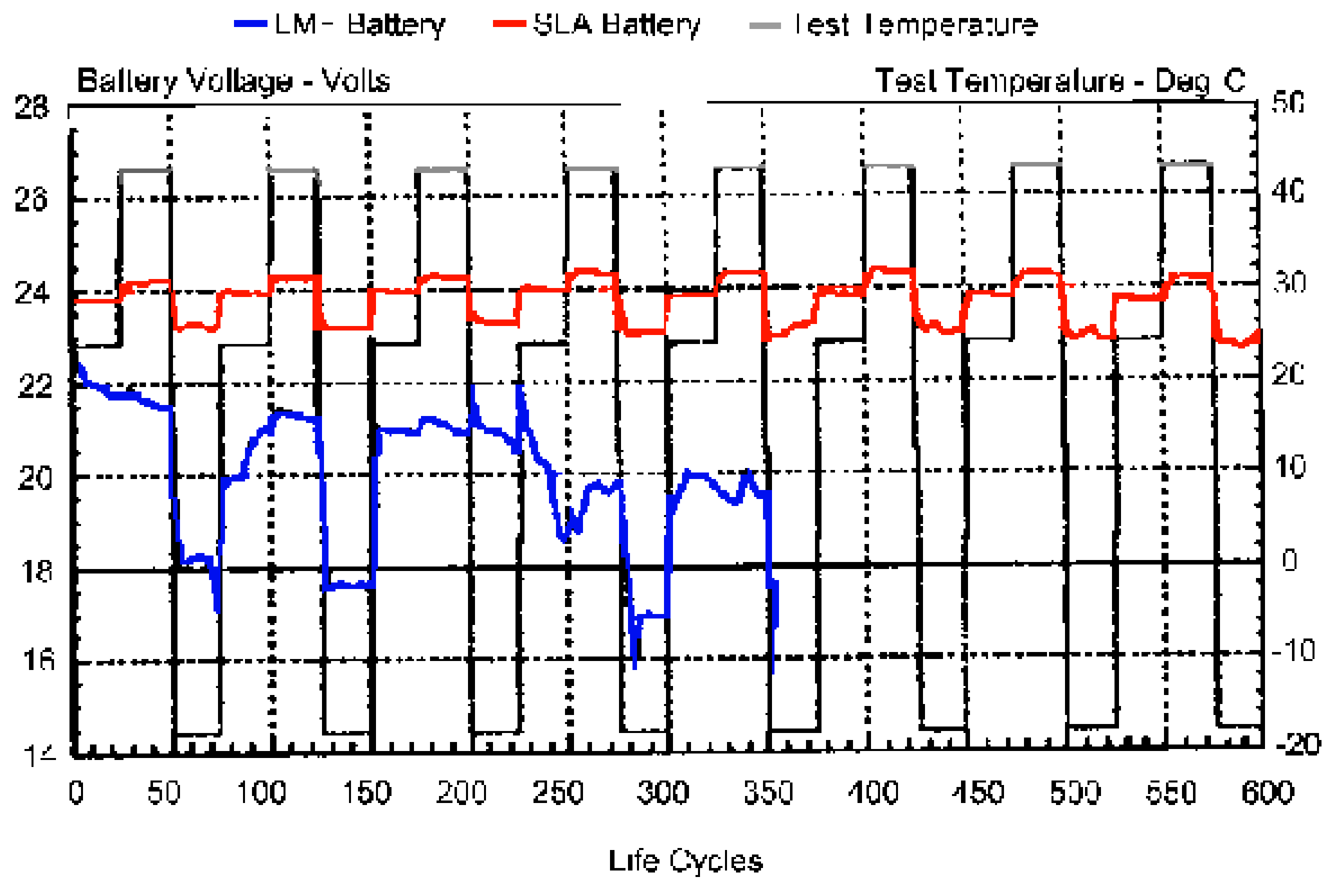

Figure 6. Battery Performance During Life Cycling Test

Table 12
Battery Performance During
and After Life Cycling

Battery SN	Test Temp (°C)	Discharge	Lowest Voltage	Measured (Ahs)	Required (Ahs)	Test Halted at Cycle
LMF-2B	-18	Aircraft Profile	15.7 Volts*	-----	-----	354
LMF-6B	24	Aircraft Profile	18.6 Volts	-----	-----	-----
SLA-2	43	Aircraft Profile	17.3 Volts*	-----	-----	-----
SLA-3	24	15.0 Amps to 20.0 Volts	-----	1.57*	7.5 MIN	-----
LMF-2B	-18	Aircraft Profile	>23.0 Volts	-----	-----	400
LMF-6B	24	Aircraft Profile	>23.5 Volts	-----	-----	-----
SLA-2	43	Aircraft Profile	>24.0 Volts	-----	-----	-----
SLA-3	24	15.0 Amps to 20.0 Volts	-----	18.37	7.5 MIN	-----

The unsatisfactory performance of the LMF battery was attributed to a manufacturing process error during the construction of the battery's negative plates.

After the SLA battery had successfully completed the life cycling test it was subjected to an additional 200 life cycles for a total of 600 life cycles. The SLA battery maintained a battery voltage at the end-of-discharge of 22.95 vdc during cycle 600 and provided 100.4 percent of its rated capacity after the 600 life cycles life test.

The SLA battery successfully completed the safety-of-flight tests except for a marginal failure after 30 days of storage at a temperature of 50°C. The LMF battery successfully met the initial test requirements, but failed to meet test requirements for battery performance during aircraft start-up loads at -30°C, hot temperature charging at 50°C and 68°C, cold temperature charging at 40°C, temperature rise and float, after vibration, and life cycling.

Final Battery Selection

SFNC battery technology was not selected for the F/A-18E/F aircraft application for the following reasons:

- Existing SFNC battery designs were not compatible with the battery volume and battery shape requirements.
- Unable to meet program schedule.
- SFNC battery requires a unique airborne charger.
- No common SFNC ground support equipment available in the field.
- High cost of SFNC battery system.

LMF battery technology was not utilized in the F/A-18E/F aircraft because of the following:

- Unsatisfactory electric performance at low and high temperature.
- Unsatisfactory electrical performance during and after life cycling.
- Unsatisfactory electrical performance after random and sinusoidal vibration.
- Program schedule and budget constraints did not allow for any further evaluation of the LMF technology pursuant to this application.

SLA battery technology was selected for the F/A-18E/F based on the following:

- Overall electrical performance.
- Overall mechanical performance.
- Common ground support equipment is available in the field.
- Simple and easily maintained system.
- Competitive system cost.

Award Contracts for EMD Batteries

Contracts were awarded for the manufacture and delivery of SLA batteries to support the F/A-18E/F aircraft 3-year EMD program during 1994 and 1995. The batteries have been delivered to the Government and are either installed in an aircraft or in storage awaiting installation.

Qualification Tests

With the selection process completed, a qualification test program was initiated and completed and the SLA batteries comply with the requirements of military specification MIL-B-8565J and the NAVSURFWARCENDIV Crane procurement specification. Also, the SLA batteries meet the requirements of Draft military specifications MIL-PRF-8565K and MIL-PRF-8565/14(AS).

Summary and Conclusions

- SLA battery technology was selected for use in the F/A-18E/F aircraft.
- The SLA battery meets the electrical, mechanical, and operational requirements of the aircraft.
- The SLA battery system is simple, reliable and easily maintained in the field.
- Common ground support equipment is available in the field to maintain the SLA battery.
- The SLA battery system is cost competitive.
- The SLA battery system is currently being used onboard the F/A-18E/F EMD aircraft.
- The Government has a qualified source of supply for the SLA battery and airborne battery charger.