

Intermixing Cells in an Aircraft Nickel-Cadmium Battery

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16. Abstract <p>Tests were performed at the Federal Aviation Administration William J. Hughes Technical Center by the Fire Safety Team of the Airport and Aircraft Research and Development Group to determine if intermixing different manufacturer cells within an aircraft nickel-cadmium battery has an effect on battery performance and if any such effect results in a safety of flight issue.</p> <p>A series of tests from RTCA/DO-293 were conducted on two batteries, one consisted of all original equipment manufacturer (OEM) cells, and one consisted of ten OEM and ten Part Manufacturer Approval (PMA) replacement cells. The tests included several rated capacity tests, a charge stability test, a duty performance test, and an induced destructive overcharge test. Throughout the tests, only slight differences between the OEM and intermixed batteries were observed. The PMA cells consistently charged at a higher voltage; however, none of the cells exceeded the maximum voltage of 1.7 V. During some tests, individual cells showed some differences in behavior and recorded battery temperatures. The most notable difference occurred during the induced destructive overcharge tests, in which a larger number of cells from the intermixed battery recorded increased voltage readings, indicating signs of thermal runaway. The results show no indication of any safety of flight issues arising from the intermixing of OEM and PMA battery cells within a nickel-cadmium aircraft battery.</p>					
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LIST OF ACRONYMS

A	Ampere
Ah	Ampere-hour
CMM	Component Maintenance Manual
EPV	End point voltage
FAA	Federal Aviation Administration
NiCd	Nickel-cadmium
OEM	Original equipment manufacturer
PMA	Parts Manufacturer Approval
V	Volt
Vdc	Voltage direct current

EXECUTIVE SUMMARY

The Federal Aviation Administration (FAA) issues Parts Manufacturer Approvals (PMA) for aircraft replacement parts that are not manufactured by the original equipment manufacturer (OEM). To obtain a PMA, the replacement part manufacturer must meet the FAA requirements for safety regulations and standards, and it must meet the OEM's specifications and standards for the part it is replacing.

Replacement battery cells within aircraft batteries are issued PMAs from the FAA under Order 8110.42C; however, some OEMs claim that intermixing PMA with OEM cells within an aircraft battery can have drastic effects on battery performance, thus causing a potential safety of flight issue. Tests were performed at the FAA William J. Hughes Technical Center by the Fire Safety Team of the Airport and Aircraft Research and Development Group to determine if intermixing cells within an aircraft nickel-cadmium battery has an effect on battery performance or safety.

For the purpose of these tests, two Saft 4078-7 aircraft batteries were used. This 20-cell, 43-ampere-hour (Ah) battery with a nominal voltage of 24 volts (V) is used to start the engine on the ground before onboard systems are normally supplied and in the case of faulty functioning or failure of normal power supply while airborne. It is charged onboard using the aircraft's 28 Vdc electrical network. One of these batteries was kept in its original form with all OEM battery cells, while half the cells (10 cells) in the other battery were replaced with PMA replacement cells.

A series of tests from RTCA/DO-293 were conducted on the two batteries, including several rated capacity tests, a charge stability test, a duty performance test, and an induced destructive overcharge test. Throughout the tests, only slight differences were observed between the OEM and intermixed batteries. The PMA cells consistently charged at a higher voltage, however, none of the cells ever exceeded the OEM-specified maximum voltage of 1.7 V.

The performance of both batteries was significantly diminished during the rated capacity test that was conducted at -22°F, with the OEM battery having a capacity of 29.3 Ah and the intermixed battery having a capacity of 22.0 Ah. During one discharge cycle of the duty cycle test, the intermixed battery recorded a capacity of 42.1 Ah, which is below the rated capacity of the battery, but not below the test specification which requires 80% of capacity during this interval of the test. Other than these discrepancies, the recorded capacities for both batteries throughout the tests were very similar.

The recorded battery temperature during the duty cycle test showed considerable differences. The OEM battery experienced significant temperature spikes of up to 138°F, lasting for brief time periods. These temperature spikes occurred during the charge and discharge periods. In contrast, the intermixed battery experienced severe increases in temperature for prolonged time periods, occurring not only during the charge and discharge periods, but also during the cycling of the battery. This temperature rise sometimes exceeded 168°F.

The overall performance of the two batteries during the induced destructive overcharge test was very similar, however, the individual cells showed some significant variations. Both batteries exhibited very large increases in current and battery temperature during the overcharge portion of the test. The OEM battery resulted in a maximum temperature of 257°F and a maximum current of 170 amperes (A), while the intermixed battery resulted in maximum values of 274°F and 164 A. The OEM battery contained 4 battery cells that exceeded 2.0 V during the test. Of those four cells, only one (cell 5) exceeded 10 V, indicating signs of thermal runaway. Other cells in the OEM battery exceeded 2.5 V. In comparison, the intermixed battery contained six battery cells exceeding 2.0 V. These cells consisted of four OEM and two PMA cells. Both PMA cells (cells 5 and 6) exceeded 10 V. Only one OEM cell in the intermixed battery exceeded 10 V (cell 9), while all three of the other OEM cells exceeded 2.5 V (cells 4, 14, and 17). Neither battery exhibited any evidence of flames or explosions during this test; however, smoke emanated from both batteries as the electrolyte within the cells evaporated due to the high temperatures. The observed smoke was similar in type and approximate volume for both batteries; following dismantling and inspection of the batteries, no evidence of any physical damage was found. The test results showed no indication of any safety of flight issues arising from the intermixing of OEM and PMA battery cells within a nickel-cadmium aircraft battery.

INTRODUCTION

BACKGROUND.

The Federal Aviation Administration (FAA) issues Parts Manufacturer Approvals (PMA) under Order 8110.42C [1] for aircraft replacement parts that are not manufactured by the original equipment manufacturer (OEM). To obtain a PMA, the replacement part manufacturer must meet the FAA requirements for safety regulations and standards, and it must meet the OEM's specifications and standards for the part it is replacing.

Replacement battery cells within aircraft batteries are issued PMAs from the FAA; however, there have been claims from OEMs that intermixing PMA with OEM cells in an aircraft battery can have drastic effects on battery performance and may cause a safety of flight issue. There is also some confusion within the FAA regulations as to what practices are acceptable relative to PMA cells.

Technical Standard Order C173 [2] is the document that specifies the minimum performance standards required for nickel-cadmium (NiCd) and lead-acid batteries. This document specifies that these batteries must adhere to the conditions specified in RTCA/DO-293 [3]. DO-293 states in paragraph 1.5.1.2, subparagraph b that, "mixing of cells or batteries is not an acceptable practice." It further states that, "Cells or batteries may have different capacities because they have different designs, manufacturing processes or storage, use or age histories. Therefore, mixing cells or batteries with different part numbers, made by different manufacturers or from different sources, is a non acceptable practice." These statements, referenced by the applicable Technical Standard Order [2], clearly advise against the intermixing of cells, yet based on Chapter 1, section 5b of Order 8110.42C, PMA replacement cells are permissible.

SCOPE.

Tests were performed at the FAA William J. Hughes Technical Center by the Fire Safety Team of the Airport and Aircraft Safety Research and Development Group to determine if intermixing cells within an aircraft NiCd battery has an effect on battery performance, and if any such effect results in a safety of flight issue.

EQUIPMENT AND PROCEDURES

TEST EQUIPMENT.

Two Saft 4078-7 aircraft batteries were used for these tests (figure 1). This 20-cell, 43-ampere-hour (Ah) battery with a nominal voltage of 24 volts (V) is used to start the aircraft engine on the ground before onboard systems are supplied normally and in the case of faulty functioning or failure of normal power supply while airborne. It is charged onboard using the aircraft's 28-Vdc electrical network. One battery was kept in its original form with all OEM battery cells, while half the cells in the other battery were replaced with PMA replacement cells. Throughout this report, these will be referred to as the OEM battery and the intermixed battery, respectively. Figure 2 shows a top view of the battery with the top cover removed. The cells are numbered 1 through 20 based on their order of interconnection within the battery. Cells 1, 3, 5, 6, 8, 10,

12, 15, 18, and 20 were replaced with PMA cells in the intermixed battery and are denoted in figure 2 by a red square around the cell's number.



Figure 1. Saft 4078-7 Aircraft Battery

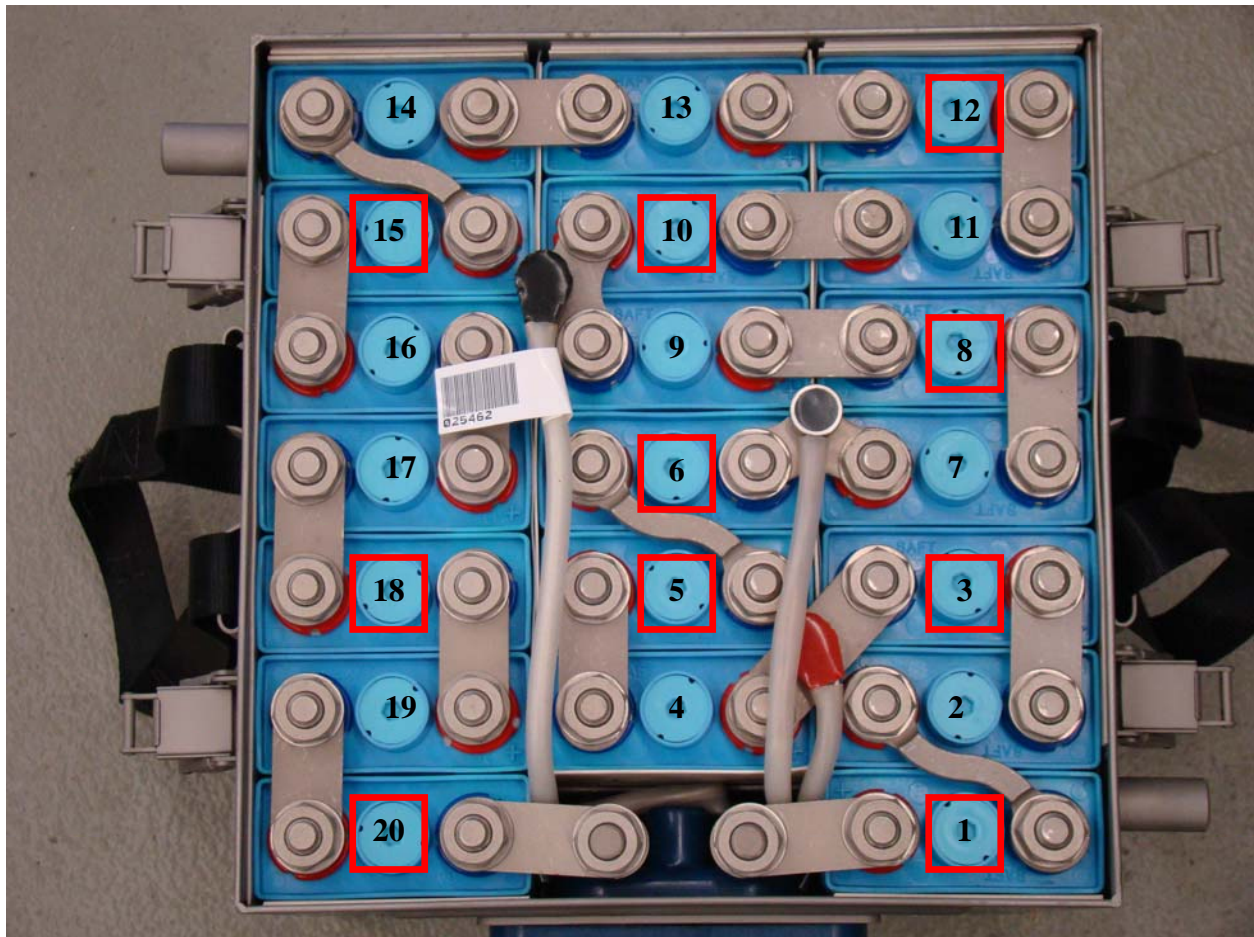


Figure 2. Top View of the Saft 4078-7 Battery With Cover Removed (The cells are numbered with the PMA cells denoted by the red squares around the numbers.)

The two batteries were initially serviced as though they were being commissioned for service onboard an aircraft. This included the following procedures:

1. Battery case and cells are visually inspected for signs of damage.
2. Battery cover is removed for internal inspection of cells and verification of correct cell polarity.
3. Cell vents are inspected.
4. Check cell-to-case insulation.
5. Torque is checked on all hardware.
6. Temperature sensor blanket is inspected for signs of wear.
7. Cannon plug pins are checked.
8. Condition of connector is inspected.
9. Cells are charged per instructions in the Component Maintenance Manual (CMM).
10. Electrolyte levels are adjusted.
11. Any spilled/bubbled electrolyte is cleaned.
12. Case cover is closed.

An Arbin Instruments BT2000 battery analyzer was used to conduct the required tests on the batteries, which included various forms of charging, discharging, and cycling of the batteries. This analyzer had a voltage range of 0-50 V and a current range of 0-400 ampere (A). It also provided the ability to monitor and record voltage data from each of the 20 cells, with a range of 0-10 V, and up to 12 temperature measurements by means of externally connected K-type thermocouples. Supplied software on a computer connected to the BT2000 controlled the analyzer charging and discharging rates and allowed for any number of test steps or cycles to be programmed by the user.

TEST PROCEDURES.

A series of tests from DO-293 were conducted on each battery to evaluate any effect that the intermixing of cells may have on battery performance. The test sequence was as follows:

1. Rated Capacity (DO-293, test 2.2.2)
2. Rated Capacity at -22°F (DO-293, test 2.2.4)
3. Rated Capacity at 122°F (DO-293, test 2.2.5)
4. Charge Stability (DO-293, test 2.6)
5. Duty Cycle Performance (DO-293, test 2.10)

6. Rated Capacity (DO-293, test 2.2.2)
7. Induced Destructive Overcharge (DO-293, test 2.14)

Each test is discussed in the following sections. The complete test specifications are found in DO-293. The charging or discharging rate is referred to as the C-rate. For a battery with a capacity of 43 Ah, such as those discussed in this report, a C-rate of 1 is equivalent to a current of 43 A and is denoted as 1C, a C-rate of 0.5 is equivalent to 21.5 A and is denoted as 0.5C, etc. All tests were initiated with an initial full charge of the battery according to its CMM. This charging process consisted of a 0.5C charge for a minimum of 2 hours. This charging rate was then continued until the battery reached 31 V, at which time it was charged at a 0.1C rate for an additional 4 hours. During the last hour of the 0.1C-rate charge, electrolyte levels were checked and adjusted (using distilled water according to the CMM) during the charge cycles following tests 3, 4, and 6.

RATED CAPACITY TEST. The rated capacity test is designed to determine the minimum capacity obtained from a charged battery when discharged at a 1C rate to its end point voltage (EPV). Following a full charge cycle, the battery rested on open circuit for 20 hours, at which point it was discharged at the 1C rate to its EPV of 20 V. This test was conducted at ambient conditions as well as at -22°F and 122°F. The -22° and 122°F tests were conducted in an environmental chamber, and the open circuit rest period was set for an additional 1 hour, for a total of 21 hours, to allow sufficient time for the chamber temperature to stabilize. The rated capacity test at ambient conditions was also repeated following the duty cycle performance test.

CHARGE STABILITY TEST. During the charge stability test, temperature measurements of the battery were recorded by inserting a K-type thermocouple approximately midway between cells 6 and 9. Following the full charge cycle, the battery was placed in an environmental chamber at 122°F for a period of 21 hours. The battery remained in the 122°F chamber while it was discharged at a 6C rate for 5 minutes and then immediately recharged at a constant voltage of 28.5 V for 10 hours. Once the constant voltage charge was completed, the battery rested on open circuit for 1 hour while still in the 122°F chamber and was then discharged at the 1C rate. Following this discharge, the battery rested on open circuit at ambient conditions for a period of 24 hours, at which point it was subjected to the rated capacity test at ambient conditions.

DUTY CYCLE PERFORMANCE TEST. The duty cycle performance test is designed to simulate engine starts and charge cycling to determine the ability of the battery to perform as intended without maintenance over a period of 100 duty cycles. During this test, battery temperature measurements were recorded in the same manner as in the charge stability test. For the purpose of this test, a duty cycle consisted of discharging the battery through a fixed resistor of 0.0195 ohms for 20 seconds. The battery was placed on open circuit for 2 minutes and discharged again through the fixed resistor for 20 seconds. Following this, the battery was charged at a constant voltage of 28.5 V for 1 hour and then placed on open circuit for 1 hour. This cycle was repeated 50 times. The battery was discharged again at the 1C rate to its EPV and recharged according to the CMM. Then it was discharged at the 1C rate to its EPV, recharged according to the CMM, and the 50 cycles were repeated. Once the final cycle was complete, the battery was discharged again at the 1C rate to its EPV, recharged according to the CMM, and discharged one final time at the 1C rate to its EPV.

INDUCED DESTRUCTIVE OVERCHARGE TEST. The induced destructive overcharge test is designed to examine the safety of the battery by simulating conditions that could occur if one or more of the cells were to short and the charger failed to shut off. During this test, battery temperature measurements were recorded in the same manner as in the charge stability test. Following the initial charge cycle, the battery was charged at a constant voltage of 36 V. This constant voltage charge was continued until the battery current had stabilized for a minimum of 1 hour. Subsequent to this charge, the battery was placed on an open circuit for 3 hours while the battery was monitored for any evidence of flame or explosion.

DISCUSSION

Both batteries successfully passed the initial rated capacity test, with the OEM battery having a capacity of 44.7 Ah and the intermixed battery having a capacity of 45.7 Ah. It was observed, however, that the charging voltage of the PMA cells was consistently higher than the OEM battery cells. Figure 3 shows the average voltages for all cells in the OEM battery. For the intermixed batteries, separate values are shown for the average of the OEM cells and PMA cells. Although the PMA cells consistently charged at this higher voltage in all tests, no cell exceeded the maximum cell voltage of 1.7 V.

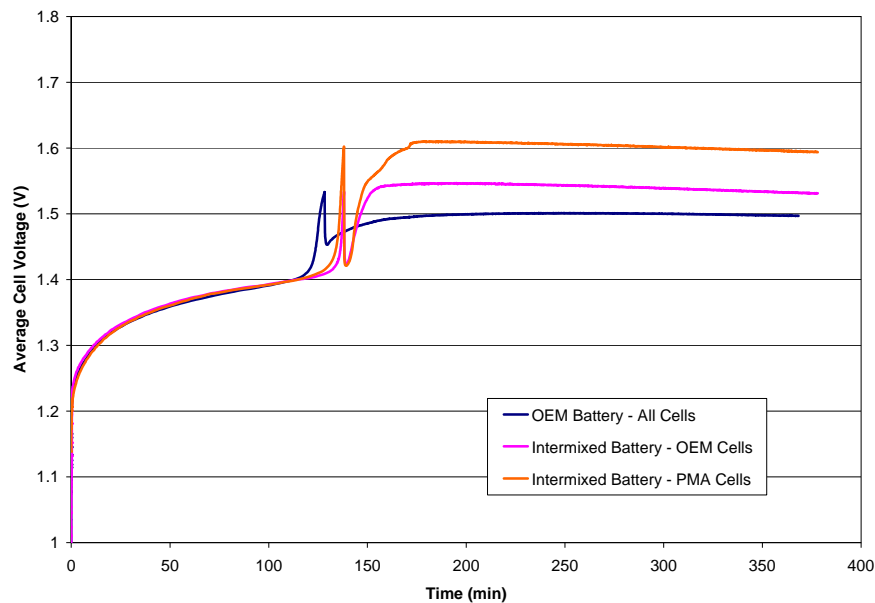


Figure 3. Average Charging Voltage of Cells During the Initial Rated Capacity Test

Both batteries exhibited diminished capabilities during the -22°F rated capacity test, with the OEM battery resulting in a 29.3-Ah capacity and the intermixed battery resulting in a 22.0-Ah capacity. In addition, the OEM battery was able to discharge at the 1C rate for a period of only 41 minutes and the intermixed battery for only 31 minutes. This is in contrast to the 60-minute minimum discharge time that the battery is capable of at ambient conditions.

The 122°F rated capacity tests resulted in both batteries exhibiting a slightly higher capacity than at ambient. The OEM battery produced a capacity of 45.0 Ah with a discharge time of approximately 67 minutes, while the intermixed battery had a capacity of 46.3 Ah with a discharge time of approximately 65 minutes.

The charge stability test was conducted in an environmental chamber with the ambient temperature maintained at 122°F. During the 6C-rate discharge, the two batteries behaved very similarly. The OEM battery exhibited a capacity of 44.8 Ah and a peak battery temperature of 170°F, while the intermixed battery had a capacity of 44.1 Ah and a peak battery temperature of 169°F. The subsequent rated capacity test resulted in a capacity of 45.3 Ah for the OEM battery and 46.9 Ah for the intermixed battery.

The duty cycle tests resulted in four separate discharge capacities being reported. The first was the discharge immediately following the first 50 cycles, and the second discharge was performed after the battery was recharged. The third and fourth battery discharges occurred at similar intervals following the second set of 50 cycles. The OEM battery recorded capacities of 47.1, 47.4, 43.4, and 46.1 Ah, respectively. The intermixed battery recorded similar capacities of 42.1, 49.0, 43.1, and 48.9 Ah, respectively. The 42.1-Ah capacity reading is below the full capacity for the intermixed battery (43 Ah), but is not below the specified requirement in DO-293, which states it must be no less than 80% of full capacity of the battery at this interval. While battery capacity did not vary greatly between the two batteries during this test, the recorded battery temperature showed significant differences. Figure 4 shows the temperature recorded for each battery from a K-type thermocouple that was inserted between cells 6 and 9 of each battery. The OEM battery experienced significant temperature spikes of up to 138°F, lasting for brief periods. These temperature spikes occurred only during the charge and discharge periods. In contrast, the intermixed battery experienced severe increases in temperature for prolonged periods, occurring not only during the charge and discharge periods, but also during the cycling of the battery. This temperature rise sometimes exceeded 168°F.

Following the duty cycle test, the rated capacity test was repeated to check the performance of the two batteries prior to conducting the destructive overcharge test. Again, both batteries successfully passed the rated capacity test; the OEM battery had a 45.3-Ah capacity and the intermixed battery had a 48.2-Ah capacity. As in the initial capacity test, it was observed that the charging voltage of the PMA battery cells was consistently higher than the OEM cells. It was also observed that the charging voltage of all cells was higher than during the initial rated capacity test. Figure 5 shows the average charging voltage of the OEM cells compared to the PMA cells. As in figure 3, figure 5 shows the average voltage for all the cells in the OEM battery and for the intermixed battery, with separate values for the average of its OEM cells and PMA cells. Although higher voltages were observed, no cell ever exceeded the maximum cell voltage of 1.7 V.

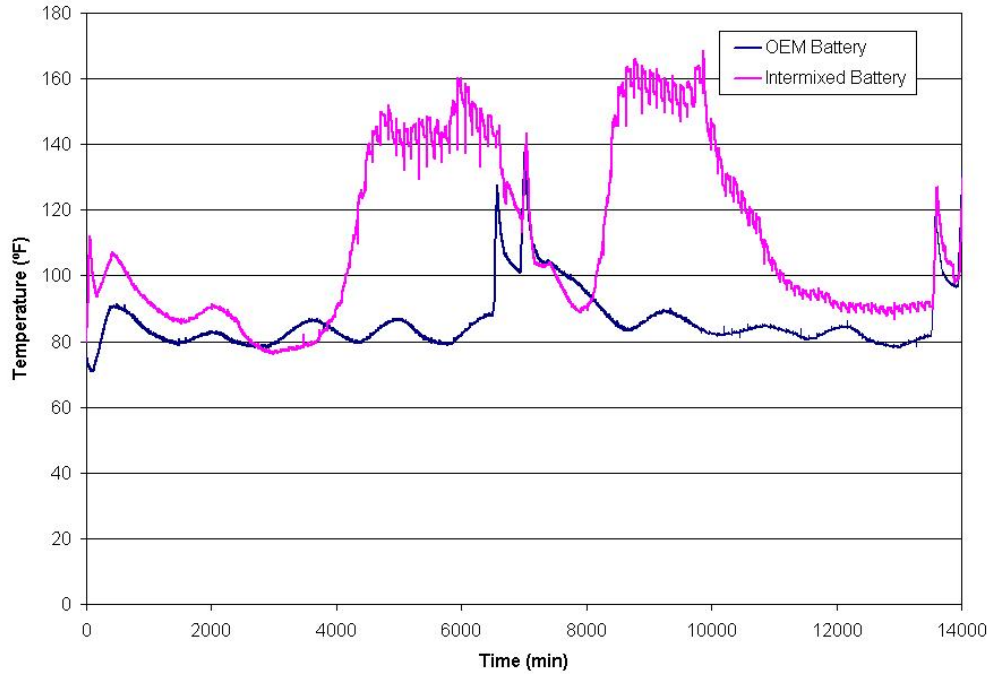


Figure 4. Recorded Battery Temperatures During the Duty Cycle Tests

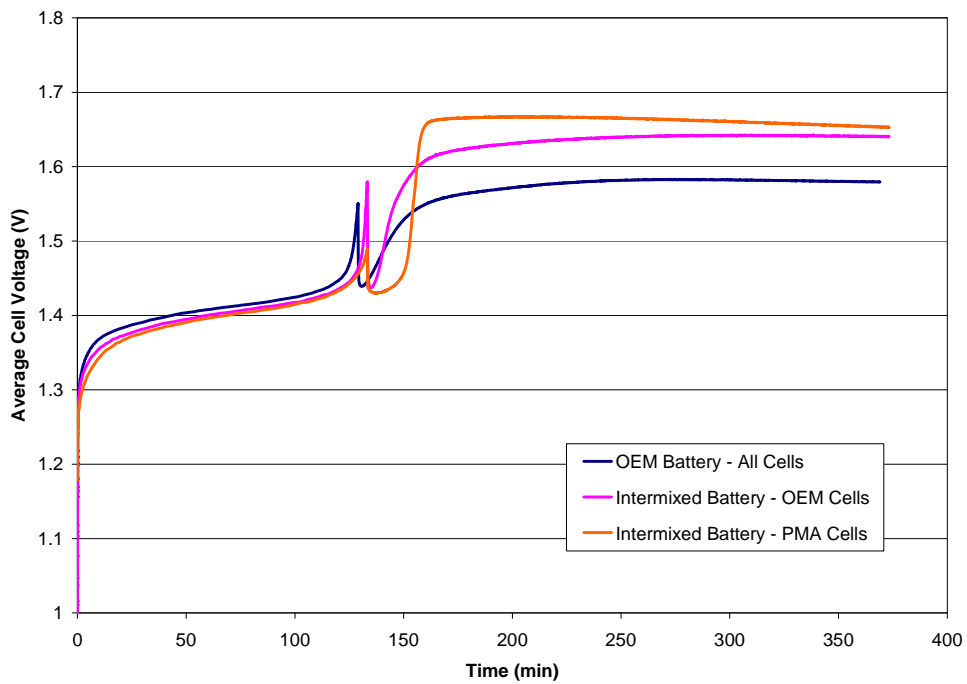


Figure 5. Average Charging Voltage of Cells During the Repeated Rated Capacity Test

The induced destructive overcharge test was the final test conducted. Plots of the charging voltages, currents, and battery temperatures for the OEM and intermixed batteries are shown in figures 6 and 7, respectively. As observed in these figures, the batteries showed very similar

behavior. Both exhibited very large increases in current and battery temperatures during the overcharge portion of the test. The OEM battery resulted in a maximum temperature of 257°F and a maximum current of 170 A, while the intermixed battery resulted in maximum values of 274°F and 164 A.

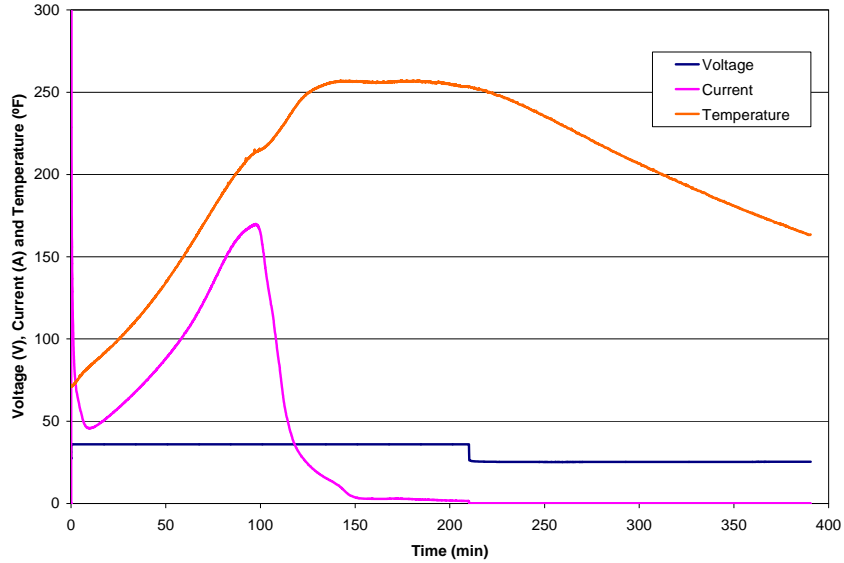


Figure 6. Charging Voltage, Current, and Battery Temperature During the Induced Destructive Overcharge Test for the OEM Battery

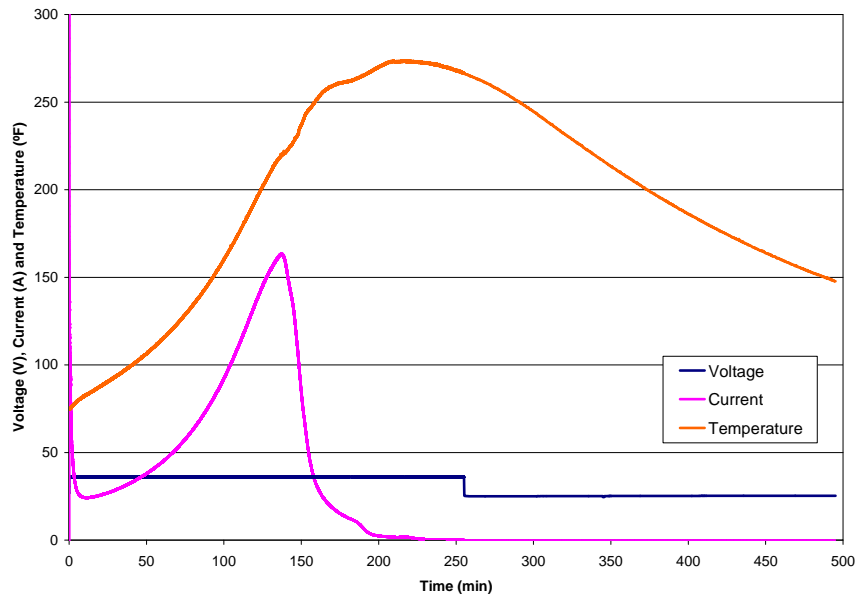


Figure 7. Charging Voltage, Current, and Battery Temperature During the Induced Destructive Overcharge Test for the Intermixed Battery

While the overall performance of the batteries was similar during the induced destructive overcharge test, the individual cells performed quite differently. Figures 8 and 9 show plots of

the individual cell voltages for the OEM and intermixed batteries, respectively, for those cells whose voltages exceeded 2.0 V at any time during the test. The OEM battery contained four battery cells that exceeded 2.0 V during the test. Of those four cells, only one (cell 5) exceeded 10 V, indicating signs of thermal runaway. No other cell in the OEM battery exceeded 2.5 V. In comparison, the intermixed battery contained six battery cells (four OEM and two PMA) exceeding 2.0 V. The two PMA cells (cells 5 and 6) both exceeded 10 V. Only one OEM cell in the intermixed battery exceeded 10 V (cell 9), but all three of the other OEM cells exceeded 2.5 V (cells 4, 14, and 17). Throughout the tests, as well as the subsequent rest period, no flames or explosions were observed from either battery; however, smoke emanated from both batteries as the electrolyte within the cells evaporated due to the high temperatures. The observed smoke was the same type and intensity for both batteries.

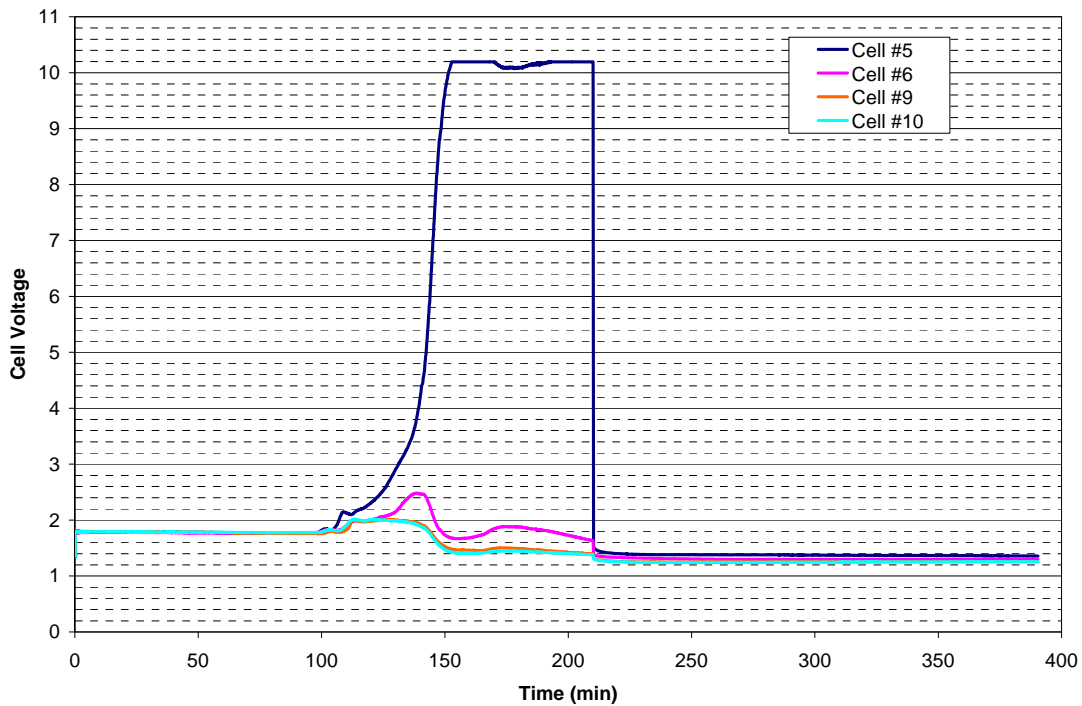


Figure 8. Cell Voltages for Cells Exceeding 2.0 V During the Induced Destructive Overcharge Test for the OEM Battery

Following the destructive overcharge test, both batteries were disassembled. All the cells were removed from the battery casing and inspected for any physical damage, including any burn marks or deformations. No physical damage was found on any of the OEM or PMA cells from either battery.

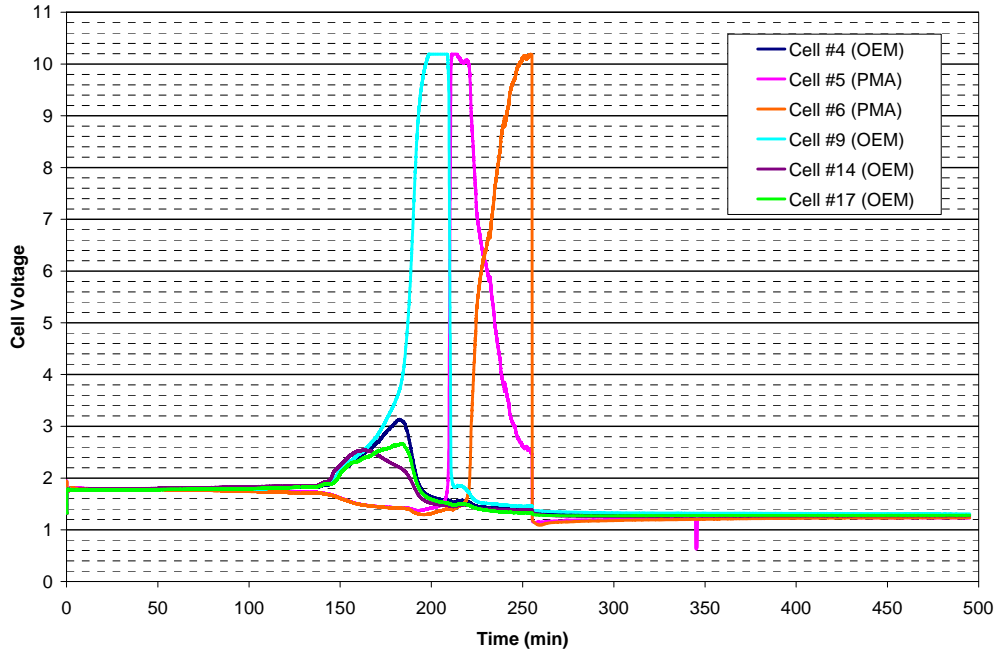


Figure 9. Cell Voltages for Cells Exceeding 2.0 V During the Induced Destructive Overcharge Test for the Intermixed Battery

SUMMARY

Tests were performed to determine if intermixing cells within an aircraft NiCd battery has an effect on battery performance and if any such effect results in a safety of flight issue. Two Saft 4078-7 aircraft batteries were used. One battery was kept in its original form with all OEM battery cells, while half of the cells in the other battery were replaced with PMA replacement cells.

A series of tests from DO-293 were conducted on the two batteries, including several rated capacity tests, a charge stability test, a duty performance test, and an induced destructive overcharge test. Throughout all the tests, only slight differences between the OEM and intermixed batteries were observed. The PMA cells consistently charged at a higher voltage; however, no cell ever exceeded the maximum voltage of 1.7 V. The performance of both batteries was significantly diminished during the -22°F rated capacity test, with the OEM battery having a capacity of 29.3 Ah and the intermixed battery having a capacity of 22.0 Ah. During one of the discharge cycles of the duty cycle test, the intermixed battery recorded a capacity of 42.1 Ah, which is below the rated capacity of the battery, but not below the test specification, which requires 80% of capacity during this portion of the test. Other than these discrepancies, the capacities recorded for both batteries throughout the testing were very similar.

The battery temperatures recorded during the duty cycle test showed considerable differences. The OEM battery experienced significant temperature spikes of up to 138°F, lasting for brief periods. These temperature spikes occurred only during the charge and discharge periods. In contrast, the intermixed battery experienced severe increases in temperature for prolonged

periods, occurring not only during the charge and discharge periods, but also during the cycling of the battery. At times, this temperature rise exceeded 168°F.

The overall performance of the two batteries during the induced destructive overcharge test was very similar; however, the individual cells varied significantly. Both batteries exhibited very large increases in current and battery temperature during the overcharge portion of the test. The OEM battery resulted in a maximum temperature of 257°F and a maximum current of 170 A, while the intermixed battery resulted in maximum values of 274°F and 164 A. The OEM battery contained four battery cells that exceeded 2.0 V during the test. Of those four cells, only one (cell 5) exceeded 10 V, indicating signs of thermal runaway. No other cell in the OEM battery exceeded 2.5 V. In comparison, the intermixed battery contained six battery cells exceeding 2.0 V. These cells consisted of four OEM and two PMA cells. The two PMA cells (cells 5 and 6) both exceeded 10 V. Only one OEM cell in the intermixed battery exceeded 10 V (cell 9), while all three of the other OEM cells exceeded 2.5 V (cells 4, 14, and 17). Neither battery exhibited any evidence of flames or explosions during this test; however, smoke emanated from both batteries as the electrolyte within the cells evaporated due to the high temperatures. The observed smoke was the same type and intensity for both batteries. Following dismantling and inspection of the batteries, no evidence of any physical damage was found. The test results showed no indication of any safety of flight issues arising from the intermixing of OEM and PMA battery cells within a Ni-Cd aircraft battery.

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