LEAD IS DEAD:

COLD CHARGING LFP VS. LEAD ACID

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ABSTRACT

Lithium iron phosphate (LFP) batteries, and Li-ion batteries in general, should not be charged at high rates in cold temperatures, to avoid Lithium metal plating on the anode. Most commercial LFP battery packs feature protection circuitry that prevents low-temperature charging from occurring. However, despite the need for such protections, the assumption that LFP batteries do not perform as well as lead acid batteries in such environments is erroneous. We demonstrate in this paper that cold temperature amplifies the Peukert Effect in lead acid batteries significantly more so than in LFP batteries. The performance of lead acid and LFP batteries under various load and temperature conditions were determined. Two new Group 31 12V 105Ah AGM batteries connected in parallel and two new Battle Born 12V 100Ah LFP batteries connected in parallel were compared. Both banks were discharged at a constant rate of 30A, 50A, and 80A at each of the following temperature ranges: 67-72° F (room temperature), 33-37°F, 26-30°F, and 13-18°F. The results show that colder temperatures limit the deliverable energy from the battery with an increasing discharge rate more significantly for lead acid batteries than for LFP batteries.

BACKGROUND

For a lead acid battery, the ampere-hour (Ah) rating is often accompanied by the number of hours for which a specific discharge current can be drawn. This is known as the manufacturer's supplied capacity, and it is typically expressed for very low currents - such as 7A at a 20-hour discharge rate. Unfortunately, these values do not extrapolate well for higher loads. In fact, a battery will deliver much less energy at higher loads. This phenomenon is known as the Peukert Effect.

In 1897, Wilhelm Peukert determined that a single equation could be used to approximate the change in the capacity of a lead acid battery, Cp, in terms of its discharge current, I [1]:

$$Cp=I^k t \quad (1)$$

In Equation (1), I is expressed in Ah and t is the time in hours. The constant, k, is known as Peukert's constant and accounts for internal losses between the active sites and electrolyte within the battery cells [2]. Peukert's equation accounts for losses associated with discharging a battery at increasingly higher rates. It was determined that, as the rate of discharge increases, the deliverable energy of the battery decreases. Doerffel and Sharkh [1] demonstrate this phenomenon in Fig. 1.

BACKGROUND

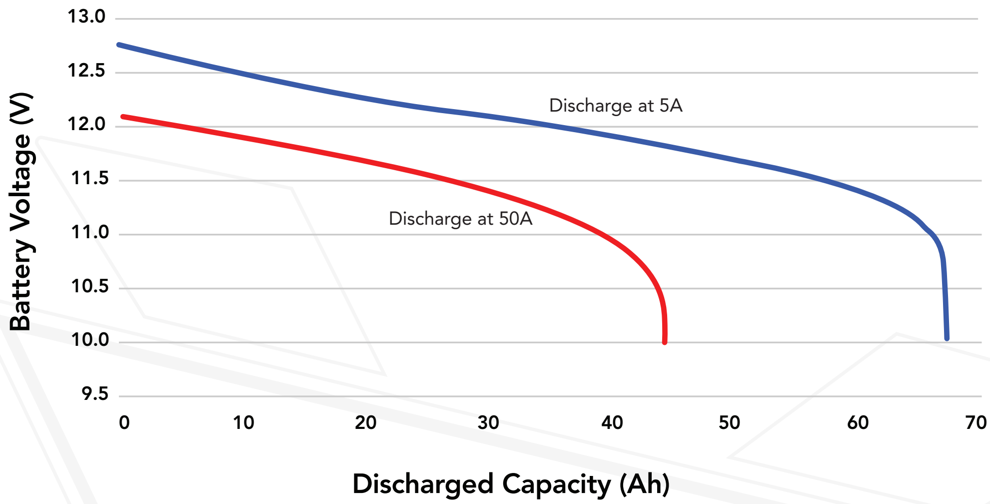

Fig. 1. Discharge data for 65Ah sealed lead acid battery discharge tests at 50A and 5A (data taken from Ref. [1]).

Peukert's law is only accurate if the battery is discharged at a constant rate and constant temperature. In most real-world cases, these conditions are unlikely. Peukert's equation has been modified to account for variable current and temperature conditions. Hausmann and Depcik [2] combined these effects into a single equation:

$$\Delta C_r = y\left(\frac{I_t}{I_{ref}}\right)^{\alpha}\left(\frac{T_{ref}}{T}\right)^{\beta}$$

Eq. 2 expresses ΔC_r, the change in maximum available capacity, in terms of current and temperature. In this equation, y relates the capacity removed to the dimensionless discharge and temperature components. I_t is the dynamic current, I_{ref} is the reference current which is typically the manufacturer's supplied capacity (such as the 20-hour discharge rate), and α is a constant that is analogous to Peukert's constant k. The term $\left(\frac{T_{ref}}{T}\right)^{\beta}$ accounts for the temperature dependence in Peukert's constant, where β is used to relate the temperature relationship of the battery chemistry and physical form of the cells.

Lithium iron phosphate batteries are characterized by a high electrochemical performance and low internal resistance [3]. The total internal resistance of the battery is comprised of multiple sources of resistance found within the electrolyte, electrodes, and interfaces. These resistances result in energy losses and can in turn affect the deliverable or receivable energy of the battery. As compared to lead acid batteries, LFP batteries are less affected by the Peukert effect due to their small internal resistance. To some extent, all battery chemistries are subject to a variance in their available capacity with a change in temperature. The available capacity of any battery will generally decrease as the temperature decreases, because chemical reaction rates are reduced. Vayrynen et al. [4] observed this effect in LFP batteries, as shown in Fig. 2.

BACKGROUND

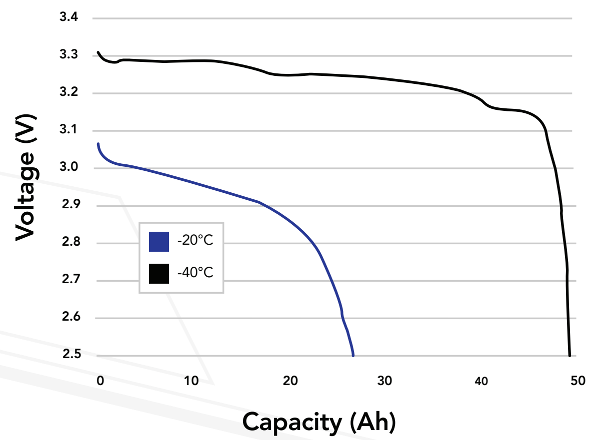

Fig. 2. Voltage vs capacity for LFP cells at various temperatures (data taken from Ref [4]).

EXPERIMENT

Two separate battery banks were tested. One bank was comprised of two Group 31 12V 105Ah AGM batteries connected in parallel to create a nominally 12V 210Ah bank. The other bank was comprised of two 12V 100Ah Battle Born 12V 100Ah LFP batteries connected in parallel to create a nominally 12V 200Ah bank. Each battery bank was connected to a Victron Energy Multiplus Compact 12V 2000kVA 80A inverter/charger programmed with the specified charging parameters from the manufacturers. The bulk and absorption voltages of the AGM batteries were set to 14.6V and the float voltage was set to 13.6V. The bulk and absorption voltages for the LFP batteries were set to the recommended 14.4V and the float voltage was set to 13.6V.

During each test both sets of voltage and current were continuously recorded by a data logger at a rate of 1 Hz. Voltages and currents were monitored using a National Instruments NI USB-6210 data acquisition system (DAQ). Voltage dividers with low variant resistors were used to ensure that the voltages conformed with the limits of the DAQ. An AcuAMP DCT 200-10B-24S DC current transducer was used to convert the charge and discharge currents to voltages that could be monitored by the DAQ.

For each series of tests, the batteries were fully charged at room temperature and were then cooled to the target temperature range. Once the batteries reached this range, they were discharged and monitored. The chest freezer was outfitted with an Ink Bird ITC-1000F electrical relay temperature controller to bypass the chest freezer's own thermal control. The controller regulated the air compressor at programmed times to accurately hold the freezer within the desired temperature ranges. The temperature ranges were: 67-72° F (room temperature), 33-37°F, 26-30°F, and 13-18°F. Both battery banks were simultaneously placed inside the temperature-controlled chest freezer for a minimum 8-hour period.

EXPERIMENT

Once a steady temperature was reached, the batteries were discharged at one of the target discharge rates through 300W .73Ω and 100W 2.9Ω divert load resistors. The target discharge rates for each test were: 30A, 50A, and 80A. The LFP battery bank was discharged down to 11.8V and the AGM lead acid battery bank was discharged down to 12.2V, as recommended by the manufacturer for 50% depth of discharge (DoD) at room temperature. It is noted that the voltage cutoff was not adjusted to account for decreased voltage at reduced temperatures for either bank to simulate the fixed voltage cutoff that exists in most battery systems.

After the first round of discharge tests, the battery banks were fully charged within the designated temperature. The AGM battery bank was charged at a 30A rate following every discharge test as recommended by the manufacturer. The LFP battery bank was charged at the same rate it was discharged for each test. Once the battery banks were brought to a complete charge, they were left to sit at 100% charge for an 8-hour period in the freezer. The battery banks were then discharged again at the same rates of 30A, 50A, and 80A to verify the accuracy of the results. After this second discharge test, the battery banks were fully charged at room temperature before a new round of tests were conducted.

RESULTS AND DISCUSSION

The following results demonstrate how the AGM bank performed in comparison to the LFP batteries at the 30A, 50A, and 80A discharge rates within the following temperature ranges: 67-72°F, 33-37°F, 26-30°F, and 13-18°F. Advanced data logging and data acquisition equipment were used to ensure that the performance results of the two battery banks were accurate. A 12.2V cutoff was implemented for the AGM battery bank as recommended by the manufacturer for 50% depth of discharge.

67-72° Fahrenheit

The results of the discharge test for the 67-72°F temperature range are shown in Fig. 3. At a 30A discharge rate, the LFP battery bank was able to deliver 3.3 times the amount of energy that the AGM bank. For a 50A discharge, LFP outperformed AGM by delivering 3.9 times the amount of energy. For the 80A discharge rate, the LFP batteries delivered 17 times more than the AGM batteries.

RESULTS AND DISCUSSION

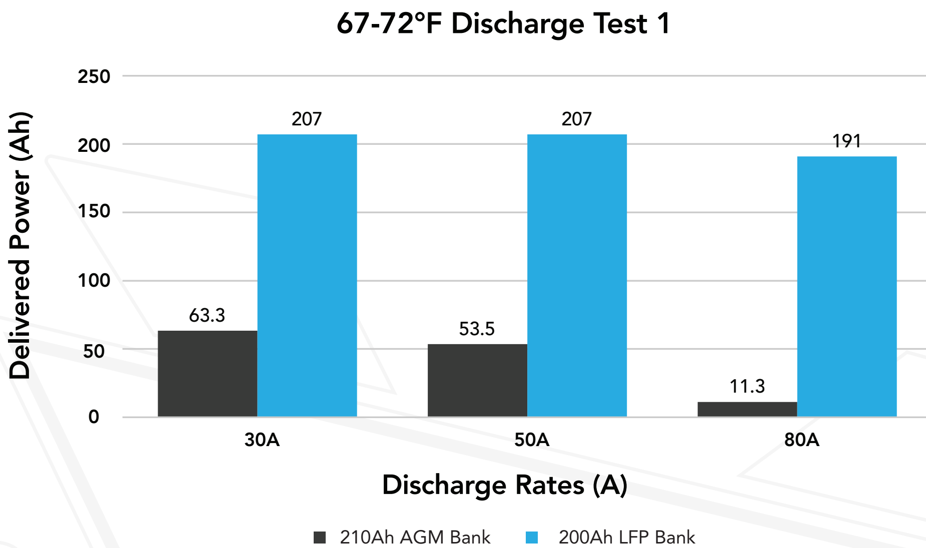

Fig. 3. Discharge Test 1 Results for 67-72° F temperature range. Shows delivered power for 30A, 50A, 80A discharge rates of AGM and LFP battery banks.

After the initial discharge tests for the 67-72° F range, the battery banks were fully charged within these temperature bounds. The AGM bank was charged at a maximum of 30A each time, whereas the LFP banks were charged at the same current at which they were discharged (30A, 50A, and 80A, respectively). Fig. 4 demonstrates the total charge in Ah accepted by the batteries. This charge data demonstrates that both the AGM and LFP, battery banks were able to recover nearly 100% of the energy they delivered in Discharge Test 1, if not more.

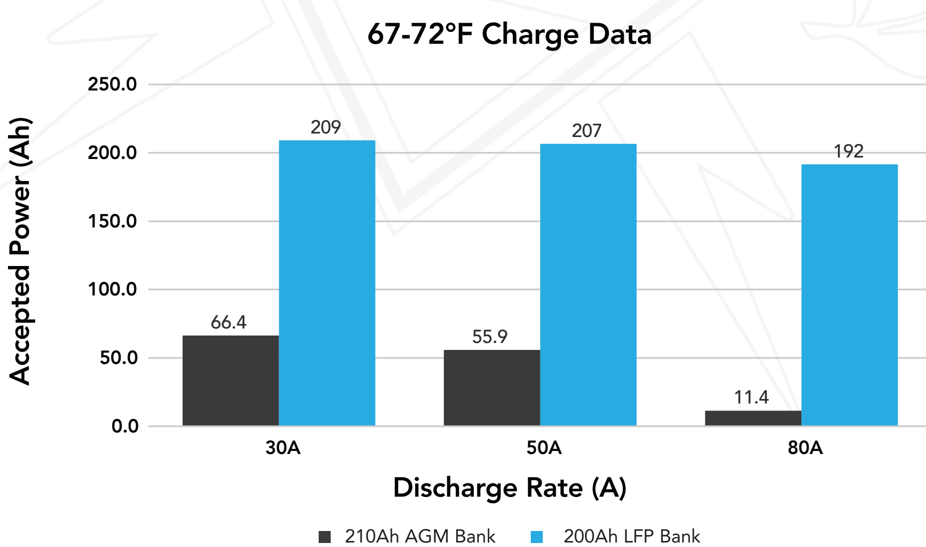

Fig. 4. Charge Data for 67-72° F temperature range. This data was collected after the first set of discharge tests performed on the AGM and LFP battery banks.

RESULTS AND DISCUSSION

Once the battery banks were fully charged, they were discharged in the 67-72°F temperature range again at the same rates as Test 1. The results of Test 2 are shown in Fig. 5. At a 30A discharge, LFP provided 3.3 times more energy than AGM. At 50A, LFP outperformed AGM by a factor of 4. At 80, the LFP output was 26.7 times that of the AGM bank.

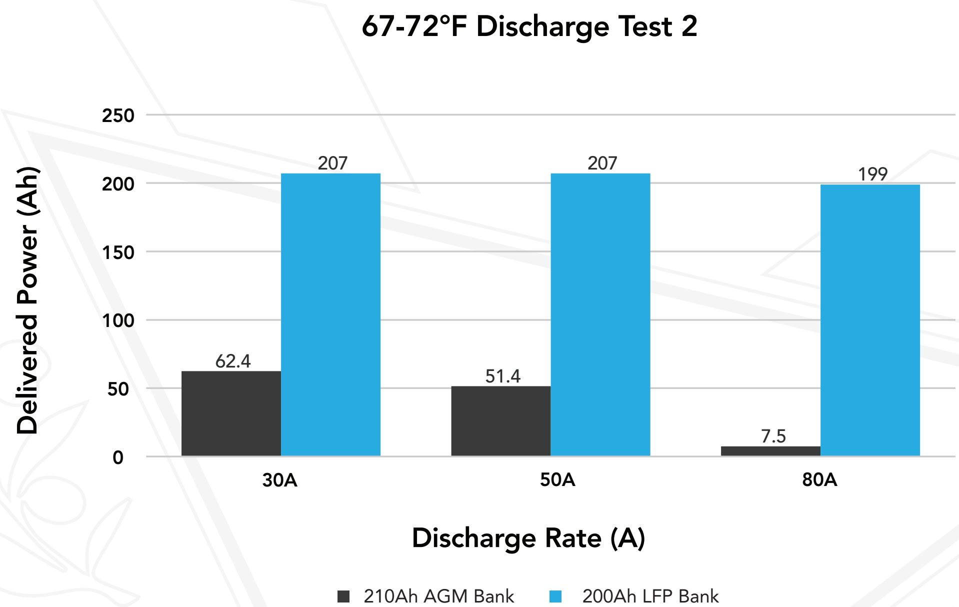

Fig. 5. Discharge Test 2 Results for 67-72°F temperature range. Shows delivered power for 30A, 50A, 80A discharge rates of AGM and LFP battery banks.

<u>33-37° Fahrenheit</u>

The next round of discharge tests was performed in the 33-37° F temperature range. The deliverable energy from the two battery banks is shown in Fig. 6. For the 30A discharge rate, the LFP battery bank was able to deliver 4.7 times more energy than the AGM battery bank. This number increased as the discharge rate increased. For the 50A test, LFP performed 5.5 times better; and for the 80A test, LFP provided 17 times more deliverable energy than the AGM battery bank.

RESULTS AND DISCUSSION

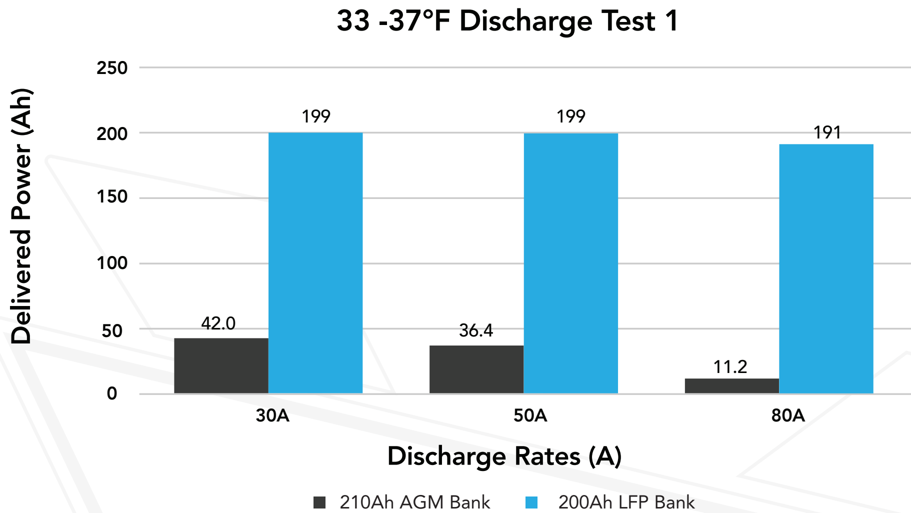

Fig. 6. Discharge Test 1 Results for 33-37°F temperature range. Shows delivered power for 30A, 50A, 80A discharge rates of AGM and LFP battery banks.

Following Discharge Test 1 for 33-37° F, the battery banks were once again fully charged- the AGM bank at 30A, and the LFP bank at 30A, 50A and 80A. The charge data are shown in Fig. 7. In this instance, both battery banks were able to recover approximately 100% or more of the energy they initially delivered in Discharge Test 1.

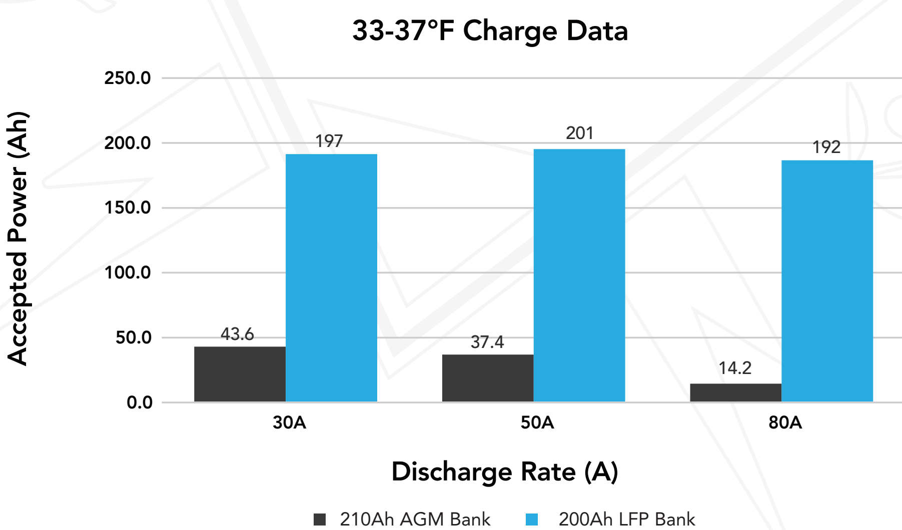

Fig. 7. Charge Data for 33-37°F temperature range. This data was collected after the first set of discharge tests performed on the AGM and LFP battery banks.

After the batteries were brought to 100% charge, they were discharged at the same rates within the 33-37° F range. The results, shown in Fig. 8, are comparable to the results of Discharge Test 1. The LFP bank still outperformed the AGM batteries in every test. LFP provided 4.8 times more energy at a 30A discharge rate, 5.5 times more energy at a 50A rate, and 17 times more energy at an 80A rate.

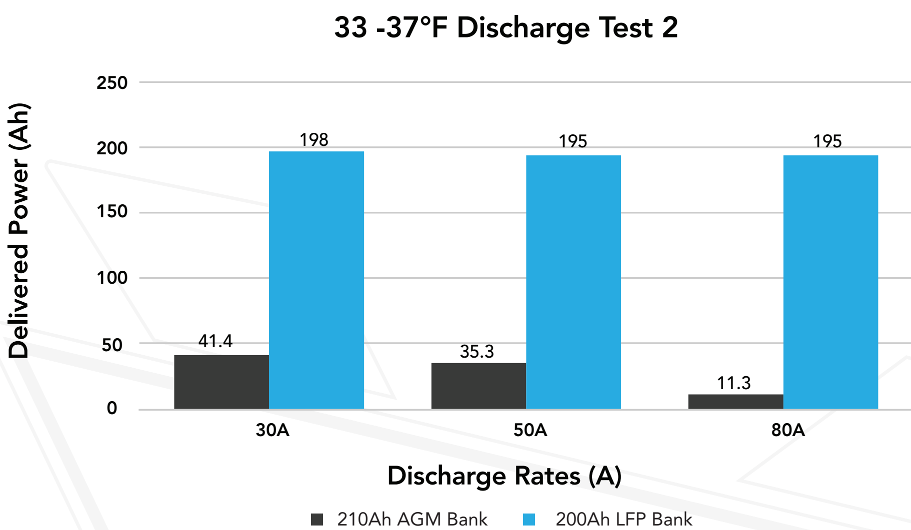

Fig. 8. Discharge Test 2 Results for 33-37°F temperature range. Shows delivered power for 30A, 50A, 80A discharge rates of AGM and LFP battery banks.

<u>26-30° Fahrenheit</u>

The 30A, 50A, and 80A discharge tests were performed within the 26-30°F temperature range. As shown in Fig. 9, LFP provided 4.3 times the amount of energy as AGM at 30A and 6.4 times the energy of AGM at 50A. During the 80A discharge test, the 210 Ah AGM battery bank was able to deliver less than 1Ah of energy before the low voltage cutoff was reached. By contrast, LFP was able to still deliver 175Ah.

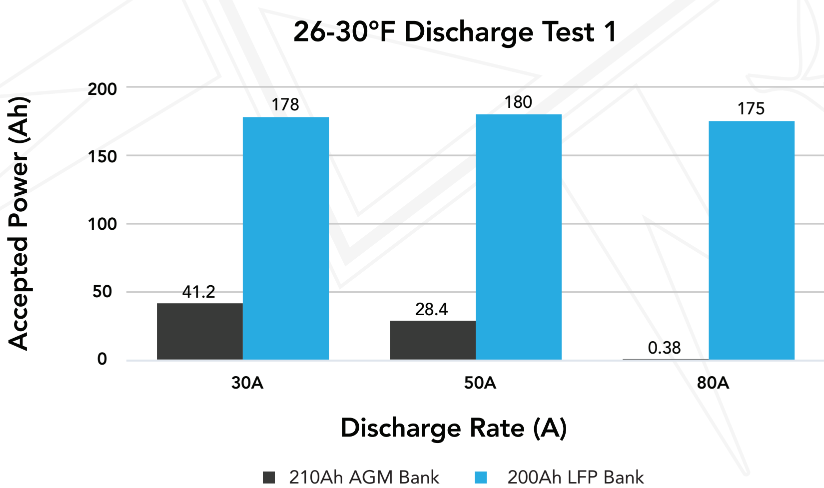

Fig. 9. Discharge Test 1 Results for 26-30°F temperature range. Shows delivered power for 30A, 50A, 80A discharge rates of AGM and LFP battery banks.

RESULTS AND DISCUSSION

The AGM and LFP battery banks were charged back up to 100% within the 26°F to 30°F parameters. The charge data found in Fig. 10 demonstrates that both battery banks were able to recover the majority of the energy delivered in Discharge Test 1.

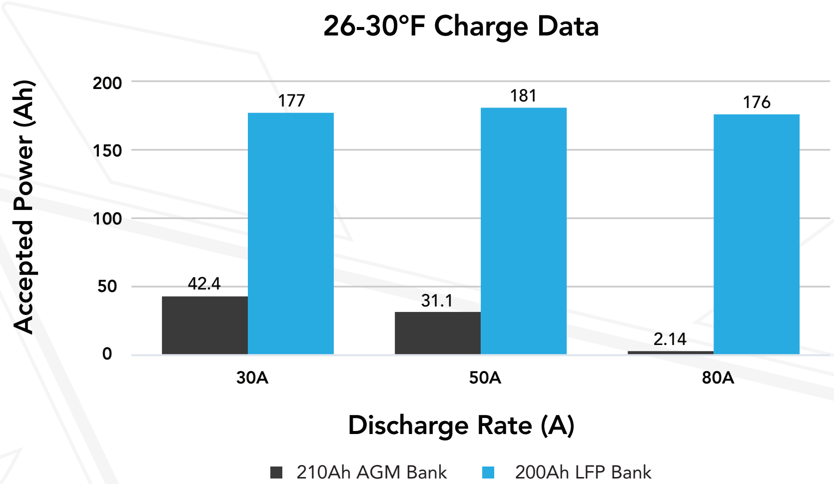

Fig.10. Charge Data for 26-30°F temperature range. This data was collected after the first set of discharge tests performed on the AGM and LFP battery banks.

A second discharge test was performed within this temperature range. The results shown in Fig.11 show that the LFP bank performed better for every discharge rate. For the 30A discharge rate, the LFP bank outperformed the AGM bank by providing 4.4 times more deliverable energy. At 50A the LFP provided 7.6 times more energy; and at 80A LFP was able to provide 138 times more energy than the AGM bank.

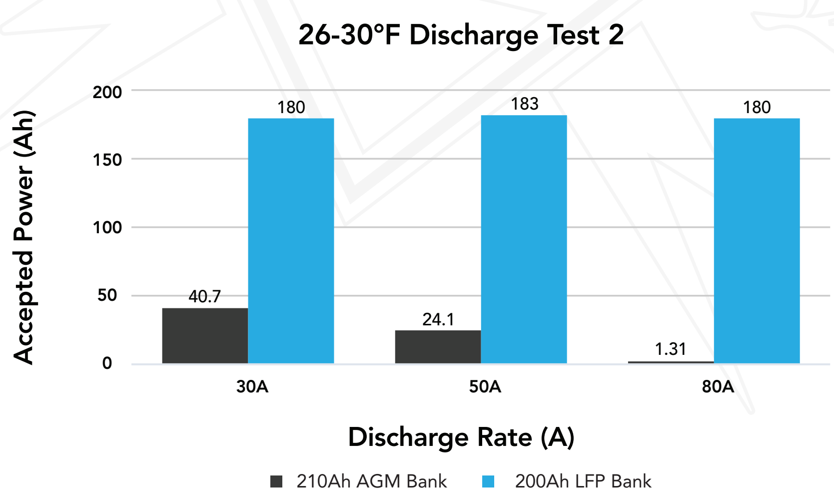

Fig.11. Discharge Test 2 Results for 26-30°F temperature range. Shows delivered power for 30A, 50A, 80A discharge rates of AGM and LFP battery banks.

RESULTS AND DISCUSSION

<u>13-18° Fahrenheit</u>

The final set of tests was performed within the 13-18°F temperature range. The results of the first set of tests are shown in Fig. 12. LFP provided 5.2 times more energy than the AGM at a 30A discharge rate and 8.5 times the energy at a 50A rate. Once again, at an 80A discharge rate, the AGM bank could not deliver an appreciable amount of energy before triggering the prescribed low-voltage disconnect.

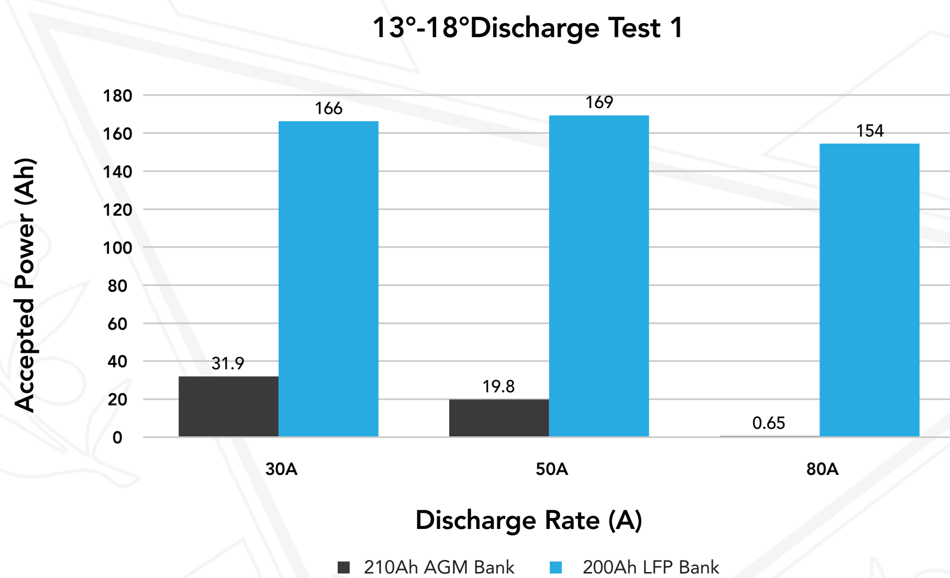

Fig.12. Discharge Test 1 Results for 13-18°F temperature range. Shows delivered power for 30A, 50A, 80A discharge rates of AGM and LFP battery banks.

At this temperature range, the LFP battery bank could not be recharged as it is below the allowable charge temperature of 25° F, as set by the BMS in the Battle Born system. Therefore, no further data was collected for the LFP bank, while the test continued for the AGM battery bank.

The AGM battery bank was brought back to 100% charge. The AGM batteries appear to recover more energy in this charge than they were able to deliver in Discharge Test 1 (See Fig. 13), though this is likely due to energy loss in the system due to high internal resistance.

RESULTS AND DISCUSSION

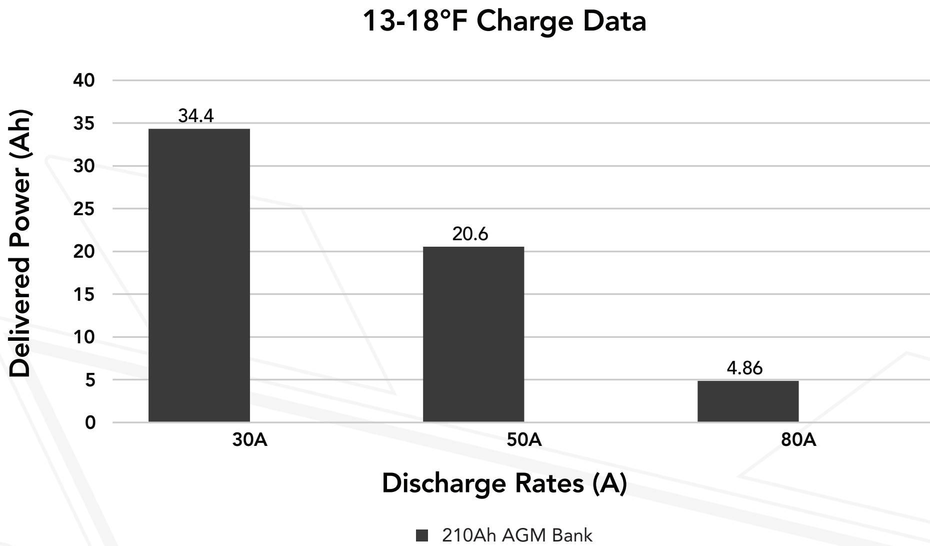

Fig. 13. Charge Data for 13-18°F temperature range. This data was collected after the first set of discharge tests performed on the AGM battery bank.

The final discharge test was performed on the AGM battery bank alone. The results of this test are displayed in Fig. 14, which shows similar results as for Discharge Test 1.

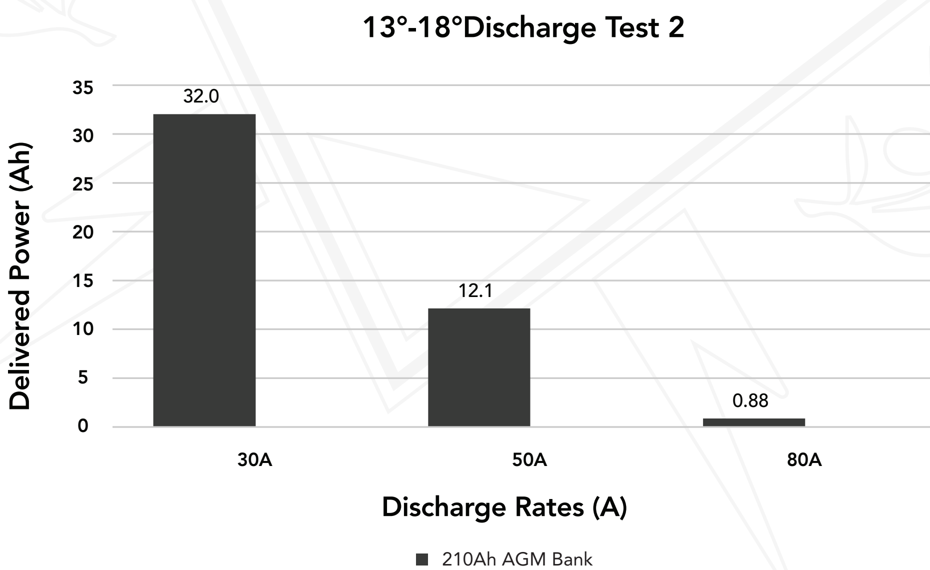

Fig. 14. Discharge Test 2 Results for 13-18°F temperature range. Shows delivered power for 30A, 50A, 80A discharge rates of AGM battery bank.

Both battery chemistries demonstrate reduced capacity as the temperature decreased. But this effect was more far more noticeable with the AGM batteries than the LFP batteries, especially when comparing the 67-72°F data to the 13-18°F data.

RESULTS AND DISCUSSION

After averaging the 30A data at 13-18°F, the AGM bank was found to provide only 51% of the energy it could provide at room temperature. By contrast, the LFP was still able to provide 80% of the deliverable energy at room temperature.

After averaging and comparing the 50A data, it was found that in the coldest conditions, 13-18°F, the AGM provided 31% of the energy it provided at room temperature, while the LFP bank was able to provide 82% of the energy it delivered at room temperature.

For 80A at 13-18°F, the AGM batteries only provided 8.2% of the power it provided at 67-72°F.The LFP battery bank was still able to provide 79% of the power it delivered at room temperature at the 80A rate.

Low-voltage Cutoff and Sulfation

Inherent to all lead acid batteries - including AGM, SLA, and flooded – is the formation of lead sulfate on the electrodes within the cells during discharge. If the lead battery is not immediately fully charged, the lead sulfate deposits can crystallize, permanently degrading the capacity of the battery. Sulfation becomes a significantly worse problem for lead acid batteries at lower voltages. Therefore, it is important to maintain the manufacturers' 50% cutoff voltage during all discharges (in our case, the specification was 12.2V). One should note that it is possible to lower this cutoff voltage and extract more energy out of the lead acid battery – even at cold temperatures and high currents. Cranking batteries, for example, are often classified in terms of their cold cranking amps (CCA), which is determined by the delivered current at 0°F when the voltage falls to 7.2V. However, for deep cycle applications, this comes at the expense of the battery life. Moreover, an inverter that converts the battery bank's DC power to the AC power required for house loads typically has its own low-voltage cutoff, which is set to the battery manufacturer's specifications. This is not a temperature dependent value. Therefore, for the typical house battery or deep cycle application, the ability to extract more current out of the lead bank under lower voltage conditions is neither recommended nor even feasible for the house electrical system.

CONCLUSION

The results of this study demonstrate that even though both lead acid and LFP batteries are affected by low temperature discharges, the LFP batteries can perform significantly better than the AGM batteries. Though the battery banks were comparable in ampere-hour size, the deliverable energy of the lead acid at the high discharge rates and lower temperatures rendered this battery bank nearly useless when a protective low-voltage threshold is implemented in the electrical. The LFP batteries outperformed the AGM batteries in every test performed.

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