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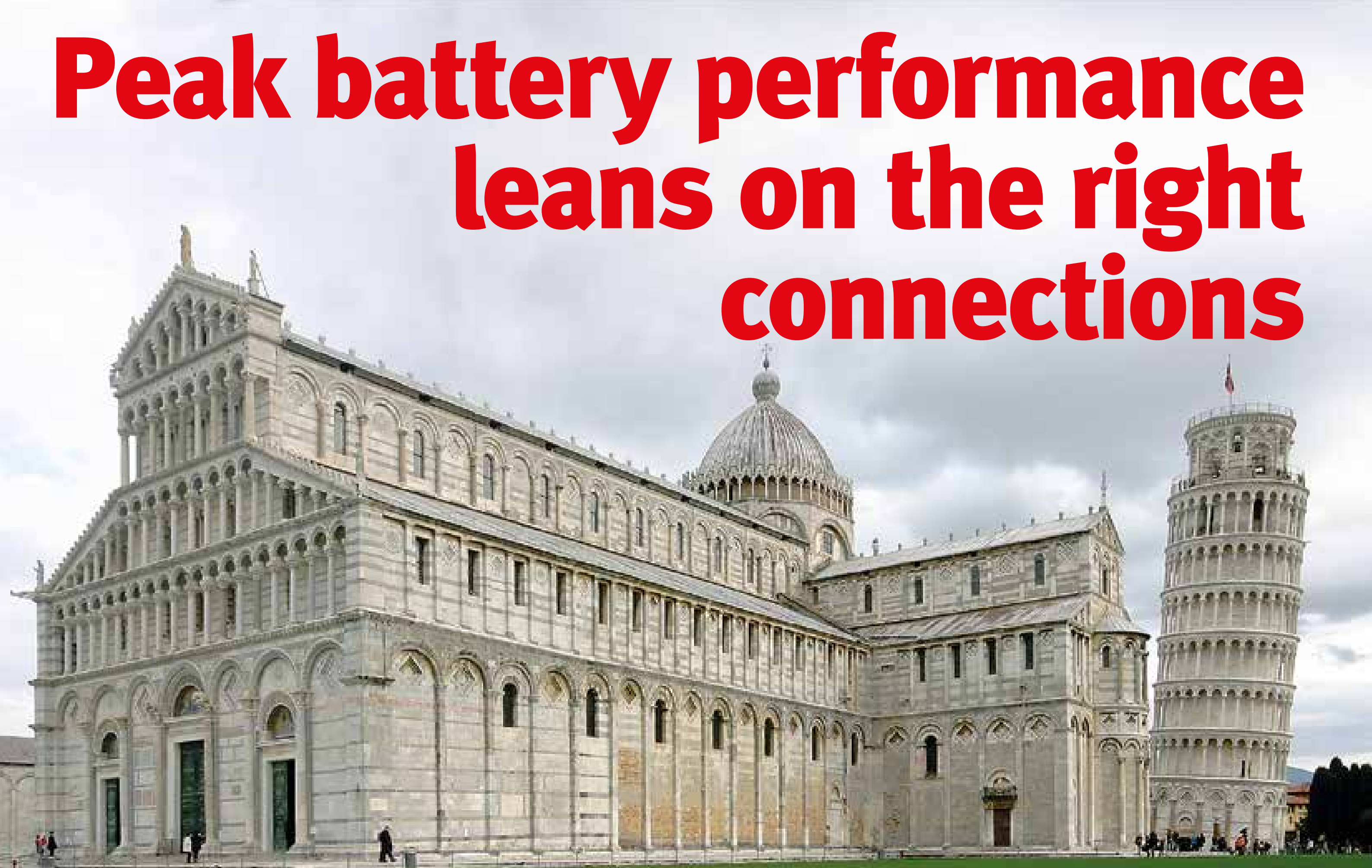
Peak battery performance leans on the right connections



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Peak battery performance needs the right connections

BESTmag technical editor Dr Mike McDonagh is back in the lab with UK Powertech's Mark Rigby and Digatron equipment— testing for formation inefficiency and energy losses from corroded connectors.

The latest in a series of tests conducted in the Manchester-based laboratory in the UK is aimed at showing how the energy losses in lead-acid battery formation processes can manifest themselves without necessarily registering as a higher energy usage on conventional formation equipment.

For instance, a high resistance connection should register as a higher voltage with the standard fixed current input programmes used in most formation programmes. However, if the resistance increase also raises temperature due to the I^2R effect, then the voltage will drop because the electrochemical resistance is reduced due the additional heat increasing the ionic mobility in the electrolyte. There is also the problem of having a voltage ceiling for lead-acid batteries due to either the electrochemical reactions that take place in the battery or, in some cases, the limit of the charging equipment. In order to show the effect of higher resistance, it was necessary to devise tests that can show the effect on the input current with fixed voltage with measurements made via formation rectifier equipment.

Mark Rigby, MD of UK Powertech, has for several years been aware of an increase in battery manufacturing companies' battery scrap and rework rates which coincides with faster formation schedules. The faster formation schedules have not increased in efficiency. This means that as a minimum, the same quantity of ampere hours (Ah) needs to be input into the battery in a shorter time period, in some cases reducing small SLI battery formation times from 24 hours to 8 hours. This represents a threefold increase in the current input to the battery. The expected outcome of putting in a higher current is that there would be more heat generated due to the battery and circuit resistance. This would mean that the battery temperatures should increase and potentially damage the battery's active materials. For this reason, modern, more efficient cooling methods have been devised, such as recirculating electrolyte, and better controlled water-cooling baths, which keep battery formation temperatures at acceptable levels.

One problem has arisen however: formation connector design and working practices in the formation departments have not changed. Because lower currents were used in the past, heat and energy losses, generated by high resistance connections, have not been noticed. Now, with currents becoming three times previous levels, those connection resistances are creating greater heat damage, terminal/connector arcing and more noticeable energy losses. Previous research carried out by UK Powertech and *BESTmag* has concluded that there is a significant cost to using old connectors that are either corroded or damaged. Reports published in *BESTmag* (Winter 2018 & Spring 2019) have predicted energy losses of up to 11% using old connectors found in everyday use in several companies' formation departments. An expected loss of 7% for most companies, based on the resistance values found with many connectors tested, would be a reasonable estimate.

The heat generated from the high resistance at the connector head/battery terminal interface is very effectively conducted into the battery through the internal lead take-offs, strap and grids of the battery. This can lead to significant temperature rises inside batteries during formation. The effect of this depends on the formation procedures which, if not temperature controlled, can damage active material as well as the external plastic materials. Although battery damage is a verifiable consequence of extreme resistance problems, there are other very damaging consequences from common resistance values measured during the research of Rigby and McDonagh. These are chiefly: high water loss during formation, leading to electrolyte levels falling below the top of the plates, increases in formation time due to batteries exceeding threshold temperatures, extra acid fumes from increased gassing at higher voltages/currents and additional cost of wasted energy.

Some processes are temperature controlled. This means that the formation current is reduced or switched off if the battery temperature exceeds a threshold value. In these cases, the heat generated from high resistance connections will almost invariably raise battery temperatures above the set values and could reduce current input significantly during the running of a programme. When this happens formation times can significantly increase when there are long interruptions. In cases studied by Rigby and McDonagh, this can amount to a 20% increase in a battery's formation time. Even a few hours per day per circuit, with 7-days-a-week working times, can lead to high percentage losses in total factory output.

Previous reports have concentrated on identifying the extent of the power consumed by the additional connector resistance and converting this to lost energy and ultimately the financial ramifications of this. As mentioned previously, there are other consequences that also add to the formation costs. These are energy consuming reactions that cannot be measured using simple current and voltage readings common to most formation programmes. In fact, there is a potential situation where a temperature increase that would cause a voltage drop would in fact register as less energy consumed (current x voltage x time), rather than more, despite there being a higher resistance. For this reason, it was necessary to devise tests that conclusively show by measuring current and voltage, that in a standard formation programme, either more energy is consumed or is used less efficiently with a higher resistance connector. In the latter case the energy input is fixed but less energy goes into forming the active materials than in secondary, parasitic reactions.

For this reason, a series of tests have been designed to show how much energy loss can occur due to high resistance effects from old, damaged or badly fitted connectors. For nearly a year, Rigby and McDonagh have been investigating and analysing the effects of the influence of formation connector condition on the lead-acid battery formation process and subsequent battery quality. The previous tests have given solid evidence that formation energy losses, due to high connector/battery terminal interface resistance, could easily be 7% of the total formation energy used by most Pb battery manufacturers. However, because of the reasons set out here relating to the ability of formation equipment to measure these losses, a new approach has been adopted. This will identify and verify these losses using an actual formation programme from a lead-acid battery manufacturer. It also identifies key measurement parameters that can be used by battery manufacturers to assess the extent of energy loss attributable to high resistance connections.

The first step was to look at actual formation programmes and how they are controlled. ***Fig 1*** is a real SLI formation schedule of a battery manufacturer based on temperature controlled current input. When the temperature reaches a predetermined value, the current is reduced to keep the temperature below this level. This gives a variable time for the duration of the formation cycle depending on how much heat is generated by the cable resistance (R_c) as well as the battery's internal resistance (R_i). The temperature of the battery is affected by two heat sources that are created by current and resistance— the I^2R effect. With normal SLI batteries that have a R_i of between 5 and 20 milli-ohms it is not difficult to effectively double or triple this resistance with corroded or damaged connectors.

Fig 2 shows the used connectors that were still in daily use when taken from a typical formation department. Four of these connectors were used to carry out the tests to compare energy consumed in the formation process when compared to new connectors.

The test is designed to show three basic aspects of the effect of higher resistance connections on the formation efficiency:

1. Higher energy for a fixed Ah input.
2. Lower efficiency of charge acceptance during formation.

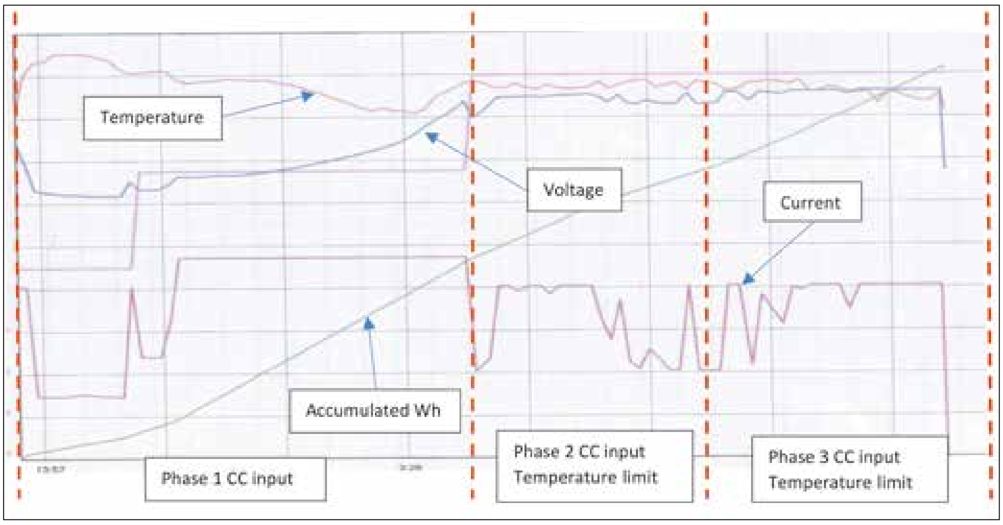
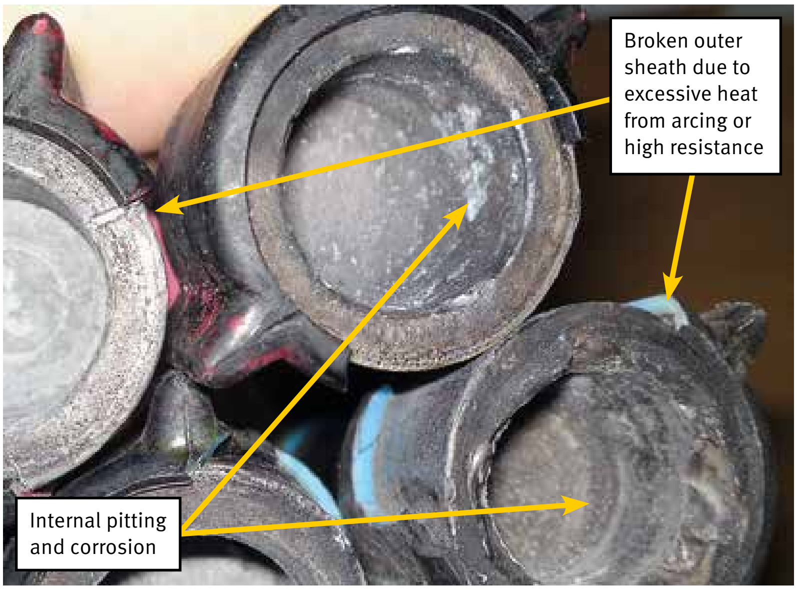


Fig 1: Real formation results for an SLI battery from a lead-acid battery manufacturer. Temperature controlled process. As a temperature limit is reached the current reduces until the temperature drops to the lower setting. In this case formation time is extended

3. Energy wastage in heat generation rather than higher voltage.

Because lead-acid batteries have a voltage ceiling during formation, a fixed current input will not necessarily result in a higher voltage during a formation programme. A higher resistance will increase energy use but it can manifest itself in ways other than a voltage rise. A battery is not an ohmic wire resistance and there are heat and parasitic reactions generated, which take energy away from the conversion of green active materials into their fully formed condition. These tests do not address the parasitic reactions of water breakdown and hydrogen and oxygen evolution at the electrodes. For these reasons purely electrical measurements of voltage and current can be misleading when

Fig 2: Typical connectors still in use and taken at random from a formation department



comparing efficiency and energy consumption. The two most common ways in which electric charge is put into a lead-acid battery are constant voltage charging and constant current charging.

In the first instance with constant voltage charging the effect of a higher resistance will be to reduce the current according to ohms law.

V = I x R or when measuring current, I = V/R

The current will decrease if a constant voltage is attained but the resistance increases. If a constant current is used then it would be expected that a voltage increase would occur if the resistance increases. For reasons already discussed, it was decided to use the constant voltage situation and measure the effect of increased connection resistance on the current drawn. This method is justified in looking at the results of a real-life formation schedule given in ***Fig 1***. This is divided into three distinct phases. In the initial stage, there is a high internal resistance which gradually declines as the surfaces of the active material particles have substantially converted from non-conducting sulfate to the positive and negative electrodes. The second phase is the slower conversion of the harder-to-reach active material in the centre of the particles. During the second phase there is a resistance rise due to the difficulty of the acid penetrating the particles, and the build up of an electrochemical layer of sulphate ions at the particles' surfaces which sets up a concentration gradient. This high sulfate ion concentration opposes the diffusion of sulfate ions going out of the AM particles and into the bulk electrolyte solution. The third phase is the least efficient as the last vestiges of lead sulfate deep within the active material are forced out into the electrolyte. It is this phase in which most of the energy input goes into water electrolysis, gassing and heat production. A future test regime will measure heat generated and water lost during a simulated formation programme using green unformed batteries.

From the graph it is clear that the voltage rises during the progress of the formation programme but then reaches a peak value (for the reasons already outlined) about one third of the way through the schedule. With the simulation test, the voltage is held constant. In this condition the reduction of the current drawn is a measure of the connection resistance between the connector and the battery terminals. It also translates into a power (amps x volts) loss and ultimately an energy loss over the time of the formation programme. This measurable energy loss is the same as that lost through heat and other parasitic electrochemical reactions such as gassing, mentioned above, which would not be measurable by standard formation equipment. For this reason, the test programme that is based on the real formation programme in ***Fig 1***, uses a constant voltage limit and measures the current reduction and therefore energy input reduction when using high resistance connections compared with low resistance connections. The difference between this value and that gained from using low resistance connections is a measure of the excess energy consumed when using bad connections. It can also be considered as energy inefficiency in the process. In a constant voltage charging condition the amount of current absorbed by the battery is a measure of its efficiency. The higher the current, the lower the resistance and more Ah that will be absorbed in forming the active materials. In a constant current situation, a higher resistance will mean that a higher voltage is required to push the current into the battery's active material to convert lead sulfate to lead and lead dioxide. This is the situation most commonly used for lead-acid battery formation programmes.

The test programme is a simulation of the three phases shown in the formation process of ***Fig 2***. These are:

Phase 1 – fixed current with a voltage limit of 16.5 V.

This is meant to simulate the first part of a typical formation programme. In this phase, because the current has a maximum value set by the equipment capability, it takes time for the battery to reach the set voltage value. it would be expected that with a fixed current the voltage would be higher with a higher resistance. In the tests conducted, this phase does in fact does show a resistance-dependant voltage variation up to the voltage limit, with the higher resistance circuits reaching the set voltage more quickly than the lower resistance circuits. This would mean that the battery with high resistance connections would continue the formation processes at higher voltages and from an earlier point in the programme. It is the higher voltages that trigger the energy wasting, unwanted reactions. This means that higher resistances would be more wasteful in energy, water loss and heat than the lower resistance situation.

Phases 2 and 3 – fixed voltage with progressively lower current limits

These phases show how efficiently the current is accepted by the battery charging reactions. For the reasons already given, the higher the resistance of the connections, the lower the current drawn by the battery. Because the voltage is limited the current drawn by the batteries will be affected by the circuit resistance, which includes the battery/terminal connection. The higher the resistance the lower the current drawn and the lower the rate of conversion of lead sulfate in the plates to lead and lead dioxide. As previously described, the limited voltage will not produce large quantities of by products such as hydrogen and oxygen gases and heat. With that restriction, the current drawn will be creating the formed active material but more slowly, with a high resistance. The higher watts, produced by the lower resistance in this case, will be a measure of the battery efficiency and directly but inversely related to the energy losses obtained from the higher resistance connections. This is the reverse of the constant current scenario of phase 1, which may seem counter intuitive but makes perfect sense. The reason for setting these test conditions is to remove the difficult-to-measure side reactions of gassing and heat and to directly measure the energy efficiency of the formation process with different connection resistances typically found in lead-acid formation departments.

For this report, fully-formed batteries were subjected to a shortened version of a formation programme ***(Table 1)***. In this version, the batteries were discharged to the same voltage, then old and new connectors were alternately fitted to the same batteries for several formation cycles. The routine was to discharge the 12V SLI batteries to 10.8V using clamped low-resistance connectors. The connectors were then changed to old connectors and put through the formation programme. The voltage, current and Ah input to the battery per programme step were recorded using the Digatron Battery Testing module. The batteries were then equalise charged and adjusted to bring them to the same condition, and discharged once more to 10.8V. The tests were then started again using new connectors. This procedure was repeated several times and the connectors alternated accordingly. This report gives the first result of these formation simulations using old connectors provided by several companies, and which were still in daily use before the tests. These were compared with the results using new connectors with the same formation schedule.

Two batteries were tested, each with new connectors, and then with used connectors

Table 1: Simulated Formation Programme (Digatron test equipment) based on real results from a lead-acid battery formation department

Step	Label	Operator	Nominal Value	Limit	Action	Registration
1		SET				STANDARD 1 min
2		TASK	0 Safe Task			
3		PAU		5 sec		
4		CHA	1A	30 sec		
5		PAU		5 sec		
6		CHA	30A 16.5V	2 hour		
7		PAU		5 sec		
8		CHA	20A 16.5V	1 hour		
9		PAU		5 sec		
10		CHA	8A 16.5V	1 hour		
11		PAU		5 sec		
12		STO				

using the Digatron test unit. The results for these tests for are given in ***Figs 3 & 4***. These show the current, volts and Ah for each of the three formation phases in the test programmes and the accumulated Wh in a single graph for both new and used connectors respectively. It is immediately apparent that the used connector has given some problems which manifested themselves as a variable connection resistance. This was probably due to the heat generated and the breakdown of some of the insulating corrosion layers during the formation period. What is also evident is that the first part of the programme, phase one, has a very similar structure to that of the actual formation results in ***Fig 1***. In this, the voltage rises for several hours at constant current before reaching a maximum value of about 16.5V per battery.

Although temperature was not recorded automatically during these tests, it was manually noted periodically and the maximum value for each circuit is included in ***Table 2***. This table compares the differences recorded between new and used connectors for the two batteries during the simulated formation cycles. In phase one, the battery voltage gradually rises to the set limit of 16.5V as a constant current is applied. During this period the new connectors have a lower voltage, giving an average of 7.35% lower energy usage for the same Ah input using a constant current. In the second two phases the batteries stay at the constant voltage limit and the current reduces as the internal resistance increases. The used connectors reduce the batteries’ Ah intake by up to 22% when compared to the new connectors. The heat generated by the battery and connector terminals give roughly similar results with around 19°C for the battery and 10°C for the connector/terminal interface for both used and new connectors. A higher temperature rise for the higher resistance connections would be expected but is most likely mitigated by the conduction of the take-off cables and having only a single battery connected to the cable heat sink.

Fig 3: Simulated formation programme with voltage limit of 16.5V – old connectors. Graphic results from Digatron test equipment

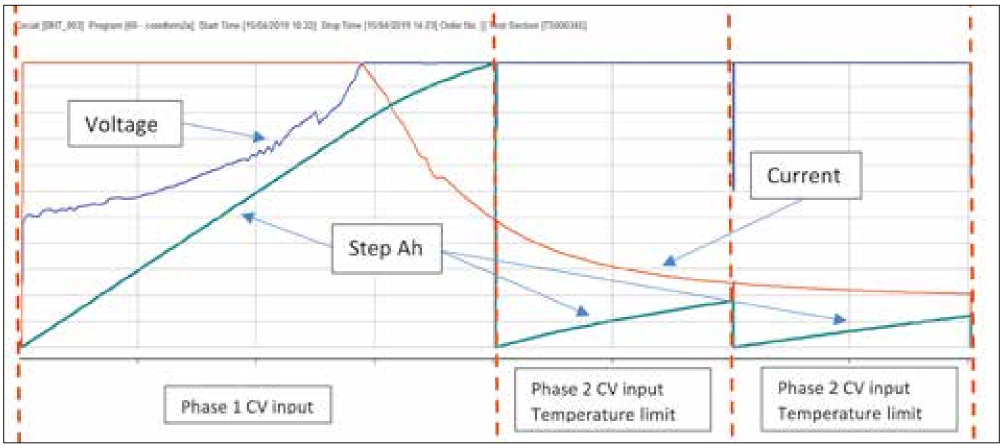
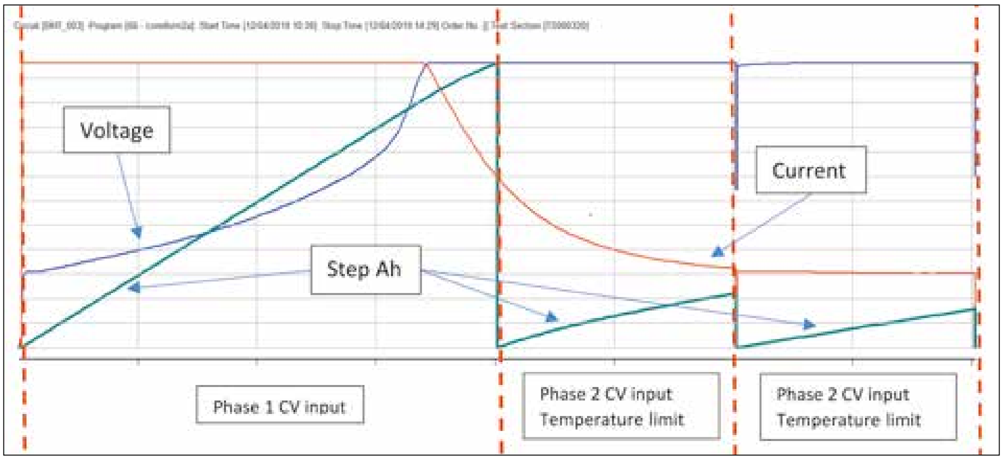


Fig 4: Simulated formation programme with voltage limit of 16.5V – new connectors. Graphic results from Digatron test equipment



The connector/battery terminal interface resistances are given in ***Table 2***, circuit 3 showing the highest difference between new and used connectors. This is reflected in the results which demonstrate quite clearly that using the older connectors make the formation process less efficient than when using newer connectors. The higher resistance of the terminal interface connector is responsible for the higher voltage response in phase one of the formation test schedule. This continues up to the voltage limit when the current starts to reduce. The faster the

Connector	Circuit	Connection Resistance (m-ohm)	Phase 1 Wh Input	Phase 2 Ah input	Phase 3 Ah input	Temp rise ^{0}C	Total Ah input
Used 1	2	390	610	8.07	5.27	19.2	66.91
Used 2	3	300	643	8.95	6.05	18.4	69.58
New 1	2	<1	579	8.55	6.01	19.7	70.08
New 2	3	<1	586	11.11	7.89	19.8	77.07

Table 2: Results from formation simulation tests for new and used connectors carried out on Digatron test unit

rise the higher the resistance value. The voltage rise for used connectors reaches the limit in 1h 24m for circuit 3, and with circuit 2, the used connector takes 1h 28m to reach the limit. This compares with 1h 32m and 1h 33m for the new connectors respectively. The difference in the watt hours absorbed in phase one for new and used connectors for each battery is given in Table 2. The batteries tested on circuit 3 have the highest difference with an increase of 9.5% in energy used for used vs. new, compared with a difference of 5.2% for circuit 2 ***(Table 3)***.

The second and third phases, which show the value of the current drawn at a fixed voltage, have a significantly lower current acceptance for the used connectors when compared with the new. The values for current draw are related directly to the circuit resistance. In each circuit this is the sum of the cable, battery and connection resistance. In order to complete the formation schedule, the process has to achieve the full Ah input for that battery model. Some companies, particularly those that interrupt a formation programme if the temperature exceeds a set limit, use an Ah counter to ensure that the full coulombic input is maintained. In these cases, when the programme stops running, the duration would be extended to allow the completion of a full programme.

For circuit 3 the time difference could result in a 4h increase on a 24hr process (based on 60% of the formation time) for the total Ah to reach the required value. In the case of constant current formation using enhanced water cooling, this level of inefficiency would result in a substantial battery temperature rise and water loss through gassing. Alternatively, if the temperature is allowed to rise unchecked, it causes battery damage and performance deterioration.

In summary, this interim formation report, comparing used and new connectors, concludes:

- The internal surface of used lead alloy cable connectors deteriorates with time in service
- This deterioration is the result of corrosion caused by an acid or humid environment where high temperatures and high currents are generated by the formation process
- This deterioration creates a high resistance interface (HRI) between the battery terminal and the connector in the formation circuit
- The HRI is responsible for higher on-charge voltage during the initial phase of the formation process which increases the energy consumption for any programme by 7% on average
- When the peak voltage is reached the high resistance

Table 3: Formation energy losses from used connectors compared with new connectors

Circuit	% Difference Phase 1 Wh	% Difference Phase 2 Ah	% Difference Phase 3 Ah	Total Ah Difference	%Total Ah Difference
2	5.2	5.95	12	3.17	4.73
3	9.5	24	22	7.49	10.57

creates inefficiency and reduces the charge acceptance value of the battery by up to 22%. This same percentage will apply to all formation schedules with subsequent implications for extending formation times

- This inefficiency creates heat, extra gassing and fumes, extends the formation time and wastes energy in ensuring the right Ah input for successful formation

The point of these tests was to isolate the energy losses due to high resistance connections in a measurable form. By restricting the voltage in order to remove those reactions which create heat and gas production and concentrate on the energy going into AM formation, it was possible to accurately identify the electrical energy inefficiency attributable to the resistance created by the connector and terminal interfaces in a formation circuit. We now know that, in one case, 22% of the energy consumed in the latter stages of a typical formation programme can be wasted.

Because of the high battery voltages typical of the majority of companies' formation programmes the wasted energy can manifest itself as heat and water loss. Because a lead-acid battery has a voltage ceiling, increasing currents would not raise the voltage. They would increase the parasitic reaction rates increasing water loss and heat generation. For these reasons, and the fact that higher temperatures in the battery caused by the connections' resistance will reduce the internal battery resistance by raising the ionic conduction of the electrolyte, the energy losses would not register as electrical energy losses.

These tests have shown that there is considerable scope to improve the efficiency of lead-acid battery formation programmes by reducing the resistance of the connector/battery terminal interface. This efficiency improvement can manifest itself in different ways:

- By reducing heat generation and therefore reducing formation times where programmes have a temperature cut-off limit

- By having reduced water loss of batteries that require topping up during the programme. Water loss can be due to either increased electrolysis and gas evolution or even higher water evaporation from higher battery temperatures.

- Lower on-charge voltages where there is no equipment voltage limitation and a fast formation programme is not being used

Apart from the monetary savings in energy, the higher efficiencies should mean higher throughputs for those companies with temperature-limited variable processes. It could be as high as an additional 5-10% productivity for some companies. It could also mean lower labour and demineralised water costs where battery topping up is less frequent during the longer processes.

There is also the case to be made for better battery quality where lower gassing can prevent electrolyte levels from dropping below the battery plates or less heat generation means less chance of battery lid and terminal damage. The benefits of better connections are clear but measuring the benefits, particularly energy consumption, can be challenging for all the reasons given.

At this stage in the testing programme, UK Powertech, *BESTmag* and Digatron have clearly shown the extent and cost of having high resistance battery terminal/connector interfaces. The causes of the high resistance have been identified and the effect on battery production and quality have also been highlighted. The extent of the energy inefficiency and the mechanisms by which it can manifest itself have been identified and the overall effect has been quantified.

The subject of the next testing phase is to identify, propose and evaluate the solutions to these problems. If you are serious about your lead-acid battery quality, your throughput and energy efficiency, you will want to see the results of the next phase of this series of tests. Only in *BESTmag*!

Any companies wanting to know more or find out how *BESTmag* testing can benefit them please contact Dr Mike McDonagh– mike@energystoragepublishing.com