Oh, Shoot: Battery knowledge gaps that plague the user community now that the old guys have retired

Dan McMenamin
President
Dan McMenamin and Associates, Inc.
West Deptford, New Jersey 08051

Abstract
Despite incremental advancements in equipment design, network failures and equipment damage often are the product of ignorance or neglect on the part of battery users.

It's been said that "Success covers a multitude of blunders. At the same time, trusting network reliability, return on investment and perhaps one's career path to the vicissitudes of luck is hardly prudent.

This paper will address many causes and cases where a lack of knowledge on the part of the telecommunications and electric utility user communities have led to poor battery performance, shortened service life and network or partial grid outages.

Introduction
Secondary batteries have been around for a century and a half now. French physicist Gaston Planté invented the first rechargeable battery in 1859 and presented his creation to the French Academy of Sciences soon after in 1860.

The Planté design was based upon two electrodes, an anode (negative electrode) of lead and a cathode (positive electrode) of lead dioxide, separated by a rubber strip. Electrons lost from the anode through oxidation were conducted to the cathode by an aqueous electrolyte of water and sulfuric acid. Once charged by external means, this storage battery could power some external device.

Today's lead acid cells are strikingly similar to Planté's original design. While modern batteries are vastly superior to those of the 1800's, many limitations and similarities remain.

- Battery cells or strings of cells need to be carefully selected to bear a given load for a given reserve time.
- Battery systems require specific environmental conditions, temperature, seismic, etc.
- Battery systems require maintenance (no matter what the cut sheets say).
- Battery systems have a finite service life that can vary wildly by environmental conditions.
- Battery systems are containers of stored energy that can be decanted slowly, under controlled conditions or disastrously under uncontrolled conditions.

Spanning the past twenty years or so, technicians have been forced into job roles where they function as generalists and often are woefully trained or equipped to maintain batteries properly. As the workforce becomes increasingly downsized, systems requiring periodic maintenance become a very low priority to corporate accountants and terrified mid-level managers caught in the funding vise. This situation is true in terms of staffing, training, spare parts inventories and man-hours allocated to routine maintenance.

Over time, power systems become taken for granted until bad things happen. At the operations and maintenance level, some bad things evolve over time and *some* bad things can get ugly very quickly.

Coup de Fouet Foibles

The term 'coup de fouet' describes a phenomenon of lead acid batteries characterized by a dip in available battery output voltage during the first seconds or minutes of discharge. The depth and duration of this voltage dip varies with the state of health of a given battery and the ampere load imposed upon it at the time. With a significant load on a relatively new string, the dip and duration will likely be small. On a battery with a poorer state of health, the dip likely would be more pronounced and the duration longer.

Some equipment manufacturers exploit the coup de fouet phenomenon as an indicator of a battery's available reserve time by deliberately imposing a known load on the battery. The depth and duration of the voltage dip is compared with the battery parameters for an estimated health check.

When the load is too great for a given battery, the coup de fouet can - and has - resulted in bus voltages that are lower than the threshold shutdown voltage for electrical or electronic systems that are powered by the battery.

Accordingly, battery systems need to be appropriately sized for the maximum load they will carry for a designated reserve interval and anticipated service life.

What kinds of coup de fouet miscalculations, glitches and gotchas have caused failures in the telecommunications and electric utility industries?

One frequent bad actor occurs when a battery string will be taken off the bus for maintenance and a temporary string placed as a precaution. If the temporary string is lacking in capacity either through ampere hour sizing or capacity loss through aging, it may be insufficient to carry the load if needed. Or, if the cabling to a temporary battery is inadequate, excessive voltage drop can cause service failures especially during coup de fouet.

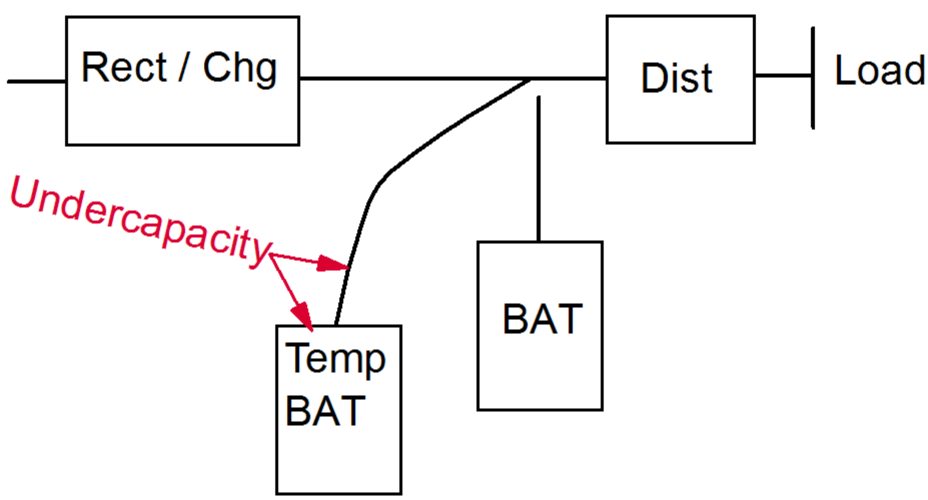

Figure 1. Under-capacity temporary battery or cabling often cause failures.

Sometimes, poor electrical connections can initially appear as a deep coup de fouet to system monitoring instrumentation. Generally, if the bus voltage doesn't recover to the battery nominal voltage within several minutes, it could be that poor connections are the cause and herald a failure. Figure 2 shows a battery post meltdown caused by poor intercell connections where resistance heating melted the lead posts.

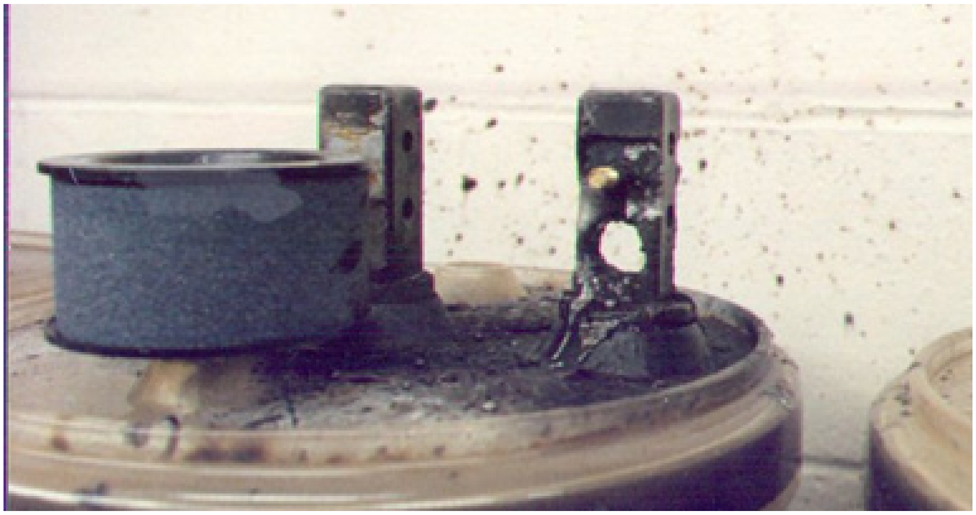

Figure 2. This photo shows a post meltdown due to a resistive intercell connection and a battery discharge.

8 ÷ 2 = 4? Uh, not necessarily

A common error in battery sizing calculations is the mistaken notion that battery outputs are linear. *They're not.* Doubling the load on a given battery does not mean that the battery will deliver half the reserve time. Figure 3 is a discharge table for a widely-used Valve Regulated Lead Acid battery. As is circled on the table, when in a good state of health, this cell is rated to deliver 190 amperes for 8 hours down to a per-cell voltage of 1.75.

If one were to double that load to 380, it would be greater than the 326 amperes that the cells can deliver for 4 hours. If systems with multiple battery strings will have strings added or removed, it is necessary to perform battery calculations by dividing the load by the actual number of strings that the load will 'see' and then consulting battery tables to determine what the load per string can yield. As a convenience, many battery manufacturers include an online calculator to help users make the correct sizing/reserve time calculations.

Amperes at 77ºF (25ºC) to 1.75 v.p.c.

Cell Type	Discharge Time - Minutes							Discharg							
	1	5	10	15	20	30	60	1.5	2	3	4	5	6	7	8
AVR95-7	360	326	296	271	250	217	157	123	102	76.1	61.2	51.5	44.7	39.6	35.6
AVR95-9	480	434	395	362	334	290	209	164	136	102	81.6	68.7	59.6	52.8	47.5
AVR95-11	600	543	494	452	417	362	261	205	170	127	102	85.8	74.5	66.0	59.4
AVR95-13	720	652	592	542	500	434	313	246	204	152	122	103	89.4	79.2	71.2
AVR95-15	840	760	691	633	584	507	365	287	238	178	143	120	104	92.4	83.1
AVR95-17	960	869	790	723	667	579	418	329	272	203	163	137	119	106	95.0
AVR95-19	1080	977	888	814	751	652	470	370	306	228	184	154	134	119	107
AVR95-21	1200	1086	987	904	834	724	522	411	339	254	204	172	149	132	119
AVR95-23	1320	1195	1086	994	917	796	574	452	373	279	224	189	164	145	131
AVR95-25	1440	1303	1184	1085	1001	869	626	493	407	305	245	206	179	158	142
AVR95-27	1560	1412	1283	1175	1084	941	679	534	441	330	265	223	194	172	154
AVR95-29	1680	1520	1382	1266	1168	1014	731	575	475	355	286	240	209	185	166
AVR95-31	1800	1629	1481	1356	1251	1086	783	616	509	381	306	257	223	198	178
AVR95-33	1920	1738	1579	1446	1334	1158	835	657	543	406	$\boxed{326}$	275	238	211	$\boxed{190}$

Figure 3. Battery cells do not have a linear discharge rate (see text).
[Used with permission of East Penn Manufacturing Corp.]

$H_2 + O_2 +$ Zzzt = BOOM!

Although rocket systems include batteries, battery systems aren't rocket science unless or until hydrogen, (electrolyzed from water) oxygen, (from atmospheric air) and heat mingle in sufficient ratios and in concentrations between 17% and 56%, the lower explosive limit and upper explosive limit. Then, all bets are off and the smart money is on the person ducking from the flying plastic parts. Generally, battery spaces are designed with ventilation sufficient that something less than $1/4^{th}$ of the lower flammability limit of 4% (<1% in atmosphere) is maintained.

Typically, battery cells are connected in series-parallel strings to accommodate the desired voltage and parallel capacity or redundancy. Each cell has internal resistance determined by its internal design and state of health. Under ideal conditions, the resistance of each cell would be the same as all other cells in the series string and the voltage drop across each cell would likewise be the same. Each of the cells would therefore have the same level of charge potential entering it.

If one or more of the cells has an internal resistance that differs significantly from its peers as may be the case when there are temperature gradients greater than permitted by the manufacturer, such cells will either overcharge or undercharge depending upon whether the temperature is higher or lower than the peer cells. Because the Float voltage is constant, if some cells undercharge due to a lower voltage per cell, the other cells will overcharge because they are 'seeing' a higher amount of voltage per cell than recommended per-cell Float voltage. Conversely, if some cells overcharge, others will undercharge. In either case, the overall battery performance is degraded and potentially, a severe trouble condition may exist. Additionally, for Valve Regulated Lead Acid batteries, higher currents will flow[i] at a set float voltage relative to that of flooded cells due to the chemistry of internal gassing.

Virtually all lead acid and Nickel Cadmium batteries produce hydrogen gas under normal or abnormal conditions. Even under storage conditions, very small amounts of hydrogen are produced. Under Float charge conditions somewhat more hydrogen is produced and proportionally, the higher the charge voltage, the more hydrogen is evolved. The hydrogen is a function of water in the battery electrolyte electrolyzing (decomposing) into hydrogen (H_2) and oxygen (O_2), the two constituent gasses that comprise water (H_2O). As is seen in Figure 4[ii], the higher the voltage 'seen' between the positive and negative plates of a lead acid or nickel cadmium battery, the more water is electrolyzed into hydrogen and oxygen.

The vented lead acid battery is a mainstay in electrochemical storage technology. Formerly known as "flooded" cells, or "wet" cells, the vented cell is so-called because one can easily replace water that is lost over the life of the cell. Each cell consists of lead grids, also called plates. Each positive plate will have a negative plate on each side of it and so there always be one more negative plate than positive ones. The plates are cast of lead or lead alloy metals with pockets, not unlike a waffle. Two paste materials are applied to the plates, typically lead oxide to the positive plates and sponge lead to the negative plates. Insulating separators prevent the plates from short circuiting to each other. An aqueous solution of water and sulfuric acid serves as the electrolyte. The electrochemical process is that the electrolyte carries ions between the negative and positive plates causing current flow. As the cell approaches a full state of charge, water (H_2O) in the electrolyte becomes electrolyzed and breaks down into hydrogen and oxygen. The hydrogen escapes the cell through an explosion-resistant vent.

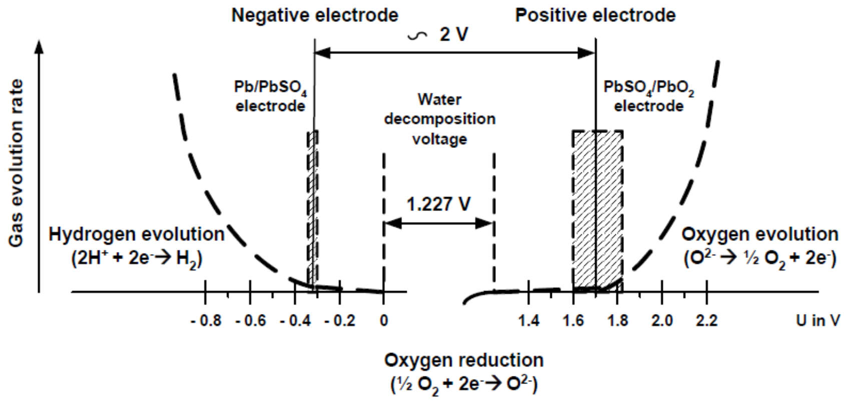

Figure 4. Water decomposition increases markedly as the voltage difference between the positive and negative electrodes (plates) increases. (Source: O'Donnell & Schiemann, Battcon paper. See Reference ii. Used with permission)

Under normal conditions, flooded cells outgas much more hydrogen than do Valve Regulated cells. This condition is because VRLA cells are maintained under a higher than atmospheric pressure condition within the battery container where hydrogen and oxygen recombine back into water that is absorbed into the electrolyte. This result is especially true if the VRLA cells have chemical catalyst bearing vent caps which tend to improve the recombination of the gasses. During abnormal conditions, such as thermal Runaway, VRLA cells will outgas every bit as much hydrogen as their vented counterparts.

Thermal Runaway is a condition often misunderstood. Generally, thermal runaway is the result of an overcharge condition that builds slowly, over weeks and months. As the temperature rises in a cell or group of cells, the internal resistance of the cell decreases. By Ohm's Law, if the impressed voltage rises, float current will increase as cell resistance decreases. In battery terms, as the float current increases, the battery becomes warmer due to I^2R (resistance) heating and the internal resistance decreases still more, thus compounding I^2R heating, a condition that in time can result in damage or even fire or explosion. Thermal runaway is not normally an overnight condition; but rather one that progresses over expanses of time. For this reason, some well-respected industry experts have coined the expression "Thermal Walkaway."

Figure 5 is a photograph showing damage to a vented string of 1,680 ampere hour cells caused by failure of the HVAC system in a telecommunications installation. Over a span of approximately 60 hours, the room temperature climbed to approximately 130 Degrees (F) (54.4^0 C). Note the bulging evident on the sides of the battery containers.

The container material is PVC which softens at approximately 160 degrees (F) (71^0 C). At this point, the battery internal resistance was functioning to some degree as an electric heater, fed by dc power from the plant rectifiers. Under such conditions, copious amounts of hydrogen are produced. Note also, that as the container sides bulged, the electrolyte level dropped beneath the filler-funnel tube of the explosion-resistant vents (sometimes called spark or flame arresting vents) atop each cell. These abnormal conditions placed the cell head-space (if not the facility itself) in a very serious threat of rapid combustion (the E-word) once the hydrogen concentration in any given volume of air would significantly exceed 4%. The cells if not the facility – as this section is named – was one spark away from a boom.

Figure 5. Lead calcium battery cells with containers that bulged due to an overheat condition in the wake of an HVAC system failure. Note the drastic electrolyte level drop (Arrows) that resulted from container bulging.

Across virtually all industries, cell destruction often is a mishandling event where ElectroStatic Discharge (ESD) of accumulated triboelectric energy leads to a spark that enters cell head space by various means and is a**n ignition** source of to hydrogen/air concentrations that are elevated during relatively high rate charging. Two examples are shown in Figure 6. Most often, the ESD source is the clothing of someone who touches the cell, thus triggering a cell explosion. Such events spawn the potential for injury or worse and can easily be avoided by awareness and proper handling techniques.

Among the simplest methods is to wear natural fiber clothing and avoid synthetics which tend to generate more ESD. Another is to discharge one's accumulated charge by toughing a rack or other nearby metal object before touching any part of a battery cell undergoing high rate charging.

Further, all manufacturer's guidelines about charging and explosion resistant vent use should be followed. Cells should be disconnected from charge for at least 24 hours before moving them.

 

Figure 6. Battery cells destroyed by ESD mishandling. Personnel injuries were minor but potentially serious.

Poor maintenance is *grounds* for concern

Intentionally grounded Battery systems, sometimes experience fires due to electrolyte streaking down the side of a battery container, usually from leaking container-to-cover seals or container cracks. Electrolyte is a conductive material when in a wet state or a residual one. If electrolyte finds an electrical path to a Grounded conductor such as a battery stand, a fire can result. Figure 7 shows a battery cell with a container to cover leak in an intentionally positive ground battery string. The streaks of electrolyte residue seen in the figure were the first reason to suspect a defective cover to container seal. The condition is then verified by connecting a voltmeter between a Grounded conductor and then tracing the other probe along the container to cover junction. If the seal is good, no voltage will be observed on the meter. In this case, 37.1 volts are seen indicating a defective seal. The voltage observed is a function of that cell's position in the string times the float per-cell voltage. In this case, cell 17 times 2.18 volts per cell equals 37 volts. Generally, the further (in cell number) above the Grounded cell, the higher the voltage available to a fault condition and therefore the greater likelihood of a battery fire.

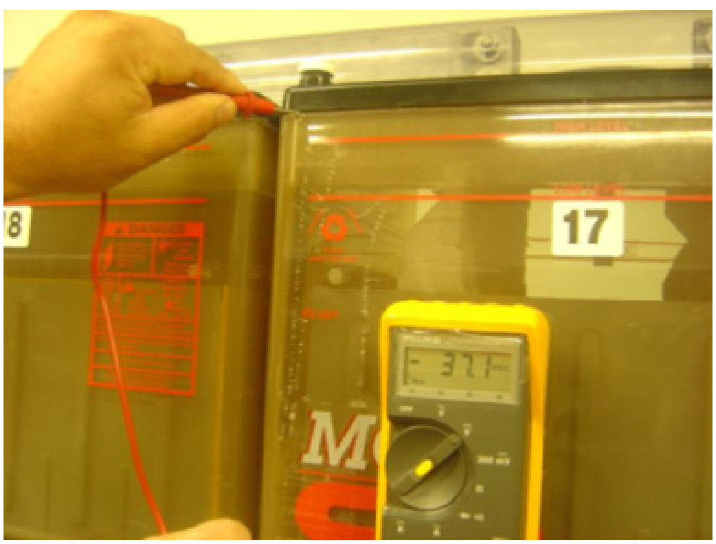

Figure 7. A leaking container-to-cover seal could result in a battery fire.

The life of a corporate bean-counter often is one of inflated authority but shy on responsibility. His or her superficial fiscal success in mandating unwisely Draconian cost reduction policies, places a company's network at risk and imposes career-limiting jeopardies upon others when something 'goes sideways'. Policy decisions that exploit the state-of-the-art capabilities of systems and subsystems under consideration certainly are an important function of Capex and Opex cost containment and are both prudent and effective. Capital expenditure (Capex) and Operational expenditure (Opex) are critical parameters used together with revenues when determining Return On Investment (ROI), the financial happy place where bean-counters go to live in peace with share-holders. Decisions that fail to fully realize the engineering realities and limitations of system elements are suboptimal or disastrous.

Design improvements have produced 'plug and play' infrastructure elements such as newer rectifiers (aka chargers) that dramatically reduce mean time to repair. Thus, in many applications it is prudent to employ a 'run to failure' maintenance approach to *those* items if there is sufficient redundancy and spare units on hand or nearby. Other system elements such as batteries and mechanical systems such as generators, pumps and HVAC equipment are flagrantly unreliable without periodic maintenance.

When considering battery system reliability, how reliable is automated maintenance? Many modern dc power plants incorporate test features that periodically disable rectifiers and measure the depth of discharge potential during the Coup-de Fouet interval. The voltage dip is assessed and reported. This automated test feature is said to provide battery state of health confidence to the user. While such tests do, in fact, provide a *marginal* confidence level, they certainly should not be the only maintenance provided. If someone is about to embark on a long trip, the fact that his or her car started yesterday and today should not be the only preparation. It is not uncommon for battery cells to carry full load for part of their rated reserve time and then experience dropout by one or more weak cells. Figure 8 is of a string of (24) VRLA cells, one of which failed 120 minutes into a 180 minute discharge test. Such failures are especially common among VRLA cells, as opposed to vented cells, usually due to dryout towards the end of life.

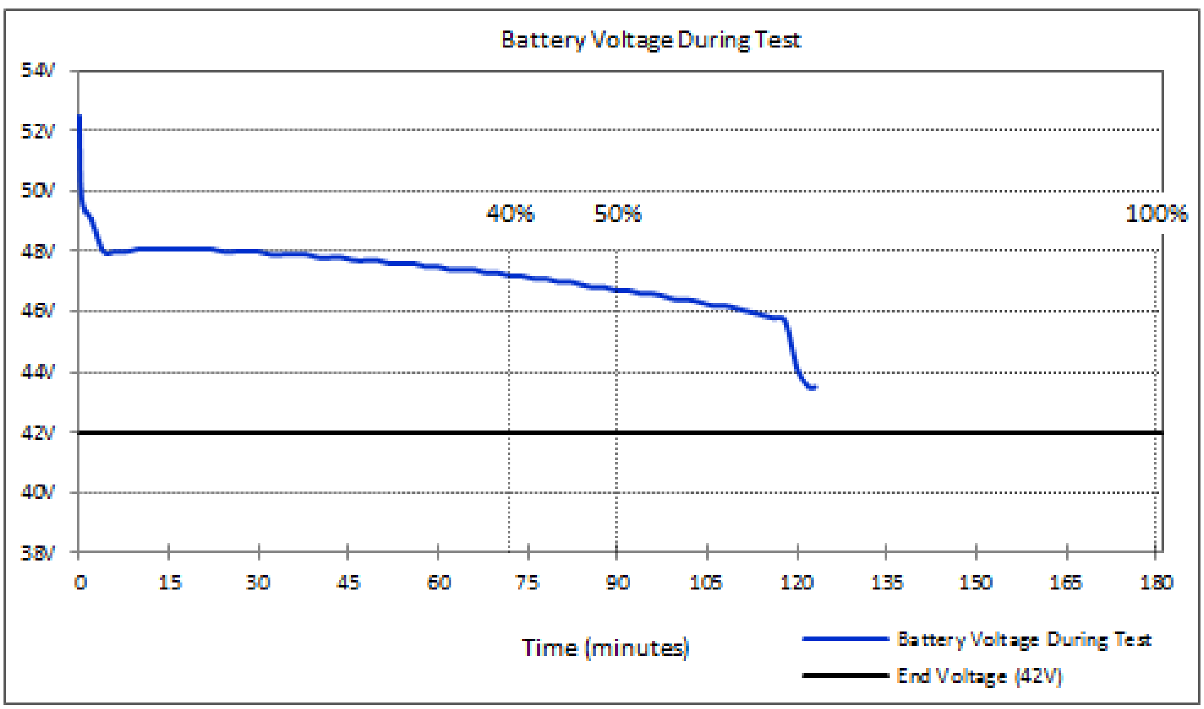

Figure 8. Impact of one defective cell that failed 120 minutes into a 180 minute test[iii].

Is someone knowledgeable checking the installation?

A design plan might be the most innovative bit of engineering since the wheel, Hula Hoop and Super Mario Brothers. Regardless, if the equipment wasn't built or installed to the specifications of the design there is a strong likelihood of issues varying from less reliable to impending doom.

Among the most ridiculous of the installations this author has encountered is one within the facility of a now defunct interstate carrier. Their stated design intent was that there would be no single points of failure and while their design failed to meet that goal, the actual installation was laughable. Figure 9 shows the original design where a single 600 Amp feed was wired to a secondary distribution bay and from there, two 150 ampere circuit breakers were intended to be the feeders to equipment with A and B inputs. The battery consisted of parallel strings of 24 cell VRLA cells floated at 54 volts. Although the equipment easily would tolerate 54 volts, the designer chose to use Counter EMF cells to reduce the voltage 'seen' by the load equipment to 52 volts when on Float operation. During battery discharge, the CEMF diode string is shunted out by a contactor.

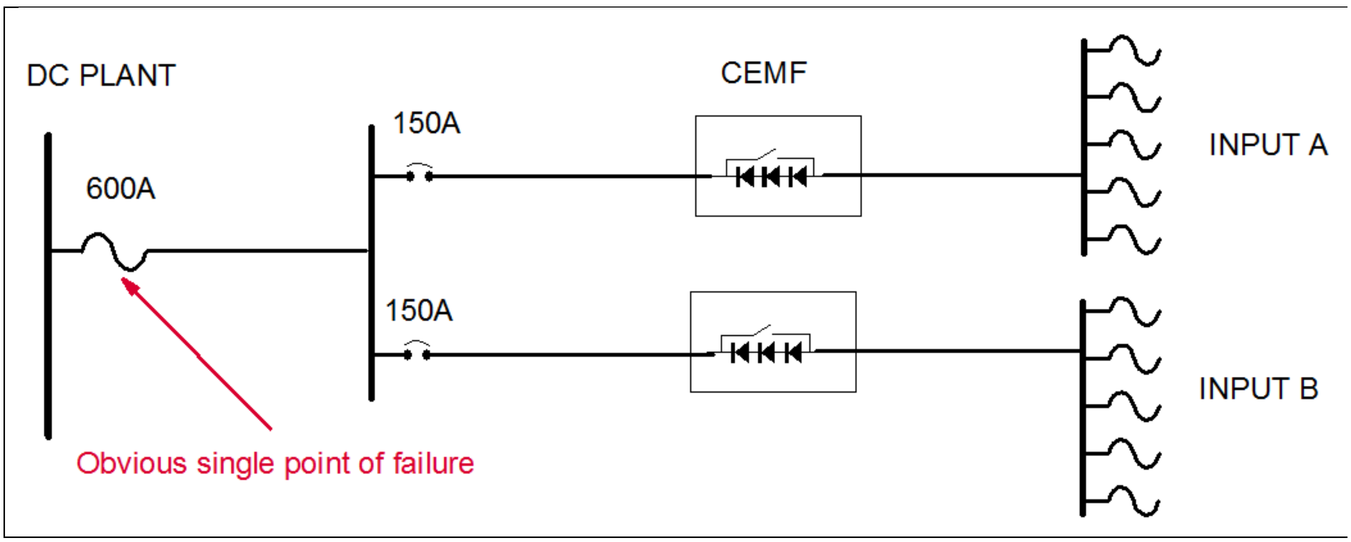

Figure 9. What was designed.

The as-built installation is shown in Figure 10 and shows that whoever installed the job was clueless to the point of dangerous. By placing the two CEMF cells in series, the equipment would 'see' about 2 volts less than normal meaning that the reserve time on battery is significantly lower than desired. Worse yet, is the fault hazard lying in wait under the raised floor.

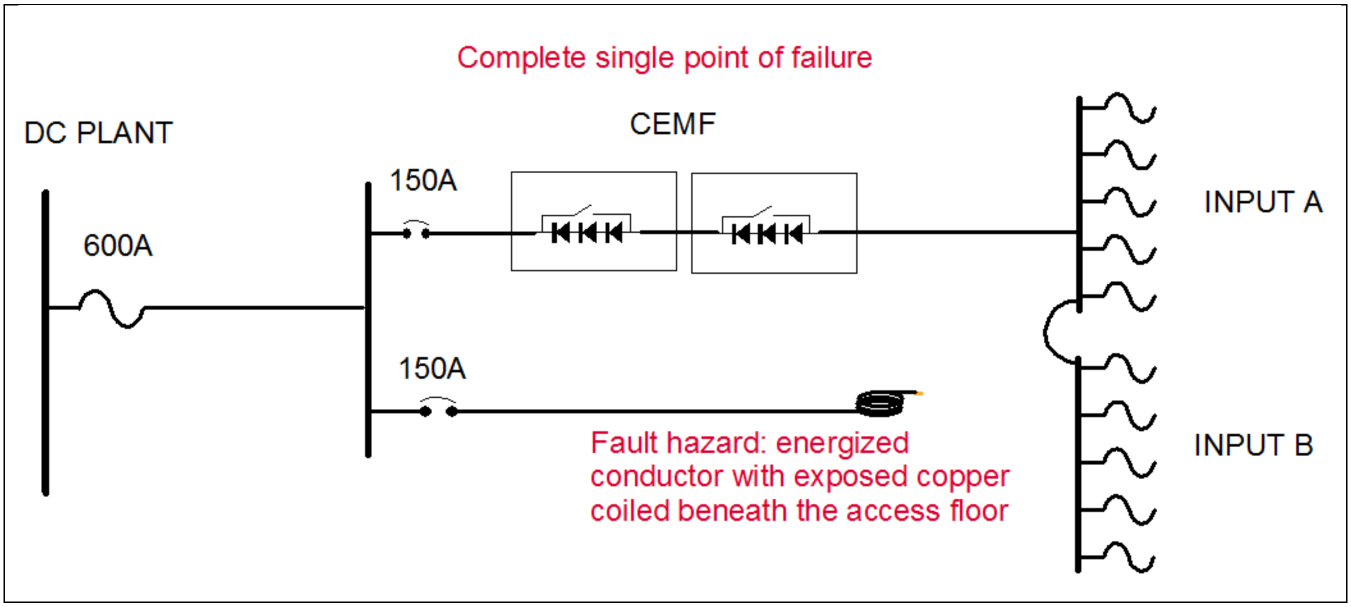

Figure 10. What was installed

Stunningly, that company's designated power subject matter expert reviewed the 'as-built' sketch above and his remark was, "I understand that you telling me that something is wrong with this installation. I don't know what it is, but we will take care of it."

The small incremental cost of bringing in a reliable third party inspector to determine that the job meets standards and that one's company is getting what they're paying for is prudent. Trying to bring someone back to correct defects once the job is complete and final-billed often is problematic.

Summary

The path to reliability includes good quality equipment, properly engineered, installed and maintained. Deviations from that path are muddy. Very muddy.

References

[i] The Basic Chemistry of Gas Recombination in Lead-Acid Batteries, Robert Nelson, Journal of the Minerals, Metals and Materials Society 53 (1) (2001) pp 28 - 33

[ii] Hydrogen Gas Management for Flooded Lead Acid Batteries, Carey O'Donnell and Michael Schiemann, Proceedings – Battcon 2008 (used with permission)

[iii] Graphic (Figure 8) courtesy of Tom Cantor, TPI Engineering, Exton PA