

Thermal Runaway - A System Solution For A System Problem

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Abstract

Thermal Runaway is a potentially destructive failure mechanism known to exist in virtually all lead/acid batteries. For the telcom engineer's purposes, it is more likely to occur in valve-regulated (also called sealed or maintenance free) batteries. This is because the power density tends to be much higher, and the cooling poor. The purpose of this paper is to share problems we've encountered in Eastern Pennsylvania, to share ideas on before and after-market solutions, and inform the equipment vendors of our interest in systemic solutions to this problem.

Background

Thermal runaway problems have begun to crop up in the network, and there is reason to believe that these first failures represent the tip of a frighteningly large iceberg.

Few events cause more stress than a disrupted telecommunications network. Our quality of life and the pace of today's world rely heavily on the free exchange of information. To the telephone user, the network is as vital to the military officer needing instant global communication as it is to the working mother keeping tabs on her kids after school. We might joke about getting away from the phone for a few days, but few of us feel very secure without one nearby.

Likewise, the flow of data, whether from an air-traffic controller's computer, a city's traffic light controls, an electrocardiogram being monitored remotely, or the bank's connection to the automatic teller machine you're using, all impact on the quality and security of everyday life. A fire or energy-source problem in the network can cause disruptions ranging from the relatively minor to those of potentially disastrous proportions. No matter how much artificial intelligence we build into the telephone network, it still requires energy to function. As such, thermal runaway is a very real concern to the men and women in the telephone business.

Scope

Flooded batteries still prevail as the technology of choice for the central office. In contrast, valve regulated batteries are deployed in nearly all Subscriber Loop Carrier (SLC) remote terminals, and customer premise installations. There are more than 50,000 remote terminal locations across North America and uncounted customer Premise locations.

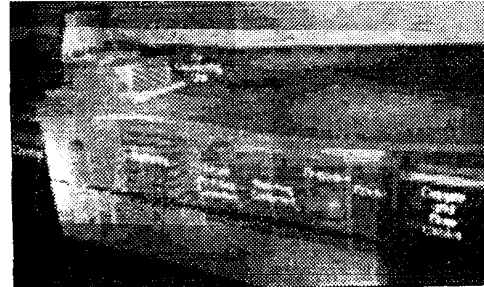


Figure 1

In addition to these uses, there is a growing trend to the deployment of remote switching modules near large telephone users such as hospitals, business campuses and the like.

These telecommunications facilities are housed in customer provided spaces or in small building structures called huts or underground CEVs (Controlled Environmental Vaults). Such vaults (Fig 1) are buried concrete tanks with telecommunications equipment and power supplies.

These power supplies may be embedded in the equipment and use relatively small (Ampere Hour AH) batteries in each equipment bay or cabinet. (Fig 2) Other CEVs are equipped with so-called "Bulk" power plants (fig 3) with larger cells (100 - 500 AH). Typically, (depending on portable generator availability) sufficient batteries are provided to maintain the system for eight hours if commercial power sources are interrupted.

Advanced cases of thermal runaway precipitate catastrophic battery failures. Such failures degrade the network by causing the electrical failure of these sites, and, perhaps, smoke or other related damage to the telecommunications equipment.

Equipment failure may be the least of our difficulties. Technicians visit these sites periodically. We must consider their possibility of exposure to fire related perils such as smoke inhalation, burns, acid burns, and, perhaps, shrapnel injuries from plastic battery cases. This becomes especially true in CEVs. One must travel narrow aisles in an underground vault anywhere from 16 to 50 feet long. The solitary escape route may be past the burning battery, and then one must climb a 10 to 16' vertical ladder through toxic smoke to reach safety.

Telcom Equipment	Telcom Equipment	Telcom Equipment	Telcom Equipment
Power Equipment: Charger Battery Distribution	Power Equipment: Charger Battery Distribution	Power Equipment: Charger Battery Distribution	Power Equipment: Charger Battery Distribution
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Figure 2

Telcom Equipment	Telcom Equipment	Telcom Equipment	Power Equipment: Charger Battery Distribution
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Telcom Equipment	Telcom Equipment	Telcom Equipment	

Figure 3

In a less dramatic or cleanup scenario the technicians must haul damaged cells out of the vault and dispose of them in an approved manner. Accordingly, there are safety and governmental issues to be addressed. Obviously, thermal runaway is a condition to be avoided and managed effectively when it is encountered.

Failure Mechanism

The thermal runaway phenomenon is generally thought to be associated with two heat reactions. The first, is the simple thermodynamics of the battery cell's chemical reaction. This reaction contributes approximately 3% of a battery's internal heat.

The second, called the Joule Effect, is the heat generated by current flow through the cell. This may be thought of as a simple resistive circuit where the battery (which has internal resistance) is connected to a current source (the rectifier/charger). By far, heat from the Joule Effect is the major contributor to thermal runaway.

When batteries recharge after a deep discharge, they draw large amounts of current. For awhile, most of this current is actually absorbed by the battery as recharge and a small percentage of it is converted to heat. As the battery approaches full charge, a declining share of the current flow is still charging plates. The remainder of the current is consumed by internal battery reactions (water decomposition and oxygen cycling). This results in heating.

Many rectifier/charger regulator circuits are insensitive to the battery and maintain relatively high voltages which result in high current depending on the internal resistance of the battery. In constant current applications, the total rectifier/charger output is the limiting factor. Most DC plants are designed for growth, so there is often extra charge capacity available.

Another overcharge scenario is the possibility that one or more cells might short or experience cell reversal during a deep discharge. Once charging resumes, the extra voltage is distributed over the remaining cells in the series string, increasing the likelihood of runaway. One European manufacturer is advertising a voltage "Shunt" accessory designed to boost charge cells by shunting float current around some cells to increase the voltage across others. This accessory might cause a much bigger problem than it is designed to cure.

In most runaway cases, a major factor is cell dryout. Valve regulated batteries maintain a certain internal pressure in the battery jar. This pressure causes recombination, a process essential to the battery's operation. Like any pressure vessel, a safety valve must be incorporated into the design to allow excess pressure to vent-off harmlessly. The valve is the reason for the classification "Valve regulated". Such batteries were once called "Sealed," or "Maintenance Free." This misnomer was rooted in artistic marketing. Most battery maintenance, such as connection cleaning/retorquing is still needed. Some engineers consider these batteries maintenance-proof because one cannot replace water or make accurate observations/measurements of the cell's condition.

As batteries undergo charge and discharge cycles, water in the electrolyte decomposes into it's component gases, hydrogen and oxygen. In flooded cells, this simply vents to atmosphere. In valve regulated cells, mounting pressure builds and hydrogen periodically "Burps" from the cell via the valve. This release of hydrogen is the major cause of water loss. Valve regulated cells have a finite amount of factory-installed water which cannot be replaced.

There is a definite relationship between water loss and internal oxygen cycling during overcharge. At normal water levels, a battery might use one ampere per 100 amperehours of battery capacity for internal oxygen cycling. Reduce the water by 10% and that figure rises to 10 or fifteen amperes. So, significant water loss dramatically increases the likelihood of thermal runaway.

A 10% loss of electrolyte water is thought to represent approximately five years (of normal cycling) in a battery's life. Frequent demands on the battery can accelerate water loss. It is noteworthy that the known cases of thermal runaway in Eastern Pennsylvania occurred in four-year-old battery cells. Similar failures in other Bell Atlantic companies also occurred in four to five year-old cells. This is cause for concern because we deployed many CEVs, huts, and customer premise installations in the middle and late 1980's. Those cells must all be considered ripe for failure.

Dr. David O. Feder, formerly of Bell Telephone Laboratories, chaired a lively workshop session at INTELEC '90, the sole agenda of the workshop was valve regulated batteries. Most of the discussions centered around this one problem. Doctor Feder is quoted as saying, "Thermal runaway has, at last, come out of the closet..... users of valve regulated batteries must build in controls and safeguards."

Doctor Feder's caveat is well taken. Virtually every battery manufacturer admits to thermal runaway, but they don't seem able to reproduce it in the lab. As a matter of curiosity, though, they do recognize high ambient temperature as a causal accelerant in the aging of lead-acid batteries regardless of cell design. The industry-standard method for accelerated life testing of a battery is to elevate the ambient temperature while on float operation. Further, generally accepted engineering principals hold that every 10 degrees (farenheight) above 77 derates a battery by a half-life. In other words, a battery designed to have 75% of it's capacity available after ten years, will degrade to that point in five years at 87 degrees, or in two-and-a-half years at 97 degrees, and so on.

Batteries release their heat in a number of ways. Radiation from the cases, or conduction to the stands, intercell connectors, and cabling, which act as a heat-sink, account for a small fraction of the released heat. Most of the heat, however, is convected to the air around the cases. This is why flooded cells rarely runaway. Generally, they sit on open racks in well ventilated or even air conditioned rooms.

Valve regulated batteries are frequently packaged in tight little compartments with little or no air circulation. This packaging is an engineering compromise between power density, battery life, and available space. To increase battery life, manufacturers tend to use thicker plates and larger cases.

Jamming wattage into the smallest box is a difficult task and isn't done capriciously. Space constraints aside, to meet Underwriter's Laboratories, Canadian Standards, and other standards agency requirements, some batteries must be made safe from accidental contact with untrained persons. Such is the case with many Uninterruptible Power Source (UPS) batteries. Valve regulated cells are tightly packaged in dead-front cabinets with little or no air flow.

The situation becomes even more thermally difficult in cabinet or stands designed for earthquake zones. Many of these designs use battery separators - sheets of plasticized foam, to retard cell movement. Unfortunately, they trap heat, and the cheaper ones have poor flame retardancy and spread characteristics. Poor thermal management, flammable cabinet parts, separators, the fact that some battery cases use flammable polymers, and the presence of explosive concentrations of hydrogen can result in a very messy package.

Prevention

Runaway batteries are much like unruly teenagers. They've been with us a few years, encountered pressure, couldn't find a way to cool off, the severity of the condition was unrecognized at first, became unstable, and is likely to cause significant distress, if not tragedy. And, like calming teenagers, with some mutual understanding and cooperation, we can probably beat this problem too. One thing we can't do is blame each other. The battery community seems to want the battery charger folks to *do something, and vice-versa*. To the telecommunications community, both are part of a power plant. As such, this is a system problem which needs a system solution. We must address two groups of power plants, the new and the existing. Preventing thermal runaway involves several areas: Good thermal design techniques, high temperature detection, appropriate action.

Cabinet Designs

Managing the environment of the battery through the use of convection or forced cooled cabinetry is one approach, although it implies lowering the power density of the system. Cooling fins on the cabinet might help, although the ambient and internal temperatures of valve regulated batteries are often very far apart.

Smart Chargers

Temperature compensated, or "Smart chargers" are a subject which comes up a lot, and should be considered part of the long-term solution. The intent is that the power plant's rectifier (or controller) would take a temperature input from the battery and adjust the float voltage if the battery gets too hot.

There are numerous opinions about as to where the temperature should be taken. A sensor might be placed in a stick-on or other device in contact with the battery case. Also, how many sensors?, one per shelf, one per string? Since the lead plate temperature is the critical item in thermal runaway, I think the best place to measure temperature is at the posts since these are in metallic contact with the plates. Bolts with thermocouples set into their heads could be used as the sensor.

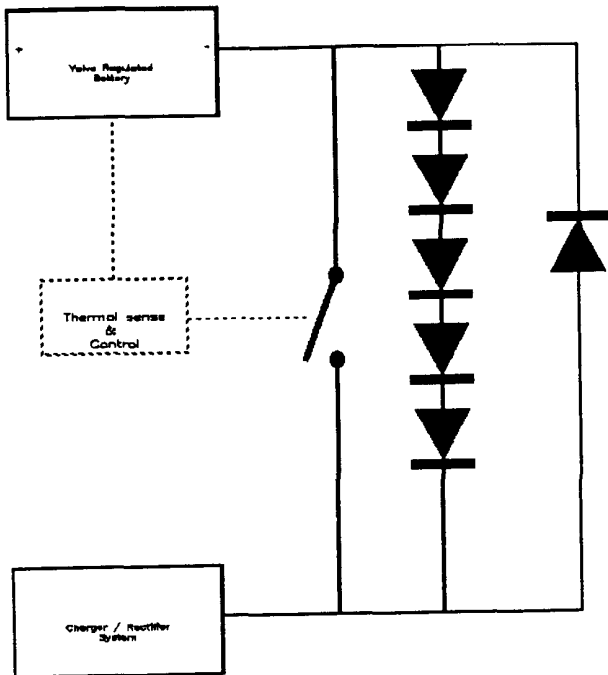
As a practical matter, there is merit to using thermal sensors in parallel, one per-battery. A high temperature detected on any cell would cause the rectifier to reduce it's output voltage until the temperature returned to normal. Portable chargers should also have thermal regulation

Thermally Compensated Intercell Connectors

Intercell units could be designed to incorporate a series resistance bypassed by a normally closed thermal safety switch similar to the overload cutout on a motor. Thus, the resistance would be switched into the circuit by a high post temperature. This could be used in new or retrofit applications, and could serve two purposes: 1, it would eliminate thermal runaway by reducing charge current; and, 2, it would eliminate post meltdown failures in high current systems like UPS.

Compensated Batteries

Resistance compensation, similar to the above intercell connector approach, might be incorporated into battery designs. Additionally, thermal fuses or automatically resetting thermal breakers might be designed into the conducting structures between the plates and the posts of storage batteries.



Electrolyte Injection

Since thermal runaway is nearly always associated with electrolyte dry-out, some research should be directed toward the replacement of the fluid Absorbed glass mat gas-recombinant cells might be extended by the injection of measured quantities of electrolyte. This might be via a factory installed fitting, or a field-retrofit kit, such as a replacement cell valve, or a solvent-bonded patch to close a drilled hole. Some agitation might be needed to distribute the electrolyte across the plated.

Conclusions

Thermal runaway may have "come out of the closet," but we aren't out of the woods, by any measure. Research and development is needed in the areas of charge equipment and monitoring systems, test and evaluation methods, battery packaging, manufacture and maintenance, and after-market products and services. Until these are addressed, telephone system engineers should be very selective about when and where we deploy valve regulated batteries in the network.

Counter EMF

An old Bell System approach, the diode counter-cell might have new life, especially for retrofit applications. Countercells are voltage dropping elements installed between the battery and the load. The intent was to limit the voltage to the load during float operation, and bypass the countercell when on battery. The opposite application - limiting the charge current to the battery might work.

Early countercells were electrochemical devices, however modern versions are simple diode strings. A power diode's junction under forward bias provides a voltage drop of approximately six-tenths of a volt. A series string of diodes might be switched into series with the charge bus under control of an array of thermal sensors to reduce the recharge voltage to the battery. A contactor would shunt around them in normal operation and open if one or more cells exceeds safe temperature limits. A reversed diode protects the load against power loss if there is a contactor failure while on battery.

Test & Evaluation

The "Maintenance-proof" aspect of valve regulated batteries must be addressed. To date, test schemes like impedance measurement have been an unfulfilled promise. About the only reliable tool is the deep-discharge capacity test. This has numerous drawbacks. Discharge tests are expensive and time consuming: some provision must be made for the protecting the load: deep cycling reduces the battery's life: accelerating the test (increasing the load) may risk post-meltdown: and, the recharge cycle might initiate thermal runaway. More research is needed. Perhaps PH sensors or optical hydrometers could be mass produced cheaply and manufactured into the cells. Perhaps water loss could be measured by cell weight.