CAN VRLA BATTERIES LAST 20 YEARS?

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1. Abstract

Experimental data shows conclusively that premium-quality VRLA-AGM cells can fail from discharged negative plates even while on steady-state float charge. The problem appears to be a fundamental one, affecting the better cell designs in particular. Consequently, VRLA cells as presently made are unlikely to last 20 years in service. However, a small, inexpensive recombination catalyst placed inside each cell solves the problem at source and brings many other benefits besides. Catalysts can even recover cells that have failed in service due to negative discharge.

But a caution is necessary: the addition of a catalyst imposes a new condition, namely, that the device itself must work safely and reliably for many years. The present paper addresses this issue and is optimistic that a suitable catalyst device has been developed.

2. Introduction

VRLA cells have successfully replaced flooded cells in many telecom and UPS applications. However, their reputation has been marred by reports of early and unexplained failures **(1)**. Statistically, long-life designs (20-year life) appear to have a bigger problem than short-life batteries (5 -10 year life).

Experimental data gathered at the PSI laboratory over several years confirmed that a serious problem does indeed exist in some long-life designs **(2,3)**. The problem is that the negative plates on premium VRLA cells are subject to self-discharge ***during float*** due to a "hydrogen imbalance" inside the cell (explained later). This imbalance plays no significant role in flooded cells so it has been largely overlooked by battery designers.

Hydrogen imbalance brings with it the curious result that cells made with the ***best*** positive grids appear to be the ***most susceptible*** to negative discharge. The implication is that VRLA cells of present design and manufacture are unlikely to last 20 years in service, even when perfectly assembled.

Several manufacturers, though initially skeptical about such a pessimistic conclusion, have now confirmed the results with their own products. One battery company has further demonstrated that the same negative discharge problem exists with VRLA batteries in deep cycle service **(4)**.

Having helped to clarify the problem **(2,5,6)**, it was natural for Philadelphia Scientific to want to develop a positive solution. That solution turned out to be the use of a recombination catalyst. Early experiments with noble metal catalysts showed promising results, so a definitive test was needed that would prove beyond all reasonable doubt that:

- the problem was real
- the solution worked

Accordingly, a long-term comparison test was designed in the form of a direct, side-by-side competition between standard cells and catalyst-equipped cells.

3. Test of premium VRLA cells.

The cells selected for this test were high quality, U.S. made, production AGM cells, designed for a 20-year service life. They were individual 2-volt self-supporting cells, intended for vertical installation, with a nominal capacity of 125 Ah.

The test arrangement is shown in **Fig.1**. Two strings of identical cells were placed in a common water bath at a temperature of 90°F (32°C). Each string was connected to its own power supply at 2.27 volts per cell. *(Note: This relatively high float voltage was chosen because the manufacturer thought it might "protect the negatives" better than a lower voltage).*

The cells in one string were equipped with catalyst devices made by Philadelphia Scientific. The other string was left unmodified and represents absolutely standard cells operating in warm, but not unusual conditions. In short, this was a ***real-time test*** and not an accelerated test.

Each cell was equipped with its own gas collecting apparatus of the proven design shown in **Fig.2.** The

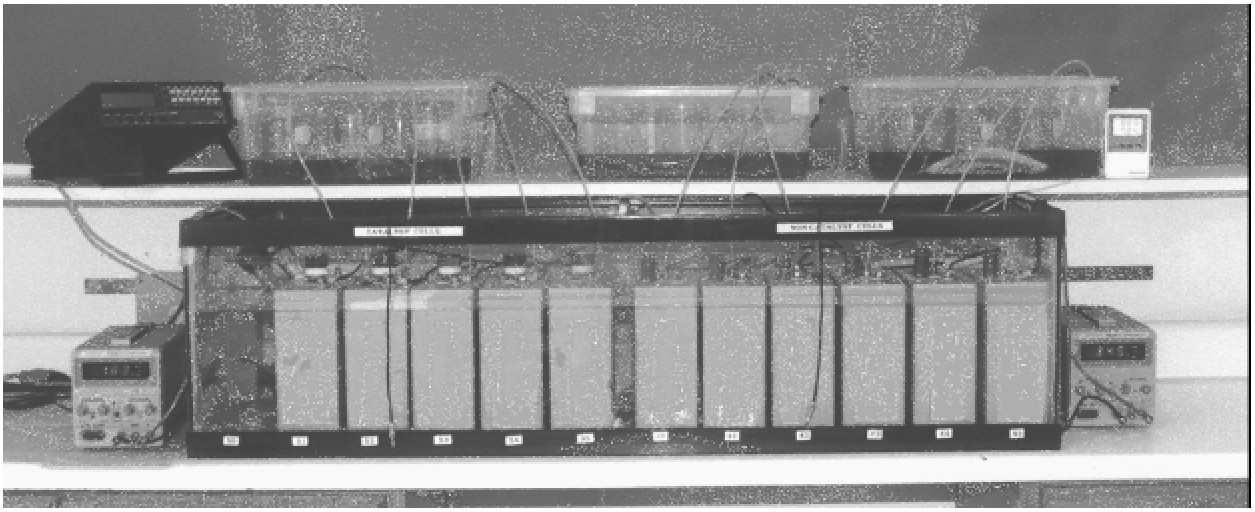

Figure 1: Test setup of VRLA cells showing common water bath and gas collection

gas collection beakers were placed at eye level to provide a direct and obvious contrast between the gassing rates of the two strings.

All connections where hydrogen leakage might take place were checked periodically with a low cost hydrogen "sniffer". This invaluable instrument detected leaks that would otherwise have spoiled this crucial part of the test.

One cell in each string was equipped with a Hg/$HgSO_4$ reference electrode, sealed into the cell cover, to check nominal plate polarizations. The added risk of hydrogen leaks around these electrodes precluded putting them in all the cells.

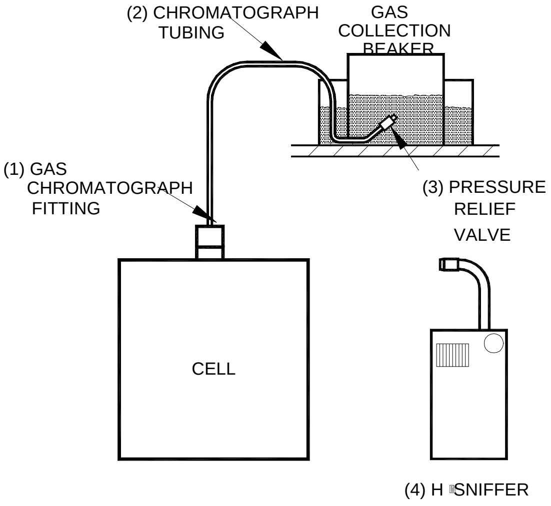

Figure 2: Gas collecting apparatus
See appendix for equipment sources

Other parameters recorded during the test were conductance, cell voltage, float current and water temperature. Unlike most reported tests of this kind, the cells were *not discharged, boosted or otherwise disturbed* during the test period; we wanted to demonstrate that the problem occurs under perfect, steady-state float conditions.

At the end of the 64 week test period, the cells were placed on open circuit for a further two weeks to check for leaks. *(Note: A catalyst cell's hydrogen emission should* ***rise*** *when the charger is turned off (5)).* Stable open-circuit voltages were also recorded from which acid densities could be calculated. The two strings were then placed on a constant current discharge capacity test at 25 amps to 1.75 volts per cell.

3.1 Cell capacities. The capacity test produced a most remarkable result:

- *The standard cells failed catastrophically while the catalyst cells yielded over 100% of their rated capacity.*

Fig.3 shows the relative capacities of both sets of cells. (The mean performance of the catalyst cells was used to define 100% capacity). On this scale, the standard cells yielded an average capacity of only 65%, with two cells failing at about 55% capacity. The reference electrode readings indicated that the standard cells had failed by negative limitation: the negative plates' contribution to the overall voltage drop was 27% for the standard cells compared with only 7% for the catalyst cell.

The results confirm that hydrogen imbalance is a real problem and obviously a very serious one for this class of cells.

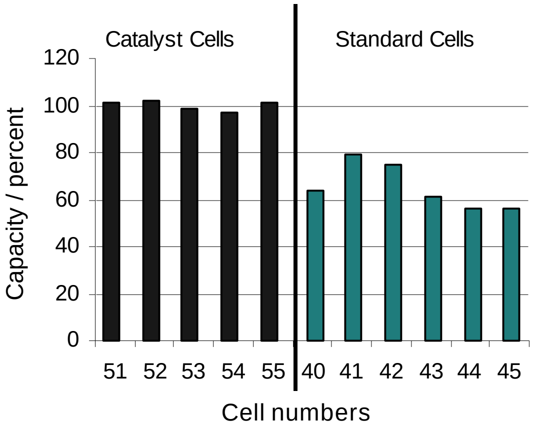

Figure 3: Capacity test after 64 weeks of float charging at 2.27 V/cell and 32°C

While such a definitive result can stand alone, it is significant that the other test results echoed the same conclusion:

3.2 Cell conductances (Fig.4). The conductance readings on the standard cells showed a huge drop (corresponding to an increase in resistance of about 60%) while those on the catalyst cells remained essentially unchanged. The conductance readings, taken just before the discharge test, had a remarkable similarity to the capacity readings (see Figures 3 and 4). This means that conductance is a valid indicator for the negative discharge problem.

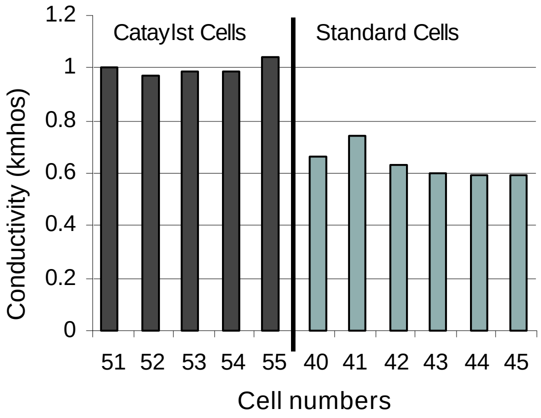

Figure 4: Conductivity after 64 weeks of float charging at 2.27V/cell and 32°C

3.3 Specific gravity. (Fig.5) Acid densities estimated from the open-circuit voltages taken just before the discharge test, show a similar pattern: the catalyst cells were all high (e.g.: 1.320) while the standard cells were all low (e.g.: 1.270). Again, this indicates serious discharge of the ***negative*** electrodes because the polarized positive plates on a VRLA cell are always overcharged. *(Note: The high acid densities of the catalyst cells were a result of initial manufacturing conditions not water loss because total water loss during the test, as measured by hydrogen emissions, was negligible).*

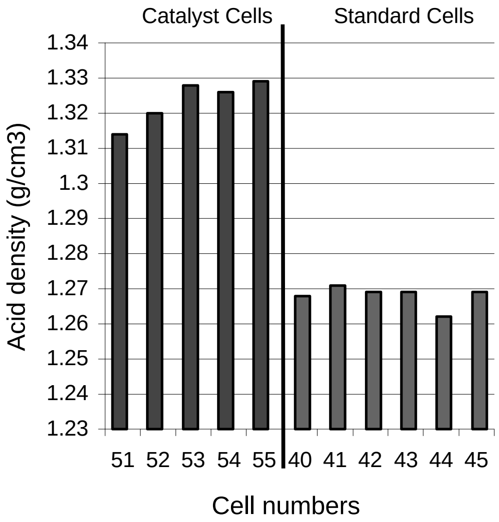

Figure 5: Acid density after 64 weeks of float charging at 2.27 V/cell and 32°C

3.4 Plate polarizations. The negative plates of the catalyst cells were always polarized during the period of the test, usually between 10 and 20 mV. By contrast, the negative polarizations of the standard cells were always zero. Even during the latter portion of the test when the negative plates were significantly discharged, the negative polarization readings did not give any indication of this condition. The cell voltages varied more on the catalyst cells due to variations in negative polarization; in this sense they behaved more like flooded cells. The cell voltages on the standard cells were very uniform as expected with non-polarized negatives.

3.5 Float current (Fig.6). When the catalysts were installed in the cells at the beginning of the test, they reduced the float current approximately in half. This is a major benefit of the catalyst in unbalanced cells and is a consequence of the slightly polarized negative plates that it produces. Moreover, as the test progressed, the float current on the catalyst string stayed constant - a necessary quality in a 20-year cell.

The float current on the standard cells, by contrast, ***increased progressively*** throughout the test. At the end of the test period, the standard cells were drawing over three times the current of the catalyst cells - and the current was still rising. Considering that the cell

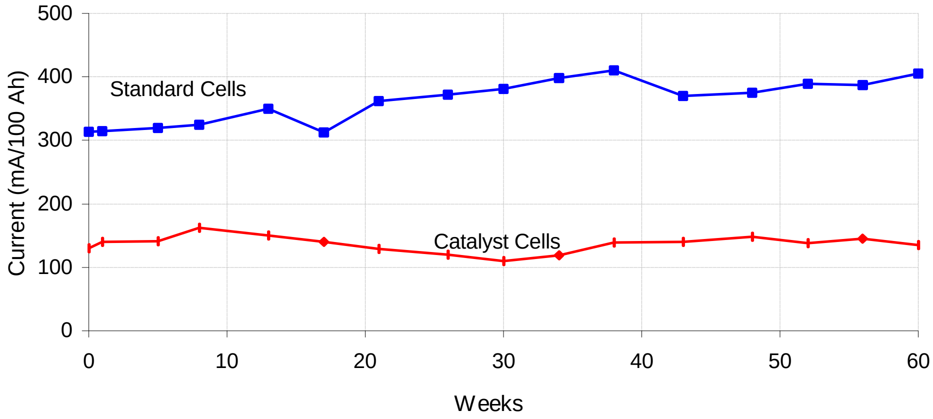

Figure 6: Influence of catalysts on float current at 2.27 V/cell and 32°C

impedance had also risen by a factor of 1.6 in the same period, the actual 1^2R heating rate was almost ***15 times higher on the standard cells than on the catalyst cells.*** This exponential rise in heating rate explains how thermal runaway conditions can occur even in the absence of short circuits. It also suggests that tests on new (ie: wet) VRLA batteries are likely to yield over-optimistic results regarding future performance.

3.6 Gas emissions. The gas emissions from the cells at the ***beginning*** of the test are shown in **Fig.7**. These emissions, largely hydrogen gas, are proportional to water loss from the cells and are directly related to dryout life. At the start of the test, therefore, the catalyst reduced the emissions from about 80 to 20 ml/day/100 Ah – a factor of about 4:1 and a huge improvement.

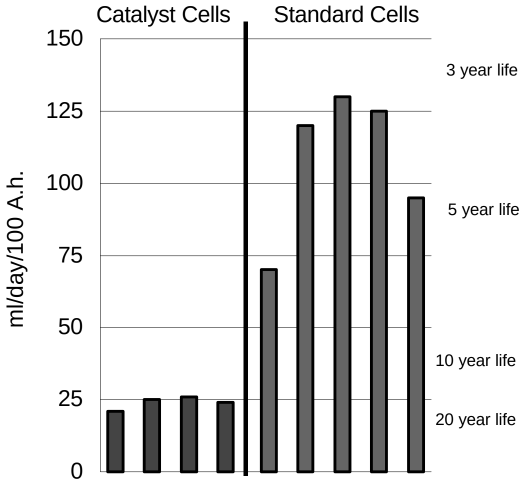

Figure 7: Comparison of initial gassing rates of standard cells versus catalyst cells at 90°F (32°C) showing increase in theoretical service life.

But there was more to come: as the test progressed, the gassing rate of the catalyst cells continued to decrease. Within three months, the rate was in the region of 10 ml/day/100 Ah making the improvement a factor of 8 lower than the standard cells.

The immediate assumption, of course, was that the cells were leaking, but no leaks could be found with the hydrogen "sniffer". Later, when all the cells were placed on open circuit, the gas emissions of the catalyst cells rose in a matter of two weeks to a value of nearly 100 ml/day/100 Ah - ***an order of magnitude higher***. This eliminates the possibility that the cells were leaking, so the low hydrogen emissions on float suggest that the corrosion rates of the positive grids had actually diminished to very low levels. But this observation has to be supported by further measurement.

But even taking the most conservative case, namely that the catalyst cells had only four time lower gas emission than the standard cells, the catalyst's effect on cell life is very significant. For example, even if the standard cells could avoid negative discharge, they would still fail by ***dryout*** in about 5 years at 90°F (32°C). The catalyst cells, on the other hand, have a predicted dryout life of 20 years at the same temperature. This is an enormous performance improvement and one that justifies the use of a catalyst in its own right.

A considerable amount of gas was emitted from the standard cells during the actual discharge itself, but very little from the catalyst cells. This indicates that the gas "squeezed" out of the plates during discharge (well known in flooded cells but unexpected here) is almost stoichiometric and is recombined by the catalyst. Therefore, we might expect the catalyst to reduce water loss significantly on cells in cycling service or in standby service where power outages are frequent.

3.7 Summary of results. Taken together, the data demonstrates beyond any reasonable doubt that the negative plates on premium VRLA cells can discharge on steady-state float. The data also demonstrates that the addition of balancing catalysts in these cells will correct the hydrogen imbalance problem at source.

To summarize the benefits of using a catalyst in the class of cells under test, the catalyst can:

- Keep the negative plates charged with about 10 to 20 mV polarization.
- Reduce the float current in half and keep it low and stable.
- Reduce cell heating by an order of magnitude thus minimizing thermal runaway.
- Reduce hydrogen emissions by a factor of 4 or more, thus improving safety.
- Reduce water loss for increased dryout life from 5 to 20 plus years at 32° C.
- Allow the use of lower float voltages such as 2.25, 2.23, 2.21 volts/cell if recharge time permits **(5)**.
- Compensate for trace impurities in the cell.
- Recombine gasses given off during discharge.
- Compensate for small air leaks **(2)**.

Other experiments have shown that catalysts retrofitted into cells with self-discharged negative plates recovered these cells on float, without boosting **(3)**.

4. Cell balance: a simplified explanation

The theoretical explanations of hydrogen balance have been given elsewhere **(7)**. A simpler model is offered here for non-technical people.

The negative plates on lead acid cells have a natural tendency to self-discharge; in doing so, they release or "leak" hydrogen into the cell. This is a simple chemical reaction which cannot be stopped. In fact, if pure lead powder is placed in a beaker of acid, it will "discharge" and produce hydrogen. It is common sense that if negative plates are losing hydrogen at a certain rate, then to maintain them at full charge, they must be supplied with the equivalent of that hydrogen, and at the same rate. In practice, this is done by charging, and the hydrogen equivalent is ***hydrogen ions + electrons.***

In other words, negative plates must be kept "topped-up" with hydrogen ions + electrons at all times to prevent them from discharging. Those ions + electrons come from water broken down at the positive plate by electrolytic action and there are only three possible sources **(Fig 8):**

- Electrolysis (classical)
- Oxygen cycle
- Corrosion (positive grid)

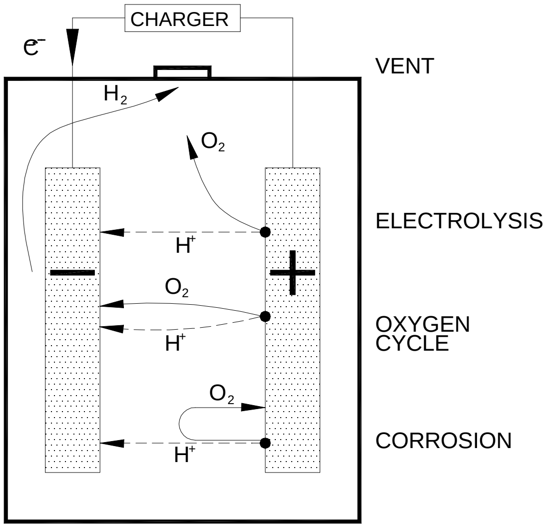

Figure 8: Schematic diagram of sources of hydrogen ions + electrons in a VRLA cell

Each of these will now be reviewed as a potential source for ions + electrons.

4.1 Electrolysis. Electrolysis is well understood in the context of a ***flooded cell***. During charge, water is broken down on the positive plate into three parts:

- oxygen gas (which bubbles to the surface of the acid and leaves the cell)
- hydrogen ions (which move as part of the liquid toward the negative plate)
- electrons (which move through the charger toward the negative plate)

It is the latter two components that charge the negative plates. The reason why discharge of negative plates is not a problem on flooded cells is that the oxygen ***leaves the cell,*** allowing the hydrogen ions + electrons to migrate toward the negative plates and charge them.

It is important to recognize that, in a new VRLA cell, there is usually an excess of electrolyte in the plates and separators, so some electrolysis takes place just as it does in a flooded cell (i.e.: some oxygen leaves the cell). Consequently, negative discharge will not take place until the cell dries out a little – which could take several years in service at low or moderate temperatures.

However, as the VRLA cell matures and dries out, electrolysis declines almost to zero, so it is not available as a long-term source of hydrogen ions + electrons and must be discounted in a 20-year cell design. In fact, there is a real danger that it can mislead by masking an imbalance problem until the cells have been in service for a few years. This appears to be the pattern of service problems of long-life VRLA cells in the telecom market.

It is very likely that our test cells were manufactured in a relatively dry condition which would explain their rapid loss of capacity. Had they been shipped in a wetter condition, their decline would have been delayed - but not averted.

4.2 Oxygen cycle. The oxygen cycle is a kind of reversible electrolysis. In a VRLA cell on float, water is broken down as in the last example but here the oxygen ***does not leave the cell***. Instead, it also reaches the negative plate and recombines there with the hydrogen ions + electrons to reform water. This recombination process ***consumes virtually all of the hydrogen ions + electrons*** so there are none left to charge the negative plate. Therefore, an efficient oxygen cycle, which is a characteristic of all mature VRLA cells, is incapable of keeping negative plates charged. Note, however, that there are ions + electrons available if the oxygen cycle efficiency can be reduced in some way.

4.3 Corrosion. The corrosion process also consumes water by electrolytic action, but in this case, the ***oxygen is absorbed into the lead grid*** and takes no further part in the process. The hydrogen ions + electrons left over find their way to the negative plates and charge them. So, of the three possible sources, corrosion is the ***only steady-state source*** of hydrogen ions + electrons in a mature VRLA cell.

Therefore, the long-life VRLA cell is totally dependent on the corrosion reaction of the positive grids to prevent discharge of its negative plates. Note that corrosion and discharge are two ***completely independent reactions*** and it would be *sheer coincidence* if they happened to be within the same order of magnitude, let alone precisely equal.

The critical question then is this: Are there enough hydrogen ions + electrons available from the corrosion reaction to keep the negative charged? According to our test data, the answer, for premium cells with superior positive grids is: ***No, not even close.***

In our test cells, grid corrosion supplied only 25% of the amount of hydrogen ions + electrons required to sustain the negative plates. *The result is that the negative plates on these cells will discharge almost as fast (75%) as if they were not being charged at all.* Further, they will continue to discharge until they reach 25% capacity - well below acceptable capacity levels.

5. How the catalyst works.

The elegance of the catalyst solution can now be seen. The catalyst works because, as Berndt **(7)** has said, it "steals" some of the oxygen from the oxygen cycle and recombines it with the hydrogen that is always available in an unbalanced VRLA cell. By removing this "excess" oxygen, it allows the corresponding hydrogen ions + electrons to migrate to and charge the negative plates. The important fact is that this happens even in a ***mature*** VRLA cell with a fully developed oxygen cycle so it is a stable effect over the lifetime of a cell and not a transient one.

A welcome and important side benefit is that while the “excess” oxygen is prevented from doing harm, it is not lost as with electrolysis and corrosion but is recombined to become useful water. Therefore, much less water is lost than from a standard cell. *(Note: In effect, the catalyst makes the oxygen cycle **less efficient**. While the word "efficient" is normally synonymous with "good", in the case of the oxygen cycle there can be too much of a good thing).*

There are, therefore, two ***stable gas emission*** rates possible from a fully charged VRLA cell.

1. The first rate is that from a standard non-catalyst cell. It corresponds to negative plate self-discharge as defined by Berndt **(8)**. VRLA cells on float cannot have gassing rates below this level. This rate defines the dryout life of a non-catalyst cell.

2. The second and lower rate is that from a cell equipped with a catalyst. It corresponds to the hydrogen component of the positive grid corrosion. This rate defines the dryout life of a catalyst cell.

The catalyst, then, reduces the emissions from the first stable condition to the second stable condition. The amount of oxygen catalyzed, therefore, depends on the cell’s imbalance; the more the imbalance, the harder the catalyst works. So even if a cell’s grid corrosion rate was not constant – as appears to be the case with our test cells – the catalyst would simply “steal” a little more oxygen until balance was restored. *The result is that the catalyst automatically reduces hydrogen emissions to the minimum.*

Do these results imply that all VRLA cells will suffer discharged negatives? No, they do not. The great irony of VRLA cell design is that a short-life cell happens to be relatively easy to balance: the high corrosion rate of its inferior grids will provide ample hydrogen ions to charge the negative plates. A catalyst would not be required to protect the negative plates, nor would it reduce gas emissions (at least once the cell matured). However, such a cell would obviously not achieve a 20-year life target. The negative discharge problem looms largest in cells with superb positive grids.

What about gel cells? Will these also be affected? The probable answer is that, due to a less efficient oxygen cycle and a greater amount of initial electrolyte, the phenomenon will simply be slower in manifesting itself.

So the issue remains: to make a 20-year battery, we MUST employ superior grids which, in present designs, MUST result in discharged negatives so, for a *practical* 20-year cell a catalyst may be mandatory.

6. Catalyst reliability

But optimism must be tempered with caution because the prospect of using catalysts in premium-quality cells gives rise to new concerns. Since Philadelphia Scientific is a manufacturer of catalytic devices (mainly ceramic enclosed palladium-based materials), we listed the concerns and set out to answer them objectively. These are the most frequently asked questions:

6.1 How long will the catalyst last?

Our experts have told us that that the life of a catalyst is theoretically unlimited at normal temperatures. The active material is not used up nor does it decompose or dissolve. If it is exposed to very high temperatures such as 600°F (300°C) for long periods, then its life will be shortened due to physical decomposition of the substrate. Since the catalyst in a VRLA cell recombines only a fraction of the Faradaic equivalent of the float current, it operates at a relatively low temperature. (Thermocouples inserted inside the catalyst chambers, recorded less than 10°C temperature rise above ambient under float conditions). Under these conditions the catalyst should last over 20 years.

6.2 Will sulfuric acid destroy the catalyst?

The concern here is that acid spray in the cell will cover the catalyst and render it inoperative. Earlier models of our catalyst suffered from this problem as the acid soaked into the ceramic chamber and coated the active material inside. *(Note: The catalyst is not destroyed by the acid; it just gets wet).* To prevent this happening, our production catalyst devices are provided with a hydrophobic coating that is highly porous to gas and water vapor but will not allow liquids to penetrate. With this coating, the catalyst devices can be immersed in acid for long periods of time without getting wet so the new design should not have a problem with acid spray for the life of the cell. Confirming long-term tests are underway.

6.3 Can the catalyst "drown" in its own product water?

This was a real problem with catalysts used on flooded cells in the 1970's in Europe. However, the atmosphere of a VRLA cell is dryer that that of a flooded cell due to its higher acid density (1.300). To prove this, we prepared samples of our catalysts by soaking them (by injection) with water and then hanging them in the gas space of a sealed beaker containing a measure of 1.300 acid. Within a few days, the catalyst devices had dried out and, when placed in our standard oxy-hydrogen test rig, immediately became operational. It appears, therefore, that devices of our design will dry out of their own accord in a 1.300 acid atmosphere should they ever become wet with their own product water.

6.4 Will the heat from the catalyst increase cell temperature?

Not in normal service. A VRLA cell is heated by the total heating power of the float current (1^2R). Most of that heat is generated by the oxygen cycle. Because the catalyst usually reduces the float current, the total heating effect will actually be reduced so a catalyst will generally tend to ***reduce cell temperature.***

6.5 How hot does the catalyst get?

Under normal float conditions, the temperature rise of the catalyst device is very small. However, if the cell is charged at an excessive rate (for example, during a failure condition) the catalyst will be recombining relatively large amounts of oxy-hydrogen. The temperature of the ceramic catalyst enclosure may then reach over 300°F (150°C) which is enough to melt low temperature plastics. Therefore, high temperature plastic components are used where they come in contact with the catalyst devices. In other models, we have reduced contact temperature of the devices by design modifications so that no special plastics are needed. *(Note: The point is probably moot since any situation that would cause a battery to produce that much gas would also kill the cell).*

6.6 Will the catalyst cause cell explosions?

No. There are two levels of protection provided in the design of the catalytic device. First, the catalyst active material is selected to be self-limiting in its rate of reaction. That is, it will not explode even if it exposed to a continuous flow of oxy-hydrogen gas under typical vent pressures of 3 psi (200 mbar).

Second, the active material is further enclosed in a microporous ceramic chamber that is a flash arrestor. To demonstrate its effectiveness, experiments were carried out using electrical sparks and other artificial ignition sources inside the ceramic chamber while the chamber itself was in a pressurized oxy-hydrogen atmosphere. Under no conditions were we able to force ignition to take place through the chamber walls.

The catalyst, therefore, is an additional *safety feature* because it should reduce the risk of:

- External explosions (because of lower hydrogen emissions).
- Thermal runaway (because of lower float current and internal resistance).

6.7 Is the catalyst active material likely to poison the cell?

No, it is almost impossible, for two reasons. First, in the Philadelphia Scientific design, the catalytic active material is enclosed in a microporous "filter". Unless this filter was installed in a broken condition, which is very unlikely, the possibility of any of the material being physically released into the cell is negligible.

Second, even if such an unlikely event did happen, and catalyst active material ***did*** fall into the cell - and get soaked in acid - the cell would still survive. This is because the catalyst material does not readily dissolve in acid and only ***dissolved impurities*** can contaminate the cell. To demonstrate this, we soaked active material in 1.280 acid at 150°F (65°C) for several weeks and, on subsequent analysis, could find no detectable trace of it in the acid.

To the contrary, the catalyst is much more likely to behave as an "anti-poison" than a poison because it ***compensates for impurities***. For example, if certain trace impurities, like antimony, find their way into a VRLA cell during manufacture, they will increase hydrogen evolution, making the imbalance problem worse. A catalyst, however, will simply recombine the increased hydrogen, correct the cell's imbalance, and allow it to function without loss of performance.

To put the matter in perspective, the risk of a premium VLRA cell suffering discharged negatives from various sources are:

- Hydrogen imbalance: ***Almost certain***
- Trace impurities: ***Quite likely***
- Air leak: ***Possible***
- Catalyst contamination: ***Very unlikely***

6.8 Can the water vapor produced by the catalyst cause corrosion on negative top-lead?

Corrosion of top lead is a complicated technical issue and has been discussed by Berndt **(9)**.

On a theoretical level, the (polarized) negative top-lead in a catalyst cell should be ***less prone to corrosion because it is cathodically protected.*** The standard VRLA cell, by contrast, has no cathodic protection when it matures and is thereby more vulnerable to negative corrosion. On a practical level, we have not detected top lead corrosion on any tested cells, even after 2 years of operation.

6.9 At what point is a cell in service too old to be retrofitted with a catalyst?

There is no simple answer. The main role of the retrofit catalyst is to recharge the negative plates. Therefore, the overall condition of the cell becomes the deciding factor. To recover older cells, perhaps a concurrent injection of water might be helpful. Field tests are underway to establish a logical procedure.

6.10 How does a catalyst perform during a discharge?

Reports to date have been positive. Tests having several hundreds of deep discharge cycles have been performed by at least two manufacturers **(4)**. Results showed major improvements in capacity retention and significant reduction in water loss - all without boosting the cells. Catalysts should probably be standard equipment on long-life, cycling VRLA batteries, AGM or Gel.

During discharges from float in standby service, the catalyst reduces gas emissions considerably (see Section **3.5** earlier) and, therefore, gets warmer than usual, but not hot. After recharging on float, the cells appear to behave normally and there have been no unpredictable effects to date.

6.11 What about the environmental issues of disposal of the catalyst?

There are no environmental problems involved because the catalyst material is classified as ***non-hazardous***. In fact, there are no current U.S. regulations preventing the material from being disposed of in landfills. So, if the catalysts were to be accidentally discarded, they would do no harm to the environment.

Another option is disposal in a lead smelter along with the recycled lead from the battery. The tiny amount of Pd would have a negligible effect on the purity of the resulting lead alloys. For example, even in the worst case where the furnace were to be filled with scrap VRLA cells, each having a catalyst, the total amount of Pd in the resulting alloy would still be well below the 0.00001% level acceptable for secondary lead. In practice, the melt will be diluted with other scrap lead so the risk is negligible.

However, by far the best option is *recycling*, so Philadelphia Scientific has established a service whereby the devices may be returned for recycling at no charge to the customer. This is possible because the re-cyclers can reclaim the precious metal in return for their efforts. Accordingly, the catalyst should be removable; for example, as part of a vent plug.

7. Conclusions

AGM cells with superior, corrosion-resistant positive grids will tend to fail by negative discharge after an initial period of drying out.

A proven and elegant modification to the cell design is a catalyst which not only restores the balance inside the cell but also provides many additional benefits. Suitable catalyst devices have been developed that promise to be economical, safe, reliable, and environmentally clean.

8. References

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9. Appendix: Equipment sources

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3. Smart Products Part Number: 302PPV-1.5, Description: 1.5 psi, polypropylene body, viton seal, Tel: 800-338-0404, USA
4. McMaster-Carr Supply Company, Part Number: 1140T11, Description: Combustible gas leak detector (made by TIF Instruments Company) Tel: 732-269-3200, USA