C&D TECHNOLOGIES

Thermal Runaway in VRLA Batteries

-It's Cause and Prevention

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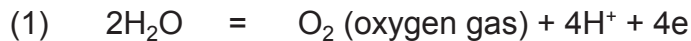## Thermal Runaway in VRLA Batteries

It would be very unusual to experience thermal runaway in a properly applied and maintained valve regulated lead acid (VRLA) battery system. However, thermal runaway and its prevention continues to be a serious concern of those using the VRLA battery in float service applications.

Thermal runaway occurs in a VRLA battery when the rate of internal heat generation exceeds the rate at which the heat can be dissipated into the environment. Should this condition continue for an extended period, the VRLA battery temperature could increase until ultimately the cells will dry-out and the container, if plastic, may soften (100°C), rupture and melt (160°C).
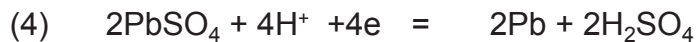
Oxygen Recombination Cycle

During charging of the VRLA battery some heat is generated internally due to charging current flowing through the resistive components of the cells (I_2R). However, the major portion of the internal heating results from the exothermic reaction at the negative plate where the oxygen gas (O_2) from the positive plate reacts with the lead (Pb) and sulfuric acid (H_2SO_4) to form lead sulfate ($PbSO_4$) and water (H_2O) as noted in equations 2 and 3 below. Approximately 90% of the current supplied to the battery during float charging is used to facilitate this oxygen recombination cycle.

Oxygen Gas Generation @ Positive Plate

$$(1) \quad 2H_2O \quad = \quad O_2 \text{ (oxygen gas)} + 4H^+ + 4e$$

Oxygen Gas Recombination @ Negative Plate

$$(2) \quad 2Pb + O_2 \quad = \quad 2PbO$$

$$(3) \quad 2PbO + 2H_2SO_4 \quad = \quad 2PbSO_4 + 2H_2O$$

$$(4) \quad 2PbSO_4 + 4H^+ + 4e \quad = \quad 2Pb + 2H_2SO_4$$

No Net Reaction

This oxygen recombination cycle is negligible in the free liquid electrolyte (VLA, vented lead-acid) cell because the oxygen gas generated at the positive plate is free to percolate up through the electrolyte to the environment rather then being redirected by an AGM separator or gel to diffuse to the negative plate. Consequently the vented liquid electrolyte lead acid cell does not exhibit oxygen recombination thus it emits oxygen and hydrogen at low float voltage, draws less float current and generates less heat than does a VRLA cell.
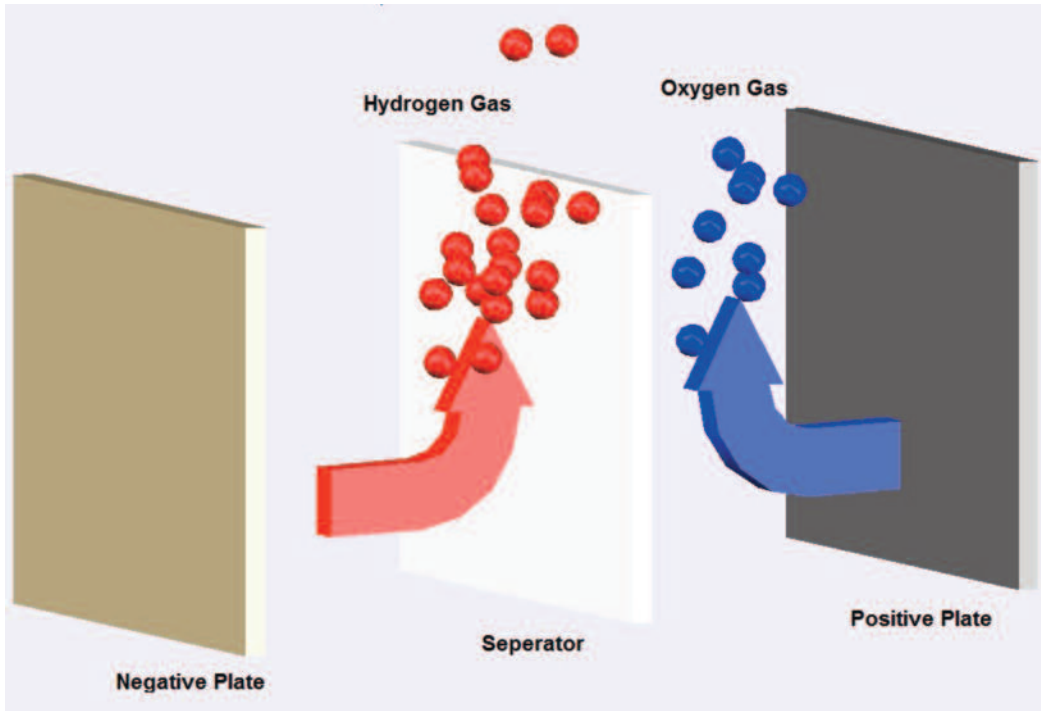
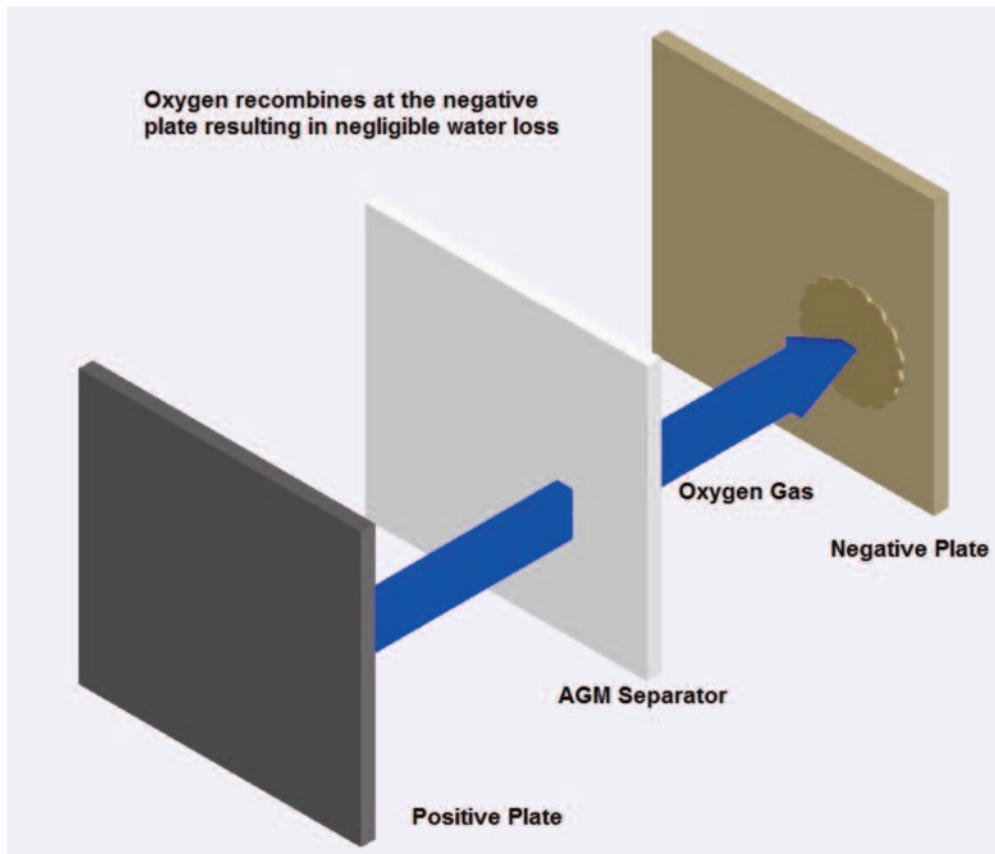Figure 1 - VLA Cell Gas Evolution

Figure 2 - VRLA Cell Oxygen Diffusion

The difference in the float current acceptance of the vented (VLA lead-acid) cell and the gelled and AGM VRLA cell is shown in Figure 3. As would be suspected, the AGM VRLA battery, with the most efficient recombination cycle, has the greatest float current . Consequently, it is also the most susceptible to thermal runaway since it is the more effective heat generator.
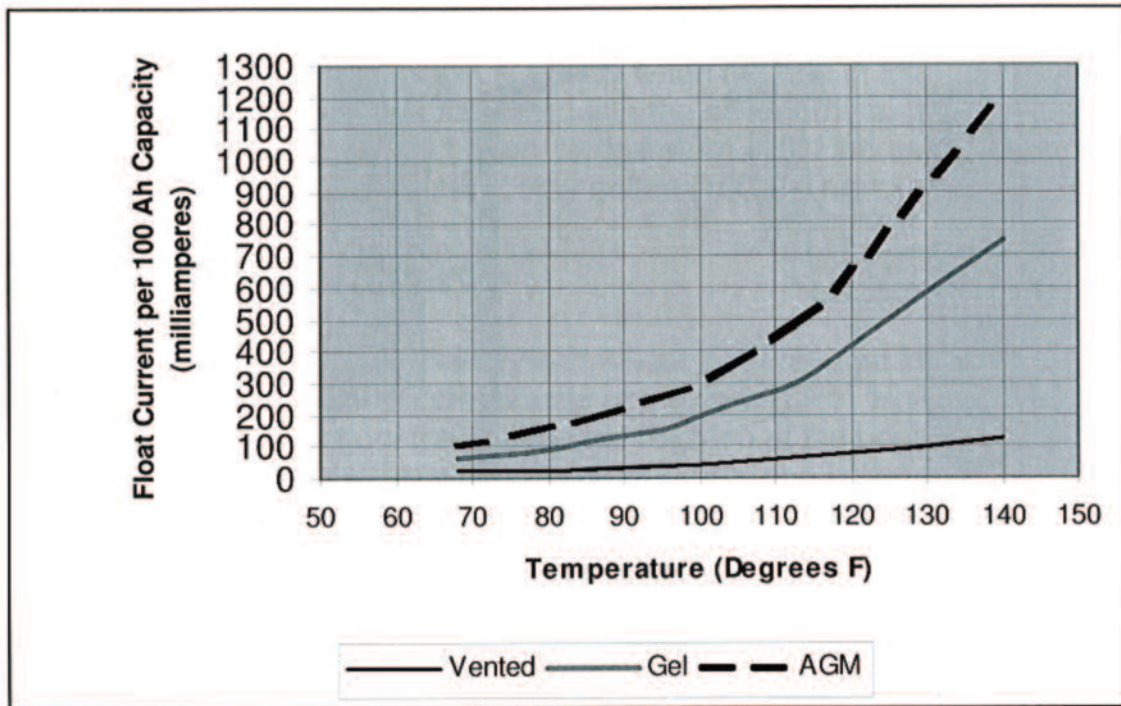

Figure 3 – Float Current vs. Temperature (@2.30 v/c)

Float Current and Temperature

Also note in Figure 3 that at a constant float charging voltage (e.g. 2.30 v/c), the float current will rise with any increase in battery temperature. This increase in current is primarily in response to the increased rate of oxygen generation at the positive plate and resulting increase in the recombination rate at the negative plate. As you would suspect, the increased rate of oxygen recombination will increase the rate of heat generation and result in a further increase of the battery temperature unless the heat can be effectively dissipated.

Float Current and Voltage

The float current is also a function of the float voltage as shown in Figure 4 where the VLA, gelled electrolyte and AGM VRLA battery float currents are compared at 2.25, 2.30 and 2.40 volts per cell. As would be suspected, the higher charging voltage will result in increased oxygen generation at the positive plate and recombination at the negative plate, resulting in increased float current and heat generation within the battery. Again, this increase in float charging voltage and resulting increase in float current will result in an increase of battery temperature <u>unless</u> the heat generated is effectively dissipated.
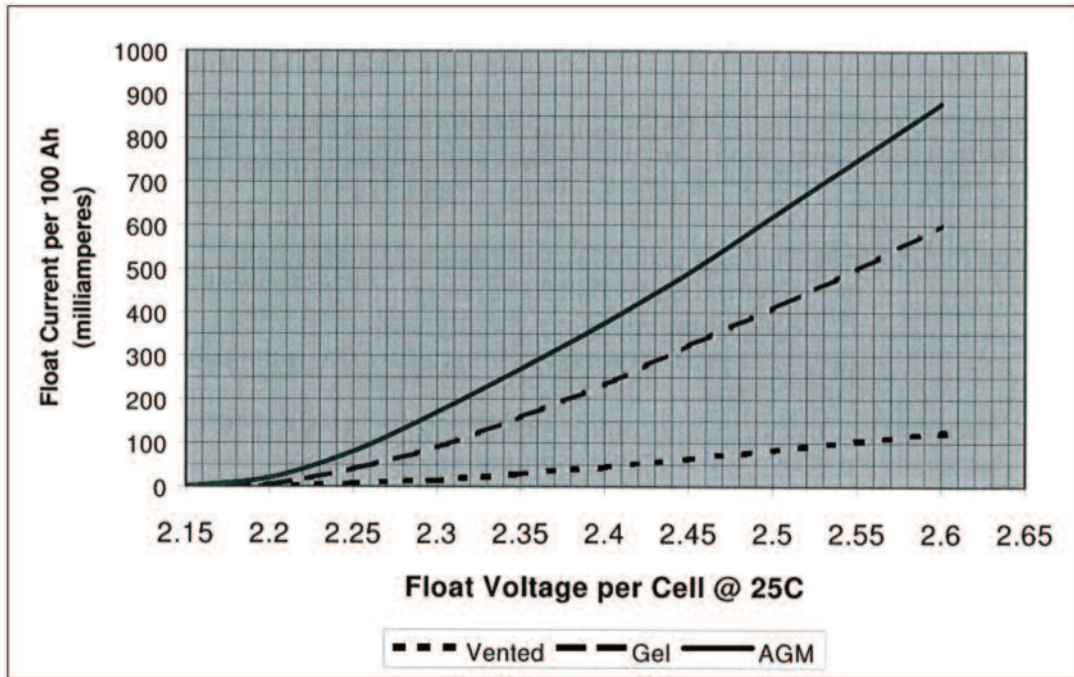
Figure 4 – Float Current vs. Float Voltage

Float Voltage and Gassing

As the float voltage applied to the battery is increased, the oxygen generation rate at the positive plate will increase. At some point between 2.35 and 2.40 volts per cell the oxygen gas generation rate at the positive plate will be greater than the rate at which it can diffuse through the gel and/or AGM separator medium to the negative plate. At this point, as shown in Figure 5, the VRLA battery gassing will increase dramatically and approach that of the VLA liquid electrolyte cell. This gassing will eventually result in dry-out of the electrolyte. As water is lost from the electrolyte it will increase the void space between the positive and negative plate. This increased void space will provide for improved diffusion of oxygen gas to the negative plate and an increase in the recombination efficiency resulting in additional heating.
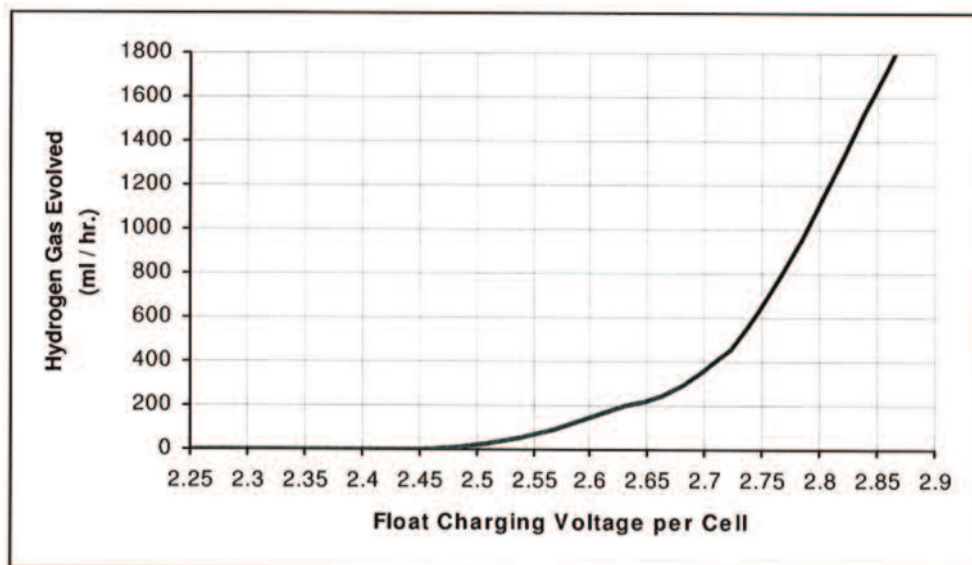

Figure 5 – Hydrogen Gas Evolution Rate vs. Float Voltage/Current

Conditions Conducive to Thermal Runaway

The conditions conducive to thermal runaway are those which either singly or in combination significantly increase the heat generated within the battery or minimize its ability to dissipate the internally generated heat to the environment. These would include:

1. Too high of float charging voltage which results in:
    a. elevated float charging current
    b. accelerated gassing and dryout
    c. increased oxygen recombination rate and resulting heating

2. Too high of recharge current resulting in an increase of 10°C (18°F) in the battery temperature above the ambient temperature.

3. Repetitive high-rate discharge – recharge cycling of the battery resulting in a long-term excessive temperature rise above the ambient temperature.

4. High temperature operating environment which results in:
    a. decreased temperature differential and ability of the battery to dissipate internally generated heat
    b. increased plate grid corrosion rate
    c. increased float current acceptance
    d. accelerated gassing and dryout
    e. increased oxygen recombination rate and heating

5. Improper enclosure design or battery installation resulting in a high temperature operating environment or inability of the battery to dissipate heat via convection and radiant techniques. These items would include:
    a. enclosure located in direct sun
    b. enclosure painted dark color
    c. enclosure lacks adequate ventilation
    d. batteries mounted "side to side" and lacking appropriate spacing which allows for convection airflow and radiant heat dissipation.

6. System or battery failures resulting in the above conditions, such as:
    a. ground faults
    b. shorted cells
    c. charger high voltage (loss of regulation) output
    d. charger excessive AC ripple voltage/current output
    e. loss of enclosure cooling/ventilation capability

Float Charging Voltage @ 25°C (77°F) and Higher

Elevated charging voltage will certainly reduce the recharge time required following discharge however, if applied during the float phase it will force increased oxygen gas generation, increased float current acceptance, gassing and heating. Since water lost cannot be replaced in a VRLA battery, this gassing and resulting water loss will result in reduced capacity and service life. This is in addition to the resulting increased void space between the plates allowing for increased diffusion rate of oxygen to the negative plate; increased efficiency of the oxygen recombination cycle and increased heat generation.

The VRLA battery should be able to withstand an indefinite period of charging at 2.40 volts per cell without entering thermal runaway even though the battery will eventually dry out and prematurely fail for other reasons. However, should the battery be continuously charged at above 2.50 volts per cell, either due to an incorrectly set charger or shorted cells within the string it can be assumed that the battery will eventually enter into a thermal runaway condition.

The charging voltage utilized under normal environmental conditions (77°F/25°C) should be as noted in Table 1 for best performance of the VRLA batteries and avoidance of thermal runaway.

Table 1 - Recommended Charging Voltages at 25ºC

Battery Series	Electrolyte Immobilization Technique	Electrolyte Specific Gravity*	Recommended Average Float Voltage	Recommended Average Cycle Service/ Equalization Voltage
BBG	GEL	1.300	2.25 - 2.30 VPC	2.40 VPC
BBA	AGM	1.300	2.25 - 2.30 VPC	2.40 VPC
DCS	AGM	1.300	2.25 - 2.30 VPC	2.40 - 2.48 VPC
UPS	AGM	1.300	2.25 - 2.30 VPC	2.40 VPC
TEL	AGM	1.300	2.25 - 2.30 VPC	2.40 VPC
VRS	AGM	1.300	2.25 - 2.30 VPC	2.40 VPC
SGC	AGM	1.300	2.25 - 2.30 VPC	2.40 VPC

*Certain models within each series may vary

As shown previously in Figure 3, as the temperature rises the float current will rise (at a fixed voltage) and this increase in float current will eventually be evidenced in the increased emission of gas from the cell as shown in Figure 6. Again, this will lead to accelerated dry-out of the electrolyte, increased void space between the plates and increased oxygen recombination and heating within the cell leading to thermal runaway.
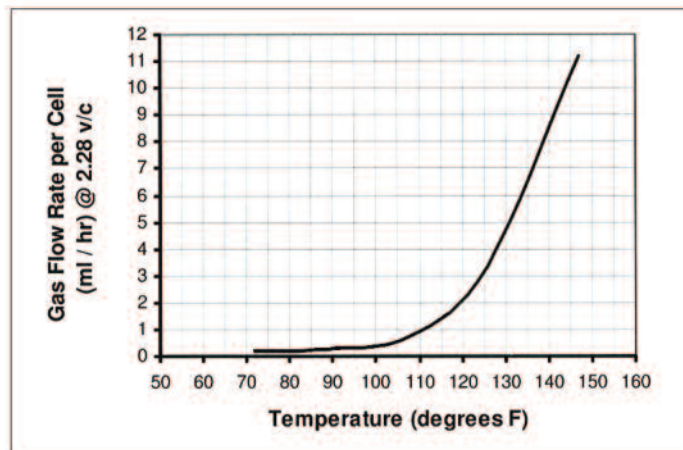

Figure 6 – VRLA Battery Hydrogen Gas Emission Rate vs. Temperature

When it is anticipated that the battery will be subjected to elevated temperatures (greater than 92°F) during continuous float charging, the charging voltage should be reduced so as to minimize the oxygen gas generation, current acceptance, gas emission, heating and potential for thermal runaway of the battery. The temperature compensation factor to be used should be between -0.002v/c per °F and -0.003v/c per °F. Figure 7 illustrates a temperature compensation factor of -0.0028v/c per °F.
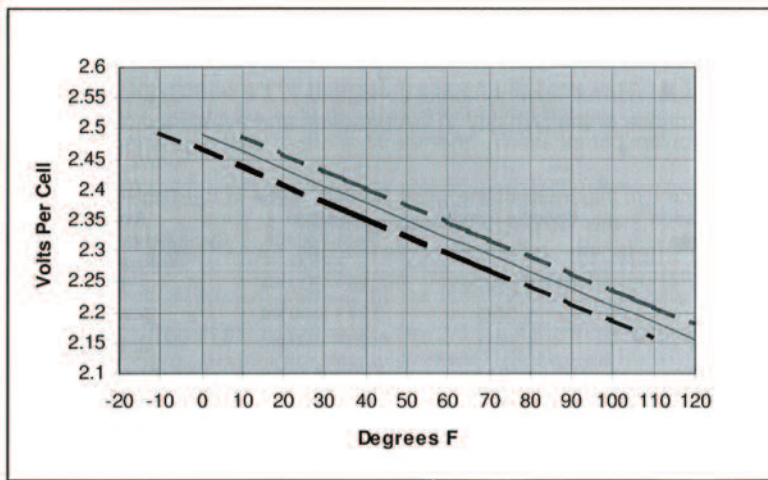
Figure 7 – Recommended Float Voltage vs. Temperature

Unlimited Recharging Current

During recharge of the VRLA battery there is heating due to the I^2R losses in the cell in addition to the normal exothermic oxygen recombination reaction occurring at the negative plate. Since the heating is proportional to the square of the current acceptance, excessive recharging current for an extended period, as with repetitive cycles, will have a pronounced heating affect on the cell. The magnitude and duration of the current accepted by the battery during the bulk phase of the recharge is directly related to the depth of the previous discharge and the current available from the charger. To limit the temperature rise of the battery to less than 10°C during the recharge, the available charging current allowed should be a function of the previous depth of discharge and limited to the maximum values noted in Table 2.

Table 2 Maximum Allowable Recharge Current

Approximate Discharge Rate and Duration	Depth of Previous Discharge (20 Hr. Rate)	Maximum Allowable Recharge Current per 100 Ah Rated Capacity
15 Minutes	45%	100 Amperes
30 Minutes	55%	50 Amperes
60 Minutes	62%	40 Amperes
3 Hours	75%	33 Amperes
5 Hours	81%	25 Amperes
8 Hours	88%	20 Amperes
20 Hours	100%	10 Amperes

High Temperature Operating Environments

Battery float charging in a hot environment is the most common cause of thermal runaway. As shown previously in Figure 3 as the temperature of the battery increases the rate of oxygen recombination and float current acceptance will increase thus causing the battery temperature to further increase – and so the cycle goes. Naturally, when the battery is charged in a "hot" environment it will not be able to efficiently dissipate the heat that is internally generated. Thus it is important to minimize the heat generated through temperature compensation of the charging voltage or removal of the charging voltage when the battery temperature exceeds 122°F (50°C) or is 18°F (10°C) above the ambient temperature.

Situations that lead to high temperature operating environments include:

1. Installation in hot environments such as boiler rooms, foundries, metal enclosures exposed to direct radiation of the sun, etc.
2. Installation in unventilated enclosures
3. Installation of batteries without adequate spacing between the units
4. Installation of batteries above or adjacent to heat producing components

Battery Failures Resulting in Thermal Runaway

A ground fault can induce excessive current and heating in a portion of a battery string and result in thermal runaway. Although there is no free liquid electrolyte to flow from a broken container, should there be a crack in the lower container, capillary action can result in a slight film of conductive electrolyte forming in and about the crack. Should this electrolyte film be in contact with an un-insulated metal component that is common to either polarity of the battery an excessive short circuit current can result. This ground fault current could result in thermal runaway of a portion of the string or even a fire.
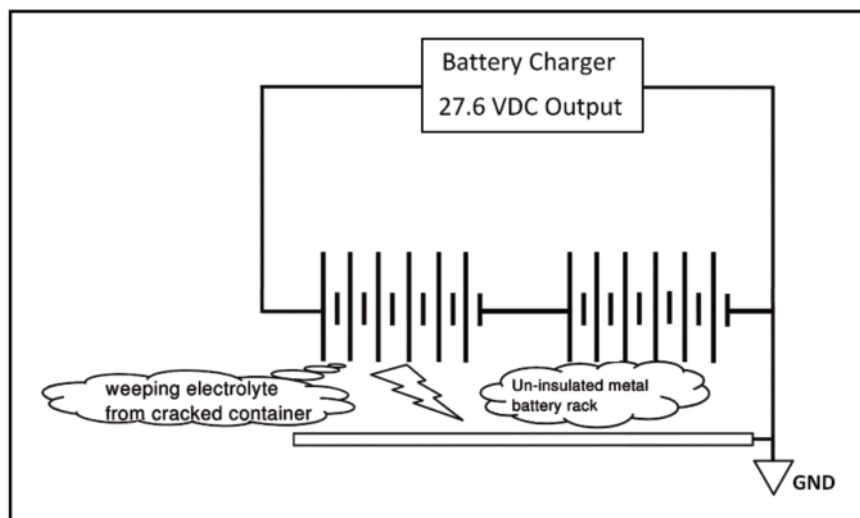

Figure 8 - Battery System Ground Fault

Continuing to charge a string of cells when one or more of the cells exhibit internal shorts, can result in thermal runaway. For example, assume a string of 12 cells is being charged at 27.6 vdc (2.30 v/c) and the string continues in operation with one of the cells shorted. In this situation the average charging voltage on the remaining 11 good cells is 2.5 v/c. While this may not result in <u>immediate</u> thermal runaway, assume that 2 cells were shorted resulting in an average charging voltage of 2.76 v/c on the remaining 10 cells. This will certainly result in very high float current and near term thermal runaway.
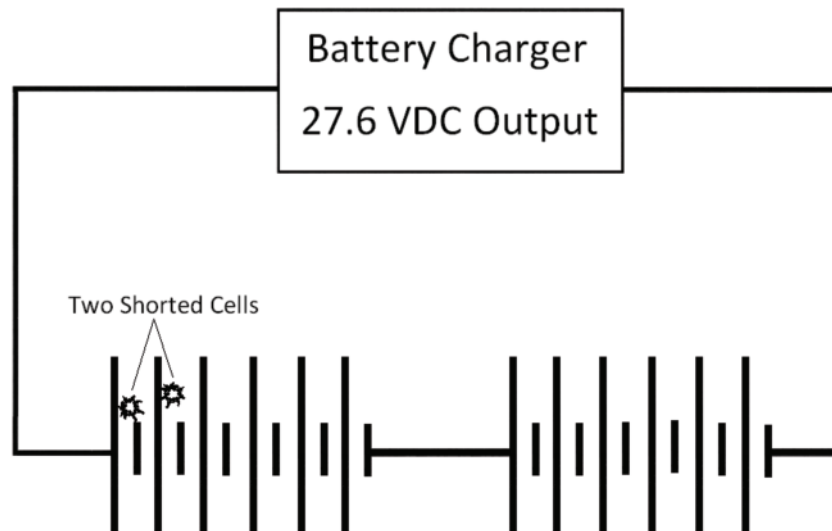
Figure 9 - Shorted Cells Within Battery System

Potential causes of shorted cells include:

1. neglect in the discharged condition
2. long term storage without a freshening charge
3. continuous undercharging resulting in sulfated plates
4. continued operation beyond a reasonable life expectation
5. mechanical damage resulting in a bent plate

System Failures Resulting in Thermal Runaway

The most obvious of system failures that could result in thermal runaway is failure of the charger in the over-voltage condition.

A somewhat less obvious but equally detrimental failure would be that of the output filtering of the battery float charger. Even though the AC ripple voltage output of the charger may be quite low (less than 0.5% rms of the float voltage), the internal resistance of the battery being charged can be extremely low and a significant AC ripple current will flow through the battery. The AC ripple current from the charger could be several amperes and can cause additional heating of the battery in accordance with I^2R.

An AC ripple voltage of only 0.3% rms (0.04 Vrms per 12-volt block) is illustrated in Figure 10. Assuming this was applied to a 100Ah battery with an internal resistance of 0.0025 ohms, it would result in an AC ripple current of 16.2 amperes rms (i = e/r). This is a considerable current and would result in additional heating of the battery equivalent to 0.656 watts/block (I^2Ri or 2.24 BTU per hour (watts x 3.4134 BTU/watt) per 12 volt block.
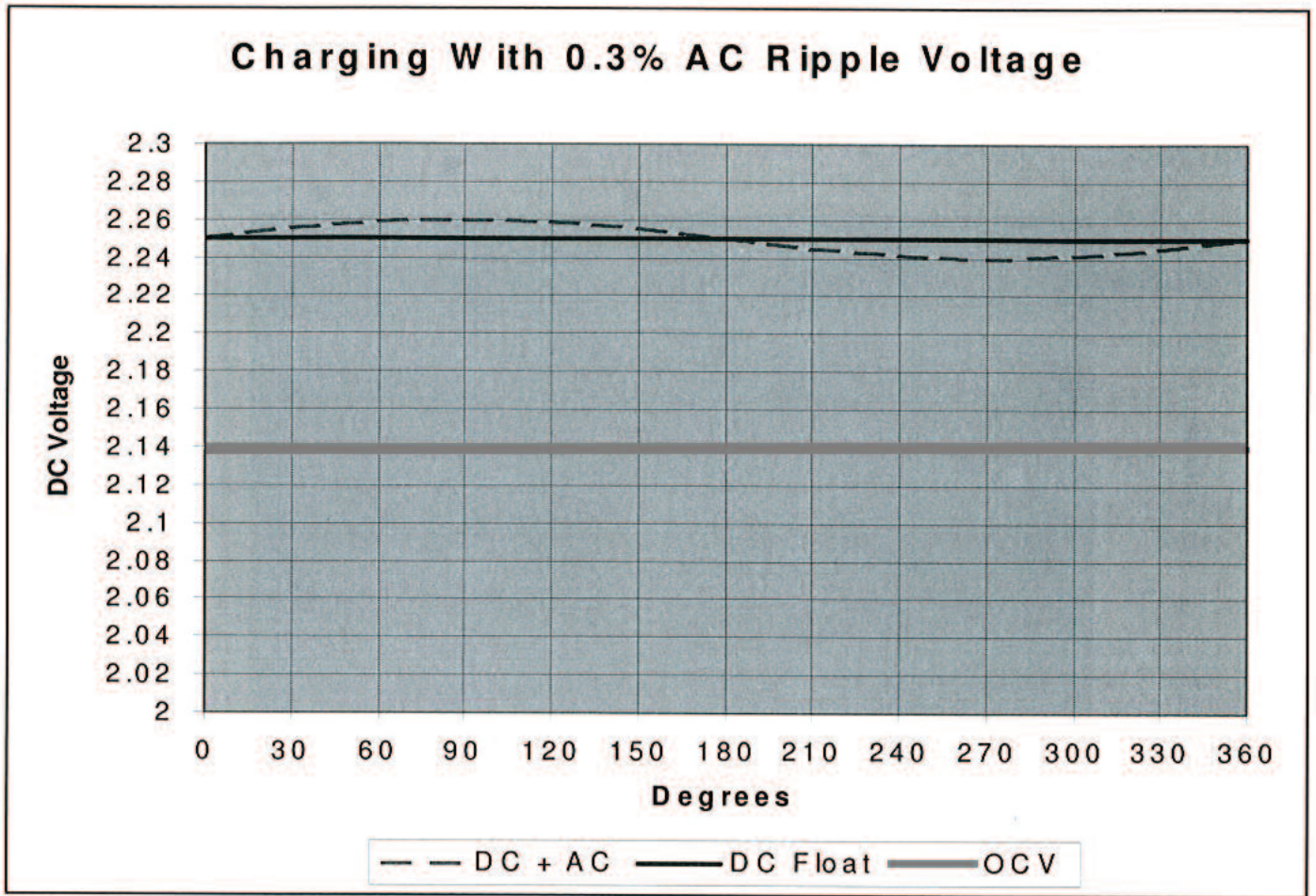
Figure 10 – AC Ripple Voltage

If the AC ripple output voltage of the charger exceeds 4% peak to peak of the float voltage, as shown in Figure 11, this could result in actual cycling of the battery and a resulting additional rapid rise in temperature, DC float current, gassing etc.

To prevent heating of the battery due to AC ripple current, the AC ripple current should be limited to less than 5 amperes rms per 100 Ah of rated battery capacity.
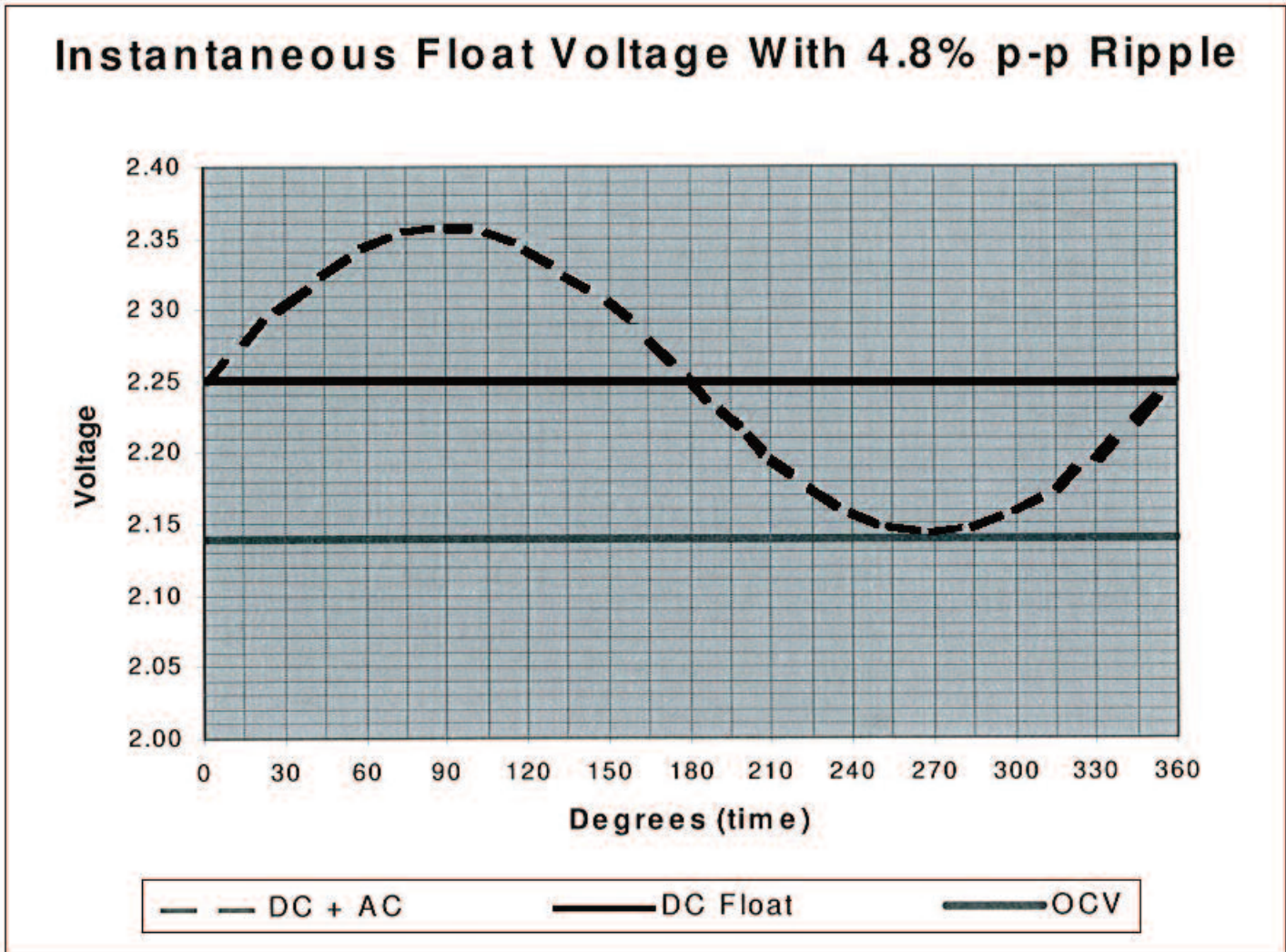
Instantaneous Float Voltage With 4.8% p-p Ripple

Figure with Y-axis labeled "Voltage" ranging from 2.00 to 2.40, X-axis labeled "Degrees (time)" ranging from 0 to 360.

Legend: DC + AC, DC Float, OCV

Figure 11 – Excessive AC Ripple Voltage

Naturally when a mechanical ventilation or cooling system is utilized to maintain an acceptable environment for the battery, any failure or interrupted service of that system can result in elevated operating temperatures and eventual accumulation of an explosive mixture of hydrogen gas with the expected results.

Prevention and Detection of Thermal Runaway

While thermal runaway can be a catastrophic failure of the battery system, proper application and system design, installation and operation can render it a non-issue. A summary of the potential causes of thermal runaway and appropriate preventative measures are noted in Table 3.

Table 3 Prevention and Detection of Thermal Runaway

Potential Cause	Prevention	Detection	Immediate Action
High Float Charging Voltage	Set to manufacturer recommendation for temperature of operation Temperature compensated charging voltage	Charger High Voltage Alarm Battery High Temperature Alarm	Interrupt charger output to battery
High Recharge Current Availability	Reduce charger output capatility or increase battery Ah capacity	Alarm on 10ºC temperature difference between battery and environment	Interrupt charger output to battery
High Temperature Operating Environment	Install in Cool area Install with 0.5" Spacing Install in ventilated space (natural or mechanical) Temperature compensated charging voltage Reflective paint and situate enclosure to avoid radiant heat sources Install active of passive cooling system	Battery High Temperature Alarm Enclosure High Temperature Alarm	Interrupt charger output to battery
Ground Faults	Observe battery containers for damage during installation	Ground Fault Detector/Monitor Float Current Monitor	Interrupt charger output to battery
Shorted Cells	Maintain "fresh" inventory Recharge within 24 hours of discharge Charge @ recommended voltage Perform recommended PM Perform periodic capacity test	OCV greater than 2.08 VPC Manual or automatic monitoring Less than 80% rated Ah capacity	Apply freshening charge Set charger output voltage to recommended value for operating temperature Replace battery
Charger excessive AC ripple voltage/current	Increase charger output filtering	Manual or automatic monitoring Battery temperature 10ºC above ambient	Replace charger output filters Interrupt charger output to battery

Should severe thermal runaway occur, it will be evidenced by permanent container distortion due to the heat and eventual emission of trace amounts of hydrogen sulfide gas (rotten egg odor) as the electrolyte is completely gassed off. Should this situation be encountered, the charging voltage to the battery should be immediately removed to stop the thermal runaway reactions and the area should be ventilated. When thermal runaway has occurred, the damage to the battery is permanent and it must be replaced.

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