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Short Communication

SAFETY ASSESSMENT OF FLAME-ARRESTING BATTERY PLUGS

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Summary

Hydrogen and oxygen produced by electrolysis during the charging of lead-acid batteries must be vented from the battery case. The accidental ignition of these gases can produce a flame which propagates back into the battery case causing an explosion. To minimise this risk, various flame-arresting vent plug designs have been marketed. To assess the performance of these, appropriate test equipment and procedures have been developed and are described in this paper. The concept of a danger zone to characterise the volume above the vent where the charge gases can be ignited is introduced. Typical results for the danger zone above an isolated hole are given.

1. Introduction

During battery charging, hydrogen and oxygen are liberated and must be vented through battery plugs to avoid a build up of pressure. Because hydrogen is inflammable, the gas flow is a safety hazard. An ignition source such as a loose contact spark can ignite the gas and air mixture outside the battery and produce a flame front which propagates back inside the battery causing a dangerous explosion.

In recent years, battery manufacturers have paid increasing attention to minimising this explosion hazard. Progress has been restricted largely to the efforts of individual companies developing explosion resistant vent plugs (a typical plug is shown in Fig. 1 of Ref. [1]*) and, to date, there is no satisfactory standard method of assessing how effective such plugs are. In the USA there is no legal stipulation of minimum performance requirements and similarly, no appropriate British Standard. Perhaps the most widely accepted test specification in current use is that formulated by the Battery Council International (BCI) [2], although the prescribed test conditions and the method of assessment are open to interpretation.

As part of a wider investigation into vent plug performance, the authors have developed tests which remedy some of the shortcomings. The considerations which led to the form of testing adopted, and the test rig and procedure, are described in this paper with a view to providing a basis for a satisfactory standard.

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*See p. 300 of this issue.

TABLE 1

Process leading to battery explosion and parameters involved

Process leading to battery explosion	Parameters involved	Required data	Remarks
↓ Spark	Gap, duration, energy.	Measure of energy in spark arising from breaking a battery contact.	'Standard' spark will have sufficient energy for kernel to propagate if conditions are right.
↓	Position of spark in relation to issuing gases.	Range of positions which form the "danger zone".	H_2—O_2 ratio will vary spatially and there could be areas where ratio is outside flammability limits.
	Mixture composition.	Variation with battery condition and rate of charge.	
	Pressure (atmospheric).	Depends on geographic latitude and altitude.	Pressure is not a strong parameter and could be assumed standard.
Ignition	Temperature range.		Temperature range difficult to simulate especially low temperatures.
↓	Moisture content.	Assume saturated.	
	Mixing with surrounding air.	Ignition limits for various mixtures from literature.	Spray entrainment may have an effect.
	Flame speed; laminar, turbulent.	Laminar and turbulent flame speeds in various mixtures from literature.	If ignition occurs the flame will normally propagate to the flame arrester as flame speed for H_2 is much higher than jet velocity. Also diffusion is fast in H_2 i.e. fast mixing rate.
Flame propagation	Issuing jet velocity.	Rate of flow of gases, effective cross-sectional area of plug.	
↓	Quenching, mixture, turbulence, distance, temp. & pressure.	Calculation of quenching distance for different operating conditions — literature.	Quenching distance or diameter may depend on material texture.
Flame travel through arrester ↓	Type of arrester, material, pore size, thickness, doping and clogging with acid.	Material data, effect of clogging, pressure drop across arrester.	Also materials are not uniform. Hence there is likely to be some risk of the flame passing through. Clogging of arrester reduces diameter but could also change chain breaking characteristics.
Explosion			

2. Factors which influence plug performance

A preliminary literature survey [3] revealed a lack of relevant fundamental data, and so our initial step towards prescribing a suitable test was to attempt a synthesis of factors which might influence performance. In this context, performance can be thought of as a measure of the plug's ability to minimise the risk of a battery explosion. Table 1 illustrates the process leading to such an explosion initiated by a spark. It is obviously complex in nature but, for performance testing, there is no need to study the mechanisms involved in detail.

Factors which influence performance can be associated with events above or below the vent plug for convenience. The initiation of an explosion occurs in the mixing region above the plug. It is influenced by the mixing process, the position of the spark, spark gap and duration, and ambient conditions. Events below the plug (within the battery case) determine the total flow rate of the charge gases, the proportion of hydrogen to oxygen being vented, and the proportion of gas to battery acid being carried into the vent plug.

A particularly important point drawn from this examination is that the venting arrangement — the number of vent holes in the top of a plug, their inclination to the plug axis, etc. — contributes to performance as defined earlier. This aspect has not been considered in earlier test specifications, although its importance can be gauged by the introduction of a danger-zone concept. By definition, the danger zone is the finite volume above the plug within which ignition of the mixing gases is possible. The zone boundary corresponds to the contour for a 4% by volume hydrogen concentration, since this is the flammability limit for hydrogen in oxygen and air. Clearly, the probability of an explosion being initiated by a spark near the plug depends on the extent and shape of the danger zone.

3. Test requirements

The ideal specification would test plug performance under the most adverse combination of conditions which could be encountered. However, such a specification would by necessity vary according to applications for specific plug designs. To provide a universal standard, it is more important that the specification ensures that consistent test conditions and procedure are maintained. To this end, the authors adopted the strategy of mounting plugs in a test box whereby the gas flow rates through the plug could be controlled in volume and proportion. This is not the case for plugs mounted in batteries. In this way, below-plug conditions are reproducible.

Above the plug, the principal variables were judged to be spark energy, duration and position. As a standard, the energy and duration of the spark have been chosen to correspond to values typical of loose contact sparks, namely 0.5 Joules and 500 μsec, respectively. These values were determined by experiment [4]. The precise control of spark energy is not critical since the minimum ignition energy for the mixing gases is many orders of magnitude smaller.

In addition to testing a plug's ability to prevent the propagation of a flame front into the battery, an overall performance assessment requires information on the extent of the danger zone. For this purpose, it is necessary to locate points around the plug where standard sparks cause ignition of the gases. In general, it may be sufficient to determine only the height and radial extent of the zone using simple traverse arrangements. The rig described here, however, utilises a comparatively sophisticated system which can be used to resolve the zone boundary in detail.

4. Test specification

The preceding considerations indicate that safety assessments should encompass two types of test. The first is to provide data on the extent of the danger zone, and the second to determine whether a plug will stop a flame propagating inside the battery. The latter requirement involves the quenching of flames incident on the plug and also the prevention of a flame from stabilising on the vent hole, for this would soon lead to failure of the flame arrester through overheating.

The mechanism of flame arresting and flame stabilisation can depend upon the gas flow rate [5], so it is necessary to test performance for the range of gas flow rates encountered in practice.

The nominal flow rates of hydrogen and oxygen from a single fully charged lead-acid battery cell are 7.0 and 3.5 cm^3/min amp respectively. For the specification, tests for a range of flow rates are required to provide a plug rating: The BCI [2] recommend charging rates of up to 40 amps corresponding to flow rates of up to 279 cm^3/min H_2, 139 cm^3/min O_2. It is also instructive, though not necessary, to extend the tests to higher flow rates to establish the actual value when the plug fails, either by causing an explosion or, more likely, by allowing a flame to stabilise on the plug. The suggested test procedure is described later.

The height and width of the danger zone depend on gas flow rate and are greatest when this is a maximum. It is best, therefore, to specify the zone height and maximum radius corresponding to the 40 amp charge-current condition as a standard.

Preconditioning of the vent plug to service condition is important. The difference in performance of wet and dry arrester discs is substantial [6]. To condition the plug it is sufficient to run it in a battery at 10 amp overcharge for 3 hours. The amount of trapped acid was found to stabilise in this time at this charge rate. The number of specimens to be tested is another consideration. This will obviously depend on the manufacturing tolerances and the stage of development of the prototype. For a prototype approaching the production stage, experience shows that twenty randomly chosen plugs constitute a statistically representative sample.

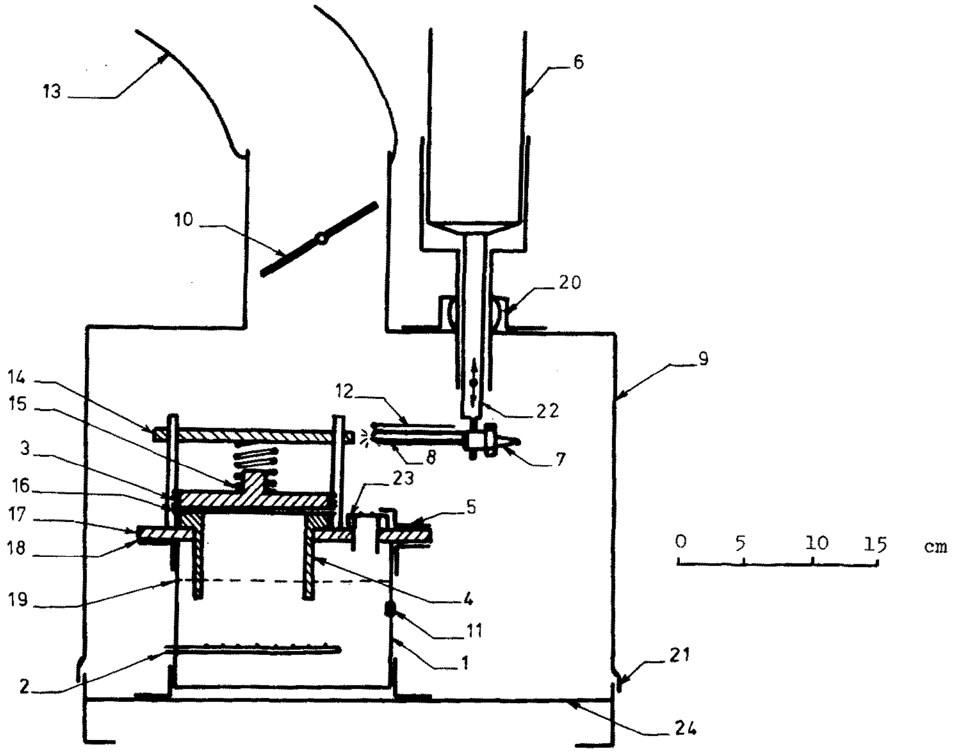

Fig. 1. Schematic diagram of ignition test rig. 1. Battery box. 2. Perforated tube for gas inlet. 3. Pressure relief plate. 4. Water sealing pipe. 5. Plug clamp. 6. Vertical Actuator. 7. Spark plug. 8. Long electrode. 9. Housing. 10. Butterfly valve. 11. Pressure transducer. 12. Thermocouple. 13. Hose to exhaust ventilator. 14. Retainer plate. 15. Spring. 16. Rubber gasket. 17. Top plate. 18. Rubber gasket. 19. Water level. 20. Ball and Socket bearing. 21. Air intake Louver. 22. Plunger (movement out of the plane of the paper is achieved by a horizontal actuator). 23. Vent plug. 24. Splash tray.

5. Apparatus

Figure 1 shows a schematic diagram of the test rig. A more detailed description is given in Ref. [7]. The rig is composed of a battery simulation box (1) with perforated tubes (2) to admit the component gases. To reduce the volume of the gas mixture the box is nearly filled with water. The box is equipped with a pressure relief valve (3) made of a spring-loaded plate. A pipe (4) is screwed to the top plate of the box so that it is dipped in water to form a water seal which isolates the gas mixture from the pressure relief plate. A clamp (5) is provided on the top of the box to hold actual vent plugs or experimental vent plugs. A vertical feedback linear actuator (6) is used to carry a spark plug (7) with long electrodes (8) to reach the vent holes. Another horizontal actuator (not shown) is used to allow the spark to be moved in a vertical plane that dissects the vent holes.

The spark ignition source produces a 0.5 J, 500 μsec spark from a capacitor and high voltage coil circuit described in Ref. [4]. The spark gap needs to be larger than the quenching distance which is about 0.28 mm, and so a gap of 1 mm was adopted.

A housing (9) is provided for safety, and to minimise air draughts around the gas jet issuing from the vent holes. Ventilation of the region above the test box is controlled by the butterfly valve (10). Air is drawn by an extractor fan downstream of the valve through louvres (21) in the base of the housing (9). Immediately before a test, the butterfly valve is closed by a solenoid to stop the ventilation and ensure quiescent conditions for the test.

Internal explosions resulting from the flame propagating through the vent plug are easily detected by ear. However a pressure transducer (11) is also

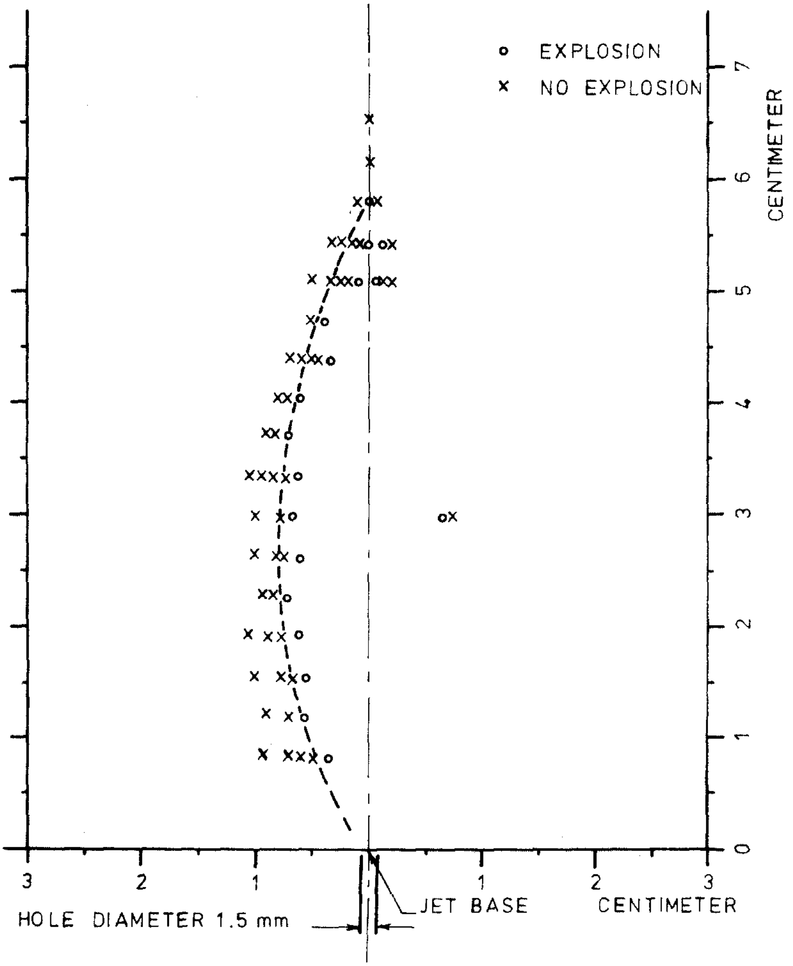

Fig. 2. Experimental plot of the danger zone for a jet of charge gases.

provided which, together with a storage scope, can be used as an additonal detector. The thermocouple (12) is used to detect flames stabilising above the vent plug. The rig is remotely controlled to ensure the safety of the operator.

6. Procedure

With the test plug or plate in position above the battery box, the position of the spark plug is set via the actuators. The flow rate of the charge gases is regulated as the gases are admitted to the battery box. Once it is established that the gases had occupied the empty space above the water level the butterfly valve is closed. An interval of thirty seconds is allowed for air currents to subside, and then a spark is produced. Internal explosions are easily detected by the loud noise, splash of water, and when a pressure transducer is used, by the pressure pulse shown on the scope which is triggered by the change of pressure. A stable flame is detected by the increase of temperature of the thermocouple. If no event is detected then another spark is applied.

In order to determine the extent of the danger zone, the flame-arresting disc is removed and sparks are produced at various positions above the vent hole. The danger zone is then the volume enclosing all the spark positions which result in an internal explosion. Typical results are shown in Fig. 2.

To determine the performance of a plug as a flame arrester, with the arresting disc in position, the test procedure is the same. The spark plug is positioned within the danger zone close to the vent hole. A total of ten sparks is used to complete one test. Specimens which fail to stand up to ten sparks by either establishing a stable flame or producing an internal explosion are disqualified and the test is stopped immediately after a failure event.

7. Discussion

Considerable experience in using the test rig and procedure has been gained without any apparent shortcomings. The principal difficulties that we anticipated were in detecting when an internal explosion occurred, or when a flame stabilised on top of the test plug. However, internal explosions were clearly audible and auxiliary instrumentation, such as pressure transducers within the test box, proved superfluous. Stabilised flames on the top of plugs were easily detected by the thermocouple placed above the plug, as described earlier.

The choice of 10 as the number of sparks for a test is a judicious one. It is more than the BCI specification of 6, and is not so large as to lead to deterioration of the plug through overheating and to premature failure later in the test.

The detection of a stabilised flame should be recorded as a plug failure, since permanent damage occurs and an internal explosion will eventually result.

The BCI specification does not require controlled spark generation. It is considered that the use of a specified spark generator is important with regard to detecting whether a spark has occurred and to ensure that the spark has sufficient energy to cause gas ignition.

The most obvious advantage of testing the plugs in a test box is that gas flow rates through the plug are monitored and can be adjusted to standard values. Thus inconsistencies between plug ratings can be avoided. In addition, the test box allows internal explosions to be used as an indicator when studying the form of the danger zone above the plug. The removal of the disc for the danger zone tests will not affect the size of the danger zone, which is determined by the size of the vent hole in the cover above the flame arresting disc, and the flow rate which is kept the same.

The authors believe that information on the danger zone should be determined as part of a performance rating. This information can be presented conveniently by specifying the radius and height of a cylinder enclosing the zone, as illustrated in Fig. 3 for a laminar jet issuing through an isolated hole.

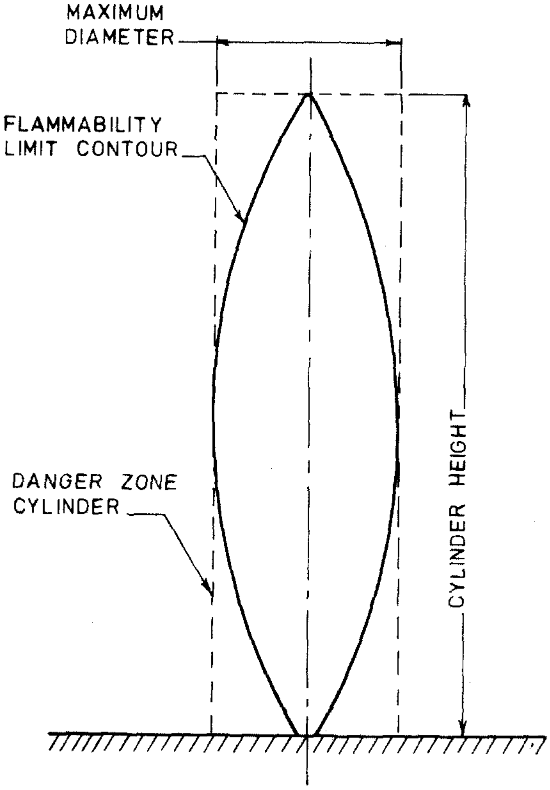

Fig. 3. Danger zone cylinder.

8. Conclusion

The principal features of the test specification which has been developed are:

(1) The introduction of the danger-zone concept to characterise a plug's susceptibility to the spark ignition of charge gases.

(2) The specification of a controlled spark generator and a standard spark of 0.5 Joules lasting 500 μsec.

(3) The use of a test box in which to mount the vent plugs, to ensure controlled gas flow conditions.

(4) The use of a thermocouple to detect stabilised-flame vent plug failures.

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