AREA CLASSIFICATION METHODOLOGY FOR HYDROGEN-COOLED ALTERNATORS IN POWER STATIONS

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Power stations using hydrogen-cooling for large alternators clearly fall within the requirements of DSEAR and need a suitable area classification exercise to be undertaken to determine the zones within the turbine hall. The existing codes and standards which are readily available consider either outdoor situations, or those inside well-ventilated comparatively small buildings. In turbine halls approaching 500,000 m^3, adequate ventilation is impractical to attain and, being enclosed buildings, it would suggest that they should not be classified as outdoors. However if the zone volume is small compared to the building volume, it effectively disperses as if it were outdoors. Hence, there is a difficulty in that the rigorous application of the existing codes requires that the entire building is classified as a hazardous area which is clearly not sensible for buoyant hydrogen gas. A methodology has been designed specifically for the potential releases of hydrogen from alternators, based on the naturally occurring ventilation within the turbine hall and computational fluid dynamics zoning, coupled to historical release rates and failure data particular to the electricity generating industry.

INTRODUCTION

The Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) have been introduced recently in the UK to implement the European ATEX Directives covering personnel safety in explosive and flammable atmospheres (Explosive Atmospheres Directive 99/92/EC and Chemical Agents Directive 98/24/EC). DSEAR requires that all potentially explosive atmospheres be identified and then assessed using the existing concept of hazardous area classification, whilst taking into account all potential ignition sources (mechanical and electrical, including those that are part of the process). Depending upon the likelihood of a flammable atmosphere occurring in the workplace, the workplace must then be appropriately classified into zones. The coolant used for the generators is hydrogen which has wide flammable limits in air of 4% v/v to 75% v/v, according to Coward and Jones (1952). Hence there is a potential to form flammable atmospheres with the air should the hydrogen leak out.

The assessment should be risk-based and hence any particularly severe consequences or potential high frequency of release are relevant in requiring higher level controls than might be obtained by simply following standards on area classification. Conversely, very low potential consequences may allow relaxation of the required controls. The methodology developed is specifically targeted at hydrogen cooling systems for large power station generators in turbine halls, and is to be used for that purpose only, as it is not intended as a guide to area classification for any other system or any gas other than hydrogen. Turbine halls can approach 500,000 m^3 in volume, and contain up to four generating sets, each typically generating 350–700 MW. At this size of building, the ventilation rate is relatively low, yet inspection of the building seen in Figure 1 shows that it is clearly has large open spaces inside, thus appearing to be "outside" in terms of the congestion and freedom for the air to circulate inside.

EXISTING STANDARDS

There are two UK-based codes which are generally recognised to be adequate for the purposes of Area Classification. These codes are essentially for the chemical and oil industries which handle large quantities of flammable gases, liquids and vapours. The first was originally developed from an ICI methodology, and is recognised as the European Standard BS EN 60079-10:2003 *Electrical apparatus for explosive gas atmospheres – Part 10: Classification of hazardous areas*, BSI (2003), colloquially referred to as "EN 60079". This is the normal "base case" code for general use and will result in an acceptably safe Area Classification. The second code is one developed primarily for the petroleum industry, *Area*

Figure 1. Typical turbine hall, showing two of the four generator sets

Classification Code for Petroleum Installations: Part 15 of the Institute of Petroleum Model Code of Safe Practice in the Petroleum Industry, Second edition 2002, Institute of Petroleum (2002), colloquially referred to as "IP 15".

There are significant differences in the way that these two codes handle hydrogen. EN 60079 simply states that the density of the gas or vapour released will alter the horizontal and vertical extents of the zone, with decreasing relative density reducing the horizontal extent and increasing the vertical extent. There is no guidance on exactly how far the zones will be extended or reduced. Similarly, there is no data given for the typical rates of release which would be expected, nor is any recognition given to the momentum of the release or the direction of the release. Hence application of the code in a rigorous way will result in unrealistically large zones, particularly in an indoor situation.

In contrast, IP 15 takes into account the momentum and direction of the release, rather than taking the buoyancy directly into account. This is based on the assumption that any gas, either denser than air or lighter than air, will entrain air as it leaks out as a jet, and the gas will be diluted rapidly. IP 15 gives tables of release rates for various assumed leak sizes, and gives some guidance as to the sort of leak rate that can be expected for various items of equipment. Cox et al. (1990) also give guidance on hole sizes and zones for hydrogen leakage. However, a majority of the items are typical of petroleum refineries and chemical works rather than power station equipment. It also devotes an Annex to hydrogen, as it is recognised that hydrogen is a special case, but the IP 15 approach is one based more on large hydrogenation units in the petroleum industry, which use hydrogen at much greater pressures, temperatures and inventories than used those on generator cooling systems. Because of this there is a tendency for the zones to be unrealistically large and release rates unduly pessimistic. Previous work by Gant and Ivings (2005) on leakage of natural gas at low pressure concludes that zones defined by the existing standards are unrealistically large.

Hence from the foregoing, it can be seen that the rigorous application of the existing standards would not only show significant differences to the zones between the two standards, but would also be likely to result in zoning of a majority of the turbine hall as hazardous. Also, as the codes were developed for the chemical and oil industries, there is little consideration of the effects of vibration on failures of pipe-work, so this needs to be considered. Consequently, it is necessary to take a balanced view of the available codes and existing ventilation available, and determine the appropriate zones from this.

HYDROGEN INSTALLATION

There are three parts to a typical hydrogen installation - the outdoor high pressure storage area; a low pressure 8 bar distribution system within the turbine hall; and a 4 bar re-circulation, cooling and drying system for each generator.

STORAGE

The storage area is located outdoors in a well-ventilated area, surrounded by a wire fence. This allows good natural ventilation, and since the area is surrounded by open land and roads, there will be little impediment to good free air flow around the area. The standard codes for area classification will be adequate for this installation, and there are no contentious issues such as accumulation of hydrogen in the event of a leak. There is generally a small roofed area covering the control panel and valve manifold, but this has a sloping roof and no walls, other than the backboard on which instruments are mounted. Hence any leaks will rapidly disperse. The storage pressure is a maximum of 130–250 bar, and is reduced locally to 8 bar for onward distribution to the turbine hall.

LOW PRESSURE DISTRIBUTION

This consists of piping carrying the hydrogen at 8 bar within the turbine hall. The piping is essentially of welded construction, with flanged valves at the take-off points. Much of this piping is within the turbine hall, and therefore cannot be classified by default as being outdoors. This is the part of the installation which requires a suitable methodology to determine the extent of the hazardous area zones.

GENERATOR COOLING SYSTEM

This consists of larger pipework feeding the generator itself, coolers, and the dryer, which operates by switching the gas stream through a desiccant bed whilst the other bed is regenerating. This operates at 4 bar and requires a suitable methodology to determine the extent of the hazardous area zones.

POTENTIAL LEAK POINTS

Where hydrogen may escape from the system, there are two consequences which need to be considered. Firstly, if the hydrogen ignites immediately, the escaping gas will form a jet fire, and the consequences will depend on both the pressure and the size of the leak. Secondly, where the hydrogen does not ignite immediately, it will rise and can accumulate within the turbine hall. If the accumulated hydrogen subsequently ignites, then an explosion may result, and the consequences will depend upon the quantity that has accumulated prior to ignition.

There are three classes of potential leak points which should be considered.

- Permanently made joints
- Dismountable joints
- Rotary seals

Permanently made joints will be regarded as secondary grades of release under normal operation. These will give rise to a zone 2 area as defined in EN 67009. However, if they are located in an area where they may be prone to accidental damage or they are in a location where vibration may occur, then the quantity that may be released could become significant, and the frequency of such a release could increase.

Dismountable joints are expected to be made and broken periodically to facilitate purging of the generator prior to an outage and recharging with hydrogen afterwards.

These are located on the supply to each generator for physical disconnects to isolate the hydrogen supply, and on the vacuum pump when this is connected to evacuate the hydrogen from the generator prior to maintenance. These joints are at high risk of leakage, and therefore undergo a leak test procedure on return to service following reassembly. They are regarded here as a primary source of release. Also in this category are the change-over valves on the hydrogen dryers. As these valves operate regularly, the stem seals are likely to wear more rapidly and so are more likely to leak than valves which are seldom operated. The adoption of these as primary sources has an effect on the value of k to be assumed, and requires a zone 1 around the potential leak point and a surrounding zone 2.

The rotary seals on the generator shafts are liable to leak hydrogen. As there are slip-rings in the immediate vicinity of the seal, unless the leakage is diluted rapidly, there is a risk of ignition. Whilst failure is not frequent, there is previous history of leakage of the seals. The seals will have to be considered as a primary source of release based on the potentially severe consequences of a catastrophic failure, rather than a secondary source of release based on the very low frequency of failure determined from operational history. Under normal conditions, the seals do not release gas - there is a continuous oil film which prevents hydrogen escaping. However, the hydrogen tends to dissolve in the oil, and has to be removed from the oil before the oil is returned to the main oil tank which is located externally to the turbine hall.

Overall, hydrogen loss during normal operation is inevitable, as it is such a searching gas which escapes easily. The overall continuous leakage rate of hydrogen can be estimated from the consumption of hydrogen for all the generators in a turbine hall. Typical total hydrogen consumption figures provided by RWEnpower were about 2.5 kg hr^{-1} for a four-turbine power station.

HIGH RISK PARTS OF THE SYSTEM

The sealing system has the potential for major loss of hydrogen to occur. Firstly, failure of the seal may release hydrogen directly into the turbine hall at the ends of the generator. Looking at the operational history of a total of 84 similar generating sets over the last 20 years grossing about 15 million hours, there have been only 16 recorded incidents involving hydrogen. Of these, four involved seals, so clearly there is the potential for the seal to be a common failure mode. Hence it was appropriate to scrutinise the seal system in general in greater depth than the pipe work, and determine potential failure rates and release rates.

NATURAL VENTILATION

There is a method of estimating the natural ventilation of a building given in a British Standard, BSI (1991). This suggests three modes of ventilation and methods of calculating ventilation rates. The methods are wind only; temperature difference only; and wind and temperature difference combined. In the case of a very large building with small ventilation openings but a reasonable temperature difference between outside and inside, the temperature difference only method would be the most appropriate, as this would give a conservative ventilation rate independent of the wind velocity. When considering the dispersion of hydrogen by natural ventilation, it will be necessary to have vents positioned directly above the point where hydrogen releases are likely. Hence the appropriate position of roof vents would be above each generator. As make-up air has to be admitted to replace that vented from the roof, low-level vents would be required. These should be permanently open, but their location is not particularly critical providing that they are as low as possible. Computational Fluid Dynamics (CFD) simulation by Swain and Swain (1992) of natural ventilation of hydrogen leaks in a domestic environment shows that the position and size of the upper vents has a more profound effect than those at lower level. However, it is essential to provide some vents at low level, otherwise the desired ventilation rates will not be achieved. The provision of low level vents will also allow the thermal effects to be felt at levels below that of the generator mezzanine level (7.6 m above floor level), so that the hydrogen dryers, which are mounted at floor level, will also be well-ventilated. This is because the air rising from the generators has to be replaced, and providing the colder air enters at ground level, it will eventually rise past the generators, be heated, and be replaced with cold air from outside, whereas vents at the mezzanine level would allow a pool of cold dense air to remain below the heat source.

Once the natural ventilation rate has been determined, it can be compared to the equivalent of an outdoor site, where the ventilation rate would be acceptable with a wind speed of 0.5 m s^{-1}. For a turbine hall 62 m wide, 220 m long and 40 m high, the volume is 545600 m^3. Since the natural ventilation will tend to result in a net upward flow of air, it would appear sensible that the horizontal cross-sectional area should be considered, rather than an arbitrary vertical cross-section with a horizontal air movement. At a wind speed equivalent to a linear velocity of 0.5 m s^{-1} over the horizontal cross-section of $62 \times 220 = 13640$ m^2, the volumetric flow required equates to $0.5 \times 13640 = 6820$ m^3 s^{-1}, or a ventilation rate of $6820 \times 3600/545600 = 45$ changes per hour to equate to "outdoors" in EN 650079. This would not be achievable easily. Since there are roof vents above each generator, taking the vertical air flow would be unduly pessimistic, and a more realistic approach might be to take the horizontal air flow, since the building is very large compared to a typical indoor situation of 1000 m^3 considered by IP 15. This would equate to a volumetric flow of $62 \times 40 \times 0.5 = 1240$ m^3 s^{-1} or 8.18 air changes per hour. This too would be difficult to achieve. However, as the building is large and the size of any flammable cloud from potential leaks is relatively small, it is still reasonable to consider that the building equates to "outdoors" for the purposes of area classification. Under such conditions, it is necessary to ensure that any flammable cloud is diluted and dispersed in an acceptably short time so as not to accumulate within the building.

Providing that the ventilation within the building is adequate, the extent of the zones around each potential leakage point can be estimated. Here there is the potential for the estimated rates to be grossly in error. EN60079 does not provide guidance on either the momentum or directional effects of leaks, and so it will be necessary to use either a code which takes such effects into consideration, or use CFD modelling.

The approach used by EN 60079 for determining V_z (the hypothetical volume over which the mean concentration of hydrogen is 0.25 or 0.5 times the lower explosive limit depending on the source of release), does not take account of the direction of the plume, so the resultant zones can be very large. Since the impressed airflow in the turbine hall will essentially be vertically upward due to the thermally driven natural ventilation, the extent of the zone vertically below and horizontally to the side will be determined more by the momentum of the release and the inherent buoyancy of hydrogen. Hence using spherical zones around the release point will always result in zones which are too large below the centreline of the release. However, as the jet is buoyant, the extent of the zone vertically above the release point may be larger than suggested by EN 60079. Where IP 15 uses direction and momentum, it may be necessary to also take into account the buoyancy of the gas, or else the zone becomes excessively large.

Since hydrogen is so buoyant it is likely that, even though the jet expansion will entrain air and dilute the gas so that the flammable cloud is large, it will tend to accumulate under the roof. This is the reason for requiring the roof vents to be directly over the major points of release, i.e. over the generators themselves.

Work undertaken by Leach and Bloomfield (1973) shows that light gases released within buildings tend to accumulate and stratify under the roof, with a substantially constant horizontal concentration gradient and a very high vertical concentration gradient. Computer simulation by Swain and Swain (1992) broadly confirmed Leach and Bloomfield's work, demonstrating that the location and size of the upper vents was more important than the size and location of the lower vents when using passive ventilation. Thus the leakage of hydrogen will not be uniformly dispersed throughout the building, since it will tend not to mix but to rise above the leak point. Hence any flammable atmosphere formed within a small area of the building, such as adjacent to the seal at the end of the generator, will tend to rise locally, and be vented out of the roof of the building, rather than freely mix with the entire atmosphere within the building.

The methodology of EN 60079 provides for an estimate of the hypothetical volume over which the mean concentration of the flammable gas will be 0.25 times the lower explosive limit. This is termed V_z, and has a direct influence on the zoning to be applied. If the natural ventilation of the building is adequate, then V_z will be small. The method of determining V_z is first to estimate the required flow of fresh air to dilute the leak to a factor k of the lower explosive limit, either 50% or 25%, depending on the grade of release. For secondary releases, the reduction would be to 50% of the lower limit, whereas for primary or continuous releases, the reduction would be to 25%. The required flow of fresh air is calculated from:

$$(\mathrm{d}V/\mathrm{d}t)_{\min} = \frac{(\mathrm{d}G/\mathrm{d}t)_{\max}}{k \times LEL_{\mathrm{m}}} \times \frac{T}{293} \tag{1}$$

where:

$(\mathrm{d}V/\mathrm{d}t)_{\min}$ = minimum volumetric flow of fresh air, $\mathrm{m^3\,s^{-1}}$
$(\mathrm{d}G/\mathrm{d}t)_{\max}$ = maximum release rate of source, $\mathrm{kg\,s^{-1}}$

LEL_m = lower explosive limit, kg m^{-3}
k = safety factor,
= 0.25 continuous and primary grades of release
= 0.50 secondary grade of release
T = ambient temperature, K

Under steady state operation, the natural ventilation rate for one turbine hall investigated was about 25 m^3 hr^{-1}, in a building of about 500,000 m^3 volume. Since the required ventilation rate to disperse a leak is determined from Equation (1), the same equation can be re-arranged to determine the maximum leakage rate that can be dissipated satisfactorily. In this case, the reverse solution of the Equation gives a maximum allowable release rate of 74 kg hr^{-1}, which is well in excess of the continuous loss experienced in the turbine hall. Consequently, under normal operation, no flammable atmosphere will accumulate within the building.

Where there are several potential release points, it is necessary to calculate $(dV/dt)_{min}$ for each source, and sum them. This is not the arithmetic sum, but a weighted sum which is explained in EN 60079. The relationship between the calculated required value $(dV/dt)_{min}$ and the actual volume under consideration, V_0, can be expressed as a volume, V_k, calculated from:

$$V_k = \frac{(dV/dt)_{min}}{C} \qquad (2)$$

where C is the number of fresh air changes per unit time, and is calculated from the total flow of fresh air through the volume under consideration,$(dV/dt)_{min}$, divided by the total volume V_0. V_k is the ratio of actual ventilation to required ventilation, and gives a measure of how effective the ventilation is at diluting releases. Once V_k has been estimated, then the theoretical release volume V_z can be calculated using a factor f for congestion. Where the air flow is ideal, and perfect mixing takes place, then f would be equal to 1, but where the mixing is impeded, f would be typically 5. In the case of hydrogen, which is particularly buoyant and may not mix well according to Leach and Bloomfield (1973), the factor f should be taken as being 5. This is also in agreement with natural ventilation, which is likely to be impeded and worse than being outdoors in a wind. Therefore V_z is calculated as:

$$V_z = f \times V_k = \frac{f \times (dV/dt)_{min}}{C} \qquad (3)$$

After a release, the concentration will approach 100% at the point of release, but will gradually reduce as the gas mixes with the air until, ultimately, it will be diluted to less than 25% of the lower explosive limit when it has reached a volume V_z. The time from when the release has stopped to dilute it to less than 25% of the LEL is the persistence time and is given by the equation:

$$t = \frac{-f}{C} \ln \frac{LEL \times k}{X_0} \tag{4}$$

where X_0 is initial average concentration of the flammable substance. The estimation of X_0 is difficult, and the guidance in EN 60079 is rather vague, stating "*However, when calculating t, the proper value for X_0 to be taken depends on the particular case, considering among other aspects the affected volume as well as the frequency and duration of the release*". If the release is continuous, then steady state conditions will apply, and a fixed concentration gradient will establish itself within the building. The required ventilation rate can be established using Equation (2).

IGNITION

Clearly, if V_z is large, then ignition would be unacceptable as the potential for injury would also be large. Therefore the zone around each potential source should be determined on a case-by-case basis. Where leakage is continuous or a primary source, then the volume V_z is likely to be too large to be considered as insignificant.

According to EN 60079, if V_z is less than 0.1 m^3, then the maximum volume of flammable atmosphere can be regarded as being equal to V_z. However, in the case of a turbine hall, the *actual volume* of any flammable atmosphere will be less than that equivalent to a sphere of radius equal to the zone radius, but may still be significant. The effect of the ignition of this volume of flammable atmosphere on the building needs to be considered. Recent work by Pritchard et al. (2004) has shown that in gas turbine housings, the ignition of a flammable atmosphere inside the enclosure created a pressure which was slightly less than the theoretical explosion pressure for a sealed enclosure. Thus in the case of the turbine hall, the overpressure generated by ignition of a sphere of say 3 m radius of a hydrogen-air mixture at stoichiometric composition would be equivalent to a sudden increase in volume from $4/3\pi r^3 = 4/3 \times \pi \times 3^3 = 113\,m^3$ to about 8 times this, or say 900 m^3 of explosion products in a volume of 500000 m^3, giving an increase in pressure of $900/500000 = 1.8 \times 10^{-3}$ bar or 1.8 mbar. It is possible that this would cause some structural damage to the building, and would be unacceptable for personnel within the building.

ZONE SIZE CALCULATION

With very large buildings such as a turbine hall, the natural ventilation rate will be much less than the 12 air changes per hour as suggested by IP 15, and hence the methodology is not appropriate. Similarly, EN 60079 suggests an airflow of 0.5 m s^{-1} as a wind speed, which is not possible in such a large building. Hence that too is inappropriate. To illustrate this, consider an example of a building with a volume of 500,000 m^3 and a natural ventilation rate of only 25 $m^3\,s^{-1}$. The number of air-changes per unit time corresponds to $(25/500{,}000) = 5 \times 10^{-5}$ changes per second which corresponds to 0.18 air changes per hour. For a release of 0.001 kg s^{-1} of hydrogen as a primary source of release, V_z can be determined using the equations $(\mathrm{d}V/\mathrm{d}t)_{\mathrm{min}} = (\mathrm{d}G/\mathrm{d}t)_{\mathrm{max}}/(k \times LEL_{\mathrm{m}}) \times (T/293)$ (1) and (3):

$$(\mathrm{d}V/\mathrm{d}t)_{\mathrm{min}} = \frac{(\mathrm{d}G/\mathrm{d}t)_{\mathrm{max}}}{k \times LEL_{\mathrm{m}}} \times \frac{T}{293} \qquad (1)$$

$$(\mathrm{d}V/\mathrm{d}t)_{\mathrm{min}} = \frac{0.001}{0.25 \times 0.00333} \times \frac{298}{293} = 1.22\ \mathrm{m^3 s^{-1}}$$

$$V_z = f \times V_k = \frac{f \times (\mathrm{d}V/\mathrm{d}t)_{\mathrm{min}}}{C} \qquad (3)$$

$$V_z = \frac{5 \times 1.22}{(5 \times 10^{-5})} = 122000\,\mathrm{m^3}$$

This volume equates to a sphere of radius of $\sqrt[3]{3V_z/4\pi} = \sqrt[3]{(3 \times 122000)/(4 \times 3.142)} = 33.86\,\mathrm{m}$. V_z is the theoretical volume of the gas cloud where the gas is diluted to less than 25% of the lower explosive limit, and takes no account of direction and momentum of the release. Although it is always larger than the equivalent zone, it is clearly a very large volume and it would require a large inventory of hydrogen to be released to form such a volume. Bearing in mind that a typical building of 500,000 m^3 would have four generators in it each having a similar zone, this would suggest that almost the entire building would have to be zoned as a hazardous area. Such a zoning is clearly unrealistic, and hence a more common sense approach is required. CFD modelling provides a method of determining typical flammable envelopes for gas leaks.

For comparison, IP 15 gives typical zone radii for leaks at various pressures from various hole sizes. These are assumed to be in well-ventilated areas, and according the IP 15 are based on the assumption that rapid dilution occurs due to entrained air, and the dispersion due to the wind or good ventilation if indoors. Such zones would be likely to be too small in this case, and those predicted by EN 60079 are likely to be too large. Hence the CFD models are more likely to be realistic.

RATES OF LEAKAGE

The rates of leakage can be estimated from those given in IP 15 or from other recognised data. However, since IP 15 covers much higher pressures than are used on the hydrogen system within the turbine hall, it will be difficult to accurately predict sensible release rates.

Clearly such leakage will inevitably end up venting into the turbine hall. If the turbine hall were completely sealed, then this leaked hydrogen would accumulate, and the whole hall would have to be zoned. Direct access to the adjacent boiler house indicates that the hall is not sealed, and there is a degree of natural ventilation provided by the roof windows and vents. Looking at the size of the hall, it is apparent that in relation to the anticipated normal continuous leak rates, it can be considered to be effectively outdoors. This can be demonstrated by a calculation on the anticipated rate of natural ventilation. The turbine hall has a high thermal loading due to the waste heat which is produced from the generators, and so natural ventilation has the potential to be classed as "good" in the EN 60079 code.

ESTIMATION OF LEAK RATES

In IP 15, there are calculations for estimating leak rates for various gases but, unfortunately, there is not a specific case for pure hydrogen. The nearest gas is Cat. G(ii) gas having an assumed molecular weight of 7.03 and a composition of 80% hydrogen, 10% methane and the balance less than 3% of each of the other components. This is close enough for pure hydrogen, as the radii of zones using this gas will be little different than those which would be calculated assuming pure hydrogen. According to International Critical Tables (1933), the viscosity of 50% methane in hydrogen is only about 15% higher than pure hydrogen. Hence the release rates can be increased by a similar factor to account for the reduced viscosity of pure hydrogen, but the viscosity correction will have little effect on the mixing of the gas once released to atmosphere.

There is a continuous leakage of hydrogen of about 2.5 kg hr^{-1} (or 0.0007 kg s^{-1}) from a typical power station. This can be accounted for by mass balance on the hydrogen brought in to make up the losses. The number of primary sources can be determined, and an appropriate factor of concurrent leakage risk determined from EN 60079. In the context of the turbine hall and the hydrogen pipework, there will be very few primary sources of release, these being the highest risk of leakage. The secondary sources can also be accounted for, and these are assumed not to release significant hydrogen during normal operation.

In determining the leakage from primary sources, IP 15 gives some guidance on the equivalent hole sizes for leaks, and the likely mass flow rates at various pressures. The major potential leaks such as the generator seals need to be considered carefully. Past history shows that four incidents involving seals occurred on a total of 84 units over a period of more than 20 years. Since each unit has two seals, the frequency of incidents based on 20 years operation for all 84 similar systems operating throughout the UK relates to less than $4/(2 \times 84 \times 20) = 1.19 \times 10^{10-3}$ incidents per year. This corresponds to the IP 15 release frequency of Level II, or between 1×10^{-2} and 1×10^{-3} per year. Note that some units may have more than 20 years operation, so this figure is conservative. The guidance in IP 15 Table C6 suggests that the seal or equipment manufacturer's data for leakage rates under failure conditions be sought. This will give the most accurate figure, but this may not be available.

As an alternative, Table C6 suggests that an equivalent leak hole at a release frequency of Level II would be 0.1 D for a single mechanical seal with throttle bush where D is the shaft diameter, or 22 mm for a compressor with a purged or floating ring seal. With a shaft diameter of 19.90 inches, the equivalent hole at 0.1 D for a single mechanical seal would be 1.99 inches or 50.5 mm. A hole equivalent to 50.5 mm is too large to be sensible. The diametral clearance for the shaft-to-seal housing is 0.004', so the leakage area would be simply the radial clearance i.e. 0.002 inches over the circumference of the shaft. This equates to $(\pi/4)(D_b^2 - D_s^2) = (\pi/4)(19.904^2 - 19.90^2) = 0.125\ \text{in}^2$ where D_b is the bearing diameter (bore) and D_s is the shaft diameter. The area equates to $80.64\ \text{mm}^2$ or a hole of diameter $\sqrt{(4/\pi) \times 80.64} = 10.13\ \text{mm}$. This appears to be more realistic, so taking a balanced view, a 50.5 mm or a 22 mm diameter hole would seem to be too large, and the 10 mm hole would be acceptable in the absence of data from the generator manufacturer.

Table C9(b) in IP 15 gives leakage rates for holes of 10 mm in diameter at release pressures starting at 5 bara, but the rate should be increased by about 20% to take account of the reduced viscosity. Since the generator is pressurised to 4 barg, no interpolation of the release rate is required as this corresponds to 5 bara. The tabulated value using fluid of Category G(ii) is a leakage of $0.04\ \text{kg s}^{-1}$, and taking the viscosity reduction for pure hydrogen into account corresponds to say $0.05\ \text{kg s}^{-1}$ for a complete seal failure. The required fresh air flow to dilute this to less than 25% of the lower explosive limit can be calculated using Equation (5), and this can be correlated to the available natural ventilation.

For secondary releases, these are typical of leaks from flanges, fittings etc. and as much of the pipe-work is welded, only the screwed, flanged or compression fittings need to be taken into account. In the case of secondary sources, the methodology in EN 60079 assumes only the largest potential leak is used, rather than accounting for all the leaks. Guidance from IP 15 suggests that for valves and bolted flanges using standard compressible gasket material (as opposed to spiral-wound or ring-type joints) the likely release rates to be assumed depend on the frequency of occurrence. These are categorised below in Table 1.

Leakage rates for these can be interpolated from the tables in IP 15 Annexe C Part 3. As the system pressure within the generator is set at 4 barg, it corresponds exactly with the pressure of 5 bara quoted in IP 15, and no interpolation for pressure is required. However, hole diameter may have to be interpolated, but as the leak rates are roughly proportional to the square of the hole diameter, non-linear interpolation is required. The appropriate rate is

Table 1. Frequency levels of releases

Frequency level	Actual frequency	Equivalent hole size: valves	Equivalent hole size: flanges
Level I	$>10^{-2}$ release per year	0.1 mm	N/A
Level II	$>10^{-3}$ release per year $>10^{-2}$	2 mm	0.5 mm
Level III	$>10^{-4}$ release per year $>10^{-3}$	0.1 × pipe diameter	2.3 mm

Table 2. Leak rates vs. hole size from IP 15

Hole diameter	Leak rate at 4 bar g., kg s^{-1}
1	0.0004
2	0.001
5	0.01
10	0.04

calculated as the square of the ratio of the required hole diameter to the nearest quoted hole diameter, multiplied by the quoted leak rate. For example, the leak rates for holes at 5 bara are quoted in IP 15 as:

Thus the appropriate leakage for a 4 mm hole would be 0.8^2 times the leak for a 5 mm hole, and for a 2.3 mm hole the rate would be $(2.3/2)^2$ or 1.32 times the leak for a 2 mm hole. Note that the flow for the 2 mm hole is probably conservative, and should be assumed to be 0.0016 kg s^{-1} to be consistent with the rates for the other three hole sizes. For the 8 bar pressure of the hydrogen distribution pipework within the Turbine Hall, the leak-rate will require interpolation. Inspection of Table C9(a) for Category G(ii) fluids shows that although the rate is not linear over low pressures, linear interpolation will not be grossly in error, and the flow rate at 8 barg (9 bara) can be assumed to be 90% of that at 10 bara as quoted in the Table. Correcting for viscosity will increase this by 15 to 20%, so a flow of 110% of the 10 bara flow will be adequate for an 8 barg leak of pure hydrogen.

ZONE SIZES OBTAINED BY DISPERSION MODELLING

The commercial consequence modelling software PHAST Version 6.4, from Det Norske Veritas plc (DNV) was used by the Health & Safety Laboratory to estimate distances to 1.0, 0.5 and 0.25 of the lower flammable limit for hydrogen releases at 4 barg. A range of hole sizes was used from 1 mm to 10 mm (simulating a seal failure). The dispersion model in PHAST does not take any account of the presence of a building or other obstructions, but does model momentum and buoyancy effects. Calculations were performed using the lowest wind speed which is allowed by PHAST, i.e. 1 m/s (at a height of 10 metres; lower closer to the ground). Three cases were considered for each hole size:

a) A vertically upwards release
b) A horizontal release
c) A release which immediately impinges on the ground so as to lose initial momentum.

Case (a) gives the maximum vertical distance from the release point, and case (b) the maximum horizontal distance. Since case (b) is dominated by the momentum of the release, the downwind distance is not as sensitive to the assumed wind speed. Case (c) simulates a release with effectively no momentum. Calculations were undertaken for all three cases and of the simulations, the Case (c) series was always smaller than the other two cases. Hence the zone radii for releases were taken as being the worst-case of the horizontal and vertical release series. For very small leaks it would be appropriate for a minimum radius to be taken as being 1 metre.

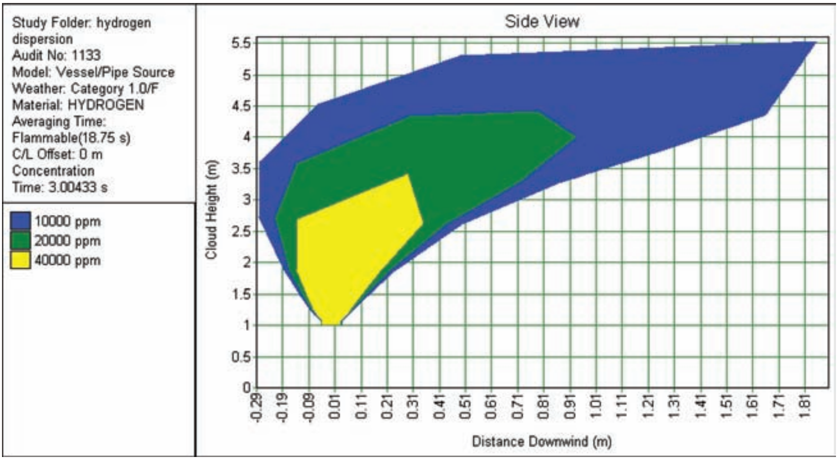
RWEnpower also undertook some computer simulation of leaks using STAR CD software, assuming three different models – 1 D, 2 D and 3 D. These considered smaller enclosed volumes, and showed reasonable agreement between themselves. Since the simulations were configured for relatively small volumes, there was considerable recirculation in the 3 D model, and the use of a vent located at the side imposed a lateral velocity in the volume. Hence there were boundary effects not present in the PHAST calculations. The 2-D model for axisymetric free jets did not have this. Although these simulations did not use identical conditions to those of the PHAST calculations, the overall results were not dissimilar to those obtained by the PHAST modelling. Therefore it can be concluded that the zone sizes calculated by the PHAST model are similar to those using the Star-CD models and are realistic for a large-size building, and are more realistic zone sizes than those quoted by IP-15.

There was little discrepancy between the PHAST *vertical* distances for the LEL and the IP 15 hazard radii for a leak at ground level. In IP 15, horizontal radii are the same as the vertical radii as IP 15 does not take account of direction of release. These radii are smaller than the *horizontal* radii determined using PHAST. This is almost certainly due to two factors. Firstly, the lack of obstructions assumed in the PHAST cases leads to mixing solely due to the momentum of the leaking gas, whereas the IP 15 data would assume that the area in which the leak occurs would have some obstructions which would increase the mixing and hence reduce the length of the flammable cloud. Secondly, the PHAST cases have an imposed wind speed on them which would lengthen the plume, and the effect of this is can be seen in the difference between the vertical and horizontal plumes in Figures 2 and 3. The plume formed under impingement, in Figure 4, shows smaller vertical and horizontal distances than either of the worst cases of vertical and horizontal releases, and hence the vertical and horizontal releases can be taken to be the governing cases.

From the above, it can be concluded that despite the PHAST simulation showing some greater horizontal distances than those recommended in IP 15, the zones calculated by computational fluid dynamics are more likely to be realistic for an enclosed, very large building such as a Turbine Hall.

INADEQUATE VENTILATION

It can be seen from the above that a large leak which cannot be diluted to a low level by the natural ventilation will ultimately accumulate within the building. This cannot be tolerated, as the result of an ignition would be catastrophic. When the methodology was applied following the above procedure, it became apparent that the sum of the potential leaks exceeded the ability of the natural ventilation to prevent accumulation. Hence the factor k could effectively exceed 1.0. In this case, the equilibrium concentration can be

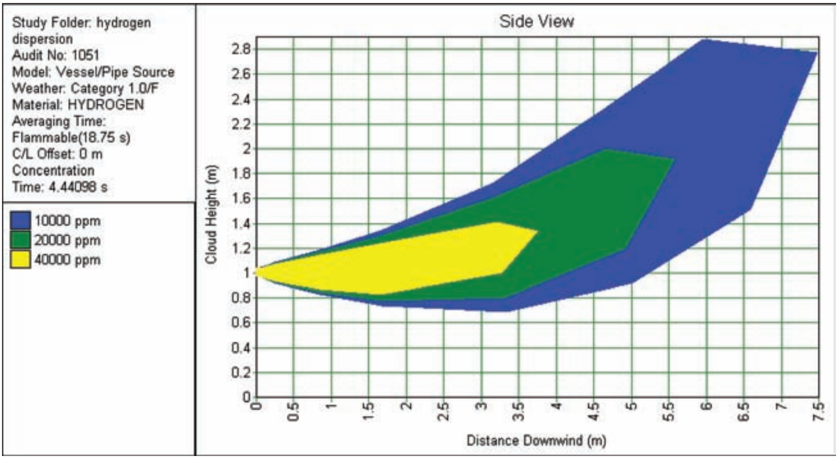


Study Folder: hydrogen dispersion
Audit No: 1133
Model: Vessel/Pipe Source
Weather: Category 1.0/F
Material: HYDROGEN
Averaging Time: Flammable(18.75 s)
C/L Offset: 0 m
Concentration
Time: 3.00433 s

🟦 10000 ppm
🟩 20000 ppm
🟨 40000 ppm

Figure 2. Vertically upwards 4 barg hydrogen releases through 5 mm diameter hole

calculated as the leak rate divided by the ventilation rate to give a steady-state natural ventilation rate concentration factor k'. The method of EN 60079 then determines a persistence time, using Equation (4), for the concentration to diminish after the leak has stopped. However, this persistence time is based on the assumption that the entire



Study Folder: hydrogen dispersion
Audit No: 1051
Model: Vessel/Pipe Source
Weather: Category 1.0/F
Material: HYDROGEN
Averaging Time: Flammable(18.75 s)
C/L Offset: 0 m
Concentration
Time: 4.44098 s

🟦 10000 ppm
🟩 20000 ppm
🟨 40000 ppm

Figure 3. Horizontal 4 barg hydrogen releases through 5 mm diameter hole

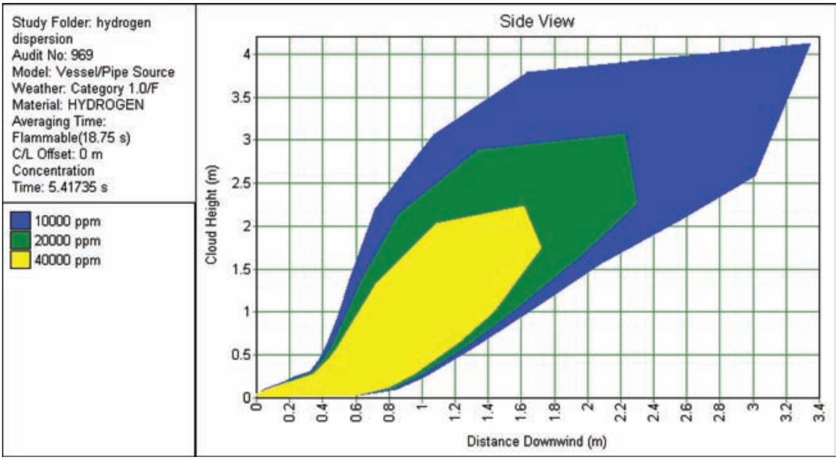


Figure 4. Impinging at point of release 4 barg hydrogen releases through 5 mm diameter hole

volume is at a uniform concentration, and consequently the persistence time is actually very long. In the case of the turbine hall, it is highly unlikely that the concentration would be uniform, and it is far more credible that the flammable cloud would be quite small. Since there is a general drift of natural ventilation upwards through the building, it is likely that the hydrogen would be carried out with this, rather than be fully mixed and dispersed throughout the building.

By taking into account the loss of hydrogen by natural ventilation, a more realistic estimate of the time to reach a fraction of the lower flammable limit is calculated by solving a differential equation, so that the time to reach a hazardous situation is determined from the equation:

$$t = \frac{V_0}{Q_b}\ln\left(\frac{q}{q - Q_b \cdot J}\right) \tag{6}$$

where J is the fractional concentration of hydrogen after time t, and q is the volumetric leak rate calculated from the mass leak rate, the mass lower explosive limit and the volumetric lower explosive limit using the equation:

$$q = \left(\frac{\mathrm{d}G}{\mathrm{d}t}\right)_{\max} \times \frac{LEL}{100 \times LEL_{\mathrm{m}}} \tag{7}$$

J is a fractional concentration because the fraction of hydrogen leaking into the building is 1, rather than being expressed as a the lower explosive limit which is measured in volume per cent. As the maximum leakage rate has already been determined, and the time to reach 25% of the lower limit is known, the product of the two is the total quantity of hydrogen needed to leak out. If this exceeds the inventory of the alternator and its associated cooling circuit, then total loss of the coolant will not form an extensive flammable atmosphere within the building.

If the persistence time is small, then it might be appropriate to classify the building as non-hazardous with small zone 2 and zone 1 areas within it. However, if the persistence time is much longer, then it is likely that the entire building should be classified as zone 2 with pockets of zone 1 within it.

Taking one typical alternator, it is operated at 4 barg pressure, but with the supply of hydrogen isolated. Hence any leakage can be determined by observing a steady reduction in pressure, and the small inevitable loss is made up periodically by simply opening the isolation valve, re-pressurising the alternator, and then isolating the supply. The volume of hydrogen at atmospheric pressure and ambient temperature held in the alternator and its cooling circuit is about 60 m^3, so under total loss conditions due to a severe leak, the maximum inventory that could be released is limited, and the fraction *J* of the lower flammable limit is calculated by re-arranging Equation (8) and substituting the time taken to de-pressurise the alternator via the leak. In the case of the alternators initially assessed using the methodology, the factor *J* was only 0.00018, giving a maximum concentration of only 0.018% of the lower flammable limit if spread throughout the building. The persistence time calculated by EN 60079 for the alternator building was found to be about 70 hours. However, the time required to reach 25% of the lower flammable limit was 37 minutes at the maximum leak rate, yet the whole alternator would have been de-pressurised within a time of only 39 seconds at the maximum rate. Hence the size of the flammable cloud is limiting, and the building does not need to be classified as zone 2.

SUMMARY METHOD

The method can be summarised into stages as follows:

- Determine the natural thermal ventilation of the building using only temperature difference based on the method in BS 5925:1991.
- Determine the maximum permissible continuous leak release rate to ensure that the hydrogen is diluted to less than 25% of the lower explosive limit.
- Examine the installation to determine all the sources of continuous, primary and secondary grades of release.
- Determine the frequency of release to decide on the rate of release for each identified source, using Table C6 in IP 15 or equivalent data.
- Summate the releases for each grade of release, and determine the worst case release rate.

- Using the natural ventilation rate, determine k', the fraction of the lower explosive limit using natural ventilation.
- If k' is less than 1.0, then the natural ventilation is acceptable for the releases considered. If k' is greater than 1.0, then the natural ventilation is insufficient, and either the ventilation must be increased, or the total inventory that can be released is considered. If the inventory is too large, then either steps must be taken to restrict the inventory and increase the ventilation, or the whole building will need to be Zoned.
- Determine the persistence time for the release based on natural ventilation and plug flow.
- If the persistence time is long, then either:

  the natural building ventilation should be increased and the persistence time recalculated

  or

  the total inventory release time should be determined and if it is much less than the time to reach 25% of the lower flammable limit, then the building can be assumed to be non-hazardous with local Zone 2 and Zone 1 areas.
- For continuous and primary grades of release, the maximum Zone radii determined by CFD are used irrespective of the direction of release.
- For secondary grades of release, use the same radii as for primary and continuous grades of release.

CONCLUSIONS

- There are existing codes for area classification which are inappropriate for a very large building such as a turbine hall at a power station.
- Hydrogen is a buoyant gas and will tend to stratify at roof level.
- The methodology of EN 60079 assumes that the area is outdoors or the building is well ventilated, and applying the method to a poorly ventilated building leads to unrealistically large zones.
- The methodology of IP 15 also assumes good mixing and a well-ventilated area, and for poorly ventilated buildings would result in zones which are unrealistically small.
- The leakage rates for fluids of Category G(ii), given in IP 15 are suitable for hydrogen, but the rate requires increasing by about 20% to take account of the reduced viscosity of pure hydrogen.
- Natural ventilation in very large buildings is adequate to prevent high concentrations of hydrogen accumulating, providing the inventory which can be released is adequately controlled.
- Computational fluid dynamic simulation of hydrogen leaks gives results which appear to be sensible and gives zones which are between the excessively large zones of EN 60079 and the small zones of IP 15.
- The methodology for area classification based on this method is only suitable for hydrogen-cooled generators in large power station turbine halls.

NOMENCLATURE

C	number of air changes per unit time $= (\mathrm{d}V/\mathrm{d}t)_{\mathrm{min}}/V_0$
D_b	diameter of bearing bore
D_s	diameter of shaft
$(\mathrm{d}V/\mathrm{d}t)_{\mathrm{min}}$	minimum volumetric flow of fresh air, $\mathrm{m}^3\ \mathrm{s}^{-1}$
$(\mathrm{d}G/\mathrm{d}t)_{\mathrm{max}}$	maximum release rate of source, $\mathrm{kg\ s}^{-1}$
Exp	natural antilogarithm function
f	factor to account for impeded air flow, value between 1 and 5
G	acceleration due to gravity $= 9.81\ \mathrm{m\ s}^{-1}$
J	fractional concentration of hydrogen at time, t
K	safety factor, $=$ 0.25 continuous and primary grades of release $=$ 0.50 secondary grade of release
k'	fraction of the lower explosive limit which is obtained by natural ventilation
LEL_{m}	lower explosive limit, $\mathrm{kg\ m}^{-3}$
LEL	lower explosive limit, % v/v
ln	natural logarithm function
r	radius of sphere
Q_b	natural ventilation volumetric air flow, $\mathrm{m}^3\ \mathrm{s}^{-1}$
q	volumetric leak rate, $\mathrm{m}^3\ \mathrm{s}^{-1}$, $q = (\mathrm{d}G/\mathrm{d}t)_{\mathrm{max}} \times LEL/(100 \times LEL_{\mathrm{m}})$
T	ambient temperature inside building, K
t	time required for average concentration to fall from X_0 to k times the LEL
t'	time required for average concentration to rise to k times the LEL
V_0	volume of building, m^3
V_k	fresh air ventilation rate divided by the air-changes per hour, $= (\mathrm{d}V/\mathrm{d}t)_{\mathrm{min}}/C$
V_z	hypothetical volume of over which the mean concentration of the flammable gas will be 0.25 times the lower explosive limit, m^3
X_0	initial concentration of flammable gas after release

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Authors' note: The views expressed in this paper are those of the authors and not necessarily those of the Health and Safety Executive.