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PROTECTION OF LARGE FLAMMABLE STORAGE TANKS DURING REPAIR BY MEANS OF NITROGEN-FILLED HIGH EXPANSION FOAM*

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Summary

Storage tanks contaminated by flammable residues require protection during repair or demolition. Nitrogen-filled high expansion fire-fighting foam has been proposed for this protection. In this series of tests a 500 tonne aviation fuel storage tank was filled with appropriate foam to observe foam behaviour with particular reference to oxygen contamination in aged foam. For comparison, gas inerting with nitrogen was included in the test series. In one test a hot cutting procedure was monitored for void formation and oxygen contamination of the foam.

Oxygen contamination was low in foam up to three hours old. Voids and oxygen introduced by hot cutting were rapidly purged. The use of foam enabled the tank to be rendered inert using less nitrogen than with the gas alone and had the additional advantage that the inerting agent was visible.

Introduction

Tanks which have been used for storage of flammable liquids may present a major fire and explosion hazard when their repair or demolition is required. The hazard may be continuous as with volatile liquids or it may arise during operations, notably by the decomposition of solid residues and subsequent ignition of the vapours by a hot cutting torch. The problem arises in fuel storage facilities, chemical plant and industries where flammable solvents are used. Although they may attract less coverage by the media than the explosions at Dudgeon's Wharf (1969) and Sheffield Gas Works (1973), reports are made all too frequently of explosions which cause loss of life and/or considerable damage. Thus the need remains for a method which is both safe and convenient for wide-spread use.

A number of methods are available for safe working when repairing or demolishing tanks but all have limitations. The safe methods are: avoidance of hot working, removal of flammable materials or of air within the tank; in practice more than one method may be required to be used. If air is not to be removed from the tank, then either all traces of flammable material must be disposed of, to permit hot working, or the freely available flammable

material must be removed prior to cold working. Cold working has practical disadvantages in that it may be slower than hot working, skilled manpower for it may be less readily available, and certain types of repair activity cannot be undertaken. Removal of flammable material can also be time consuming, particularly where tenacious residues are present and where special constructions may have to be put inside the tank to clean the less accessible surfaces, e.g. the underside of the roof. Obtaining protection by removal of air, that is by introduction of an inert gas or steam, avoids some of the labour-intensive requirements, but operational difficulties may be encountered particularly on large tanks. Ensuring that the whole of the atmosphere within the tank is safely inerted, both at the beginning of the operation and during its progress, when openings in the tank may be formed, can become difficult and would require expertise in gas sampling and analysis. Water can be used to displace vapour/air mixture from a tank but there are substantial limitations to its effectiveness. Petroleum products, with associated sludge and other water-immiscible materials are difficult, if not impossible, to displace by a water purge. There remains a need for an inerting method which requires simple criteria to describe safe conditions and which will cope effectively with the hazards arising from hot cutting procedures.

A relatively new and promising approach uses high-expansion fire-fighting foam with an inert gas as an inerting medium. The advantages of the method are:

(1) positive displacement of flammable vapours from within the tank;

(2) visual indication of the inerting medium;

(3) possible suitability for hot cutting, subject to rapid displacement of foam destroyed by the heat;

(4) avoidance of need to dispose of large volumes of contaminated water.

The process has been used commercially [1] but the trials described in this paper were made in order to examine certain aspects in more detail. The investigation concentrated on the following:

(a) to investigate whether a large tank could be satisfactorily filled with high-expansion foam without forming large voids within the volume or on the underside of the roof;

(b) to establish that foam stability was sufficient to enable the tank to be filled even when conditions of limited access for foam were simulated i.e. the foam becomes aged;

(c) to examine the extent to which air (oxygen) could penetrate the top surface of the foam in the tank and thereby dilute the nitrogen which originally formed the bubbles. Conversely the extent to which nitrogen from the foam would dilute the air could also be examined;

(d) to study the effect of hot cutting of the steel tank on adjacent foam and associated void formation;

(e) to compare the effectiveness of foam inerting with the introduction of nitrogen gas alone.

A commercial, as distinct from laboratory, scale was chosen and, indeed,

the 500 tonne tank made available, by courtesy of the Property Service Agency, appears to be the largest storage tank test for which reports are available.

In addition to the aspects studied in the present work, other factors are of practical importance and should be considered in relation to the widespread adoption of the technique. In particular, the rate at which flammable vapour can diffuse through the foam must be taken into account, and the behaviour of solid deposits of relatively low ignition temperature may also be important. The present work was aimed at answering those questions which were particularly applicable to the large volume tank which became available for the experiments.

For technical and economic reasons the usual choice of inert gas is nitrogen, although carbon dioxide, inert gas from burners, and even argon may be used as conditions require.

The synthetic foaming agents used for high-expansion fire-fighting foam, normally filled with air, are applicable to the inerting process. The requirements for foam for inerting are:

(1) good fluidity for reaching corners, purging pipework, etc., although in special circumstances a "stiff" foam may be required;

(2) low drainage rate, since drained foam is likely to be *(a)* less fluid since smaller "lubricating" bubbles tend to disappear because of gas diffusion into the larger ones, and *(b)* more susceptible to contamination by diffusion of flammable vapours both because of time factor and the thinning of the bubble walls;

(3) reasonably dry, to minimise losses while hot cutting;

(4) commercially realistic.

Conventionally, foams are specified by expansion ratio and drainage rate. For the present exercise expansion ratio has some effect on ease of hot cutting while drainage rate may reflect problems of increasing stiffness and vulnerability to contamination. However a quantitative description of fluidity was desirable. A foam generator suspended above a clean flat surface will normally produce a conical heap of foam. In this exercise the base angle of this cone (the repose angle) was estimated but two problems were encountered:

(a) a foam with low repose angle in bulk may present a relatively steep angle as its leading face moves across a surface;

(b) the surface of foam is usually uneven and, with small quantities, it may be difficult to decide on a mean value.

Test programme

The final choice was influenced by tank availability and size, costs, staff available etc. as well as the technological aspects. The series thus became:

(1) purging with nitrogen to provide a basis for comparison for reaching inert conditions;

(2) filling with foam from the top of the tank with a target fill time of two hours;

(3) filling with foam from near the base of the tank with a target fill time of two hours;

(4) filling with foam from the top with a target fill time of nominally five hours.

The generation of foam is largely based on empirical procedures and, on the scale of these tests, requires considerable support facilities. Contractors were therefore employed for foam generation.

Description of tank

The tank was of steel plate, 14.6 m (48 ft) diameter with cylindrical walls 3.7 m (12 ft) high and a conical roof 4.6 m (15 ft) above the base at its peak: its capacity was thus around 670 m^3 (23500 ft^3). For foam access a number of 0.61 m (2 ft) diameter manheads were available. For a base fill a manhead near ground level was chosen; for a top fill one in the roof but close to the wall. A 15 cm (6 in) manhead near the peak of the roof served as the principal vent. Fig. 1 shows the tank and the general site layout.

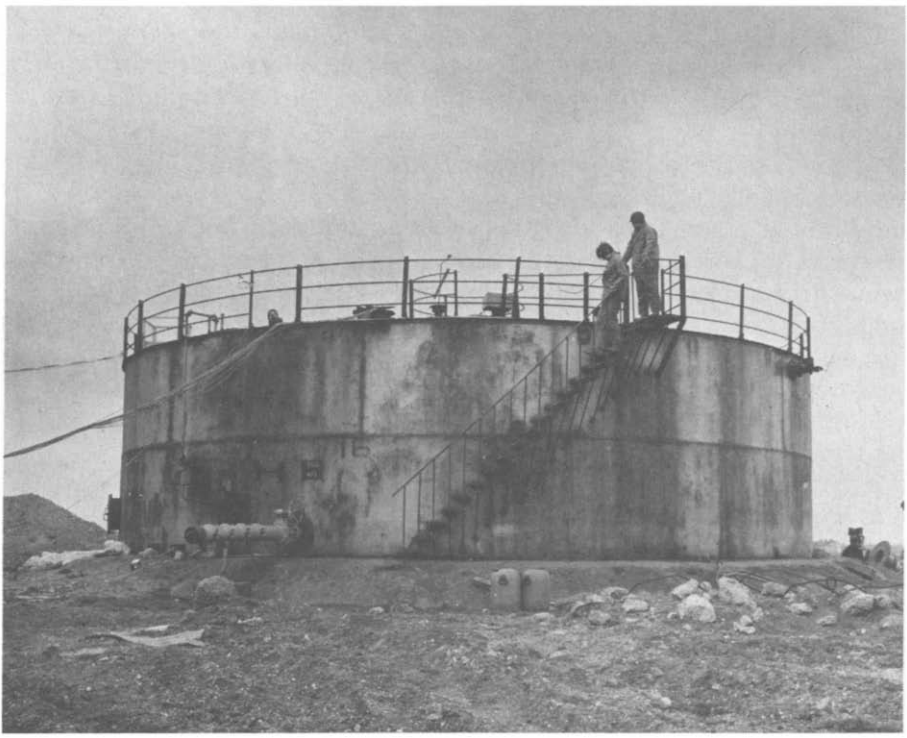


Fig. 1. General view of tank.

As a basis for design for monitoring the tank during a foam filling exercise, it was assumed that a void not exceeding one per cent of tank volume could be tolerated. This figure is the highest desirable since under the worst conditions an explosible void of this size might lead to tank disruption, if it was ignited. However, the exercise was essentially aimed at producing information relevant to industrial conditions rather than guaranteeing comprehensive safety of an actual hazard. The one per cent criterion corresponds in this tank to the equivalent of a 1.8 m (6 ft) cube and would have required at least 150 sampling points for full coverage.

The basis criterion for safety is the absence of an explosible atmosphere. However gas analysis on the scale implied above would be demanding on equipment and time. As discussed below three banks each of nine sample lines were constructed. Two banks were used to give full analytical coverage to the sector of the tank most prone to contamination i.e. furthest from the foam input. The remaining bank was distributed round the walls of the tank approximately at the remaining points of the compass. These gas analysis lines were supplemented by foam detectors which, in conjunction with gas analysis, can be used to infer safe conditions. On the assumption that a source of ignition would arise only external to the tank, e.g. sparks from a cutting torch, foam detection points were confined to positions close to the walls and roof with an inner ring to allow for spark penetration.

Experimental

Foam properties

It was impracticable to determine foam properties reliably on the exposed test site. Preliminary tests at the Fire Research Station had shown that the larger of the generators used (designated "12 inch") produced foam with expansion ratios from 115 to 300 and half drainage times from 4.2 to 25.0 min. These figures do not correspond to each other and there was no simple relationship between generating conditions and foam properties. Operational conditions at the site were not identical but if differences are discounted, then, based on the laboratory tests, the expansion ratio was probably in the range 120—180 and the half-drainage time was of the order of 20 min. For a fill from the base the back-pressure of foam may have affected the properties.

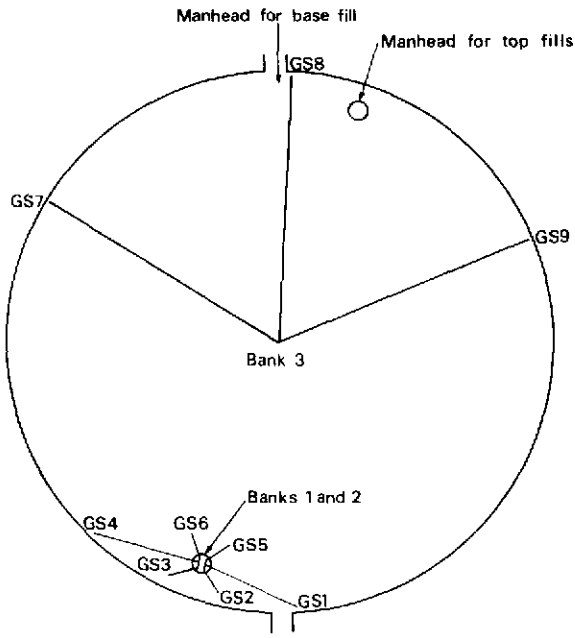
Again, although conditions were different, the small (designated "4 inch") generator used for most of the last test produced foam of similar expansion ratio and drainage rate.

Gas analysis

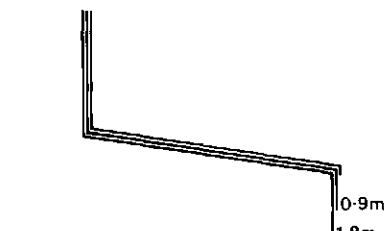
For oxygen determination three paramagnetic oxygen meters with recorder outlets were used. As the tank was to be filled in two hours (or more) a determination at each sample location at 10 min intervals was adequate. A sample rate of one per minute per oxygen meter was allowed. Three

banks were made each containing nine sample lines of 6-mm bore mild steel with a tenth line to fresh air for frequent calibration checks. A diaphragm pump was used to transfer the samples. The appropriate line was chosen by opening a solenoid valve operated by a "master" cam timer on a 10-min cycle. As the air to foam interface was the principal interest, provision was made to move the sample points vertically as the fill progressed. Each bank was arranged as a 3 × 3 matrix horizontally and vertically. One bank of nine lines was allocated to three points around the circumference while the other two banks were used to sample one "sector" more intensively (Fig. 2).

To remove foam from the gas sample foam breakers were used. The sample was sucked through two compartments in cascade, each of which contained 15 cm^3 of defoaming liquid, before passage along the sampling line to the meter.



a) Plan view of sampling points



b) Side view of typical gas sampling array

Fig. 2. Arrangement of gas sampling lines.

Since the sampling required physical removal of foam, channelling through a thin layer of stiff foam to the atmosphere could lead to spuriously high oxygen readings. With possible exceptions in the last, there is no evidence of channelling during these tests.

Foam detectors

Two types were used: one depending on the electrical conductivity of foam and the other on its optical absorption.

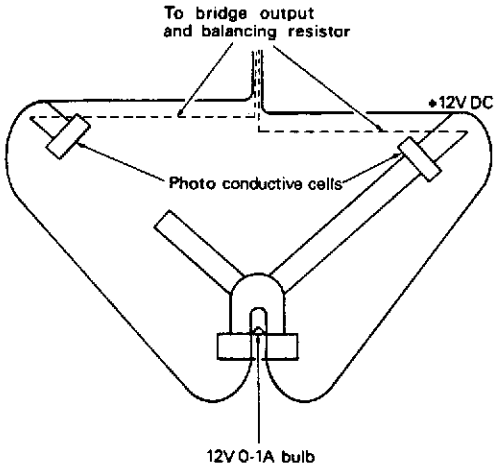
Conductivity plates. These comprised a pair of 10 cm square copper plates, parallel and separated by 10 cm to form a conductivity cell; the outward facing surfaces were painted to provide electrical insulation. The electrical cables also acted as the means of suspension. In operation, 12 V dc was applied across the selected pair of plates and the current measured. (dc was found preferable to ac as problems due to polarisation were less than those of capacitance). The plates could give rise to spurious readings if mounted close to metal walls or fittings. They provided a comparative indication of foam condition but quantitative interpretation would only have been possible if: (a) the foam liquid was of constant known composition; (b) the relationship between conductance and drainage (which may not be linear) was known. These conditions did not apply in these tests.

As a check on foam continuity between successive pairs of plates the input potential was also applied across one plate each of successive pairs. Because of their simplicity, a large number of conductivity plates were used to give coverage approximately equal to the detection of a void of regular shape of one per cent of the tank volume.

Optical detectors. To supplement the conductivity plates, photoresistive cells were used in conjunction with a light source (Fig. 3). The cells formed two arms of a Wheatstone bridge completed by two sections of a small trimmer resistor external to the tank. With no foam present the bridge was balanced. When foam penetrated the open light path the bridge became unbalanced to give a potential of one to two volts. No quantitative interpretation of results has been attempted but foam movement caused variation of the output potential. The optical detectors could be mounted close to walls, roof trusses, etc., and were used to supplement conductivity plates in the shoulder and roof of the tank. One set of five was suspended across the tank to give a general picture of foam movements.

Recording system and tank layout

Groups of 5 or 10 were adopted for all systems. Continuous recording of all sample points was not practicable and not necessary. The core of the system was a single pen chart recorder set to a 0—10 mV range since this corresponded to full-scale deflection on the oxygen meters. The input was controlled by banks of relays. Each recording cycle was triggered by a cam on the master timer.



Components supported by 10 gauge copper wire framework with all junctions bedded in polyester resin (not shown)

Fig. 3. Optical detector.

(1) Oxygen analysis: the output from each meter was fed successively to the pen recorder for a second or so towards the end of the minute sampling period. The position of the corresponding valve opening was noted manually but since only one note of this for each test was needed, the system was virtually automatic.

(2) Conductivity plates: these were arranged in groups of five: the 3.7 m tank height allowed a 0.9-m vertical separation between each pair. With ten sets of five distributed round the outer (wall) ring, the horizontal spacing averaged 4.6 m. A second ring of ten was arranged 1.8 m from the wall. Near the peak of the roof two sets were paired to give a ring of five close to the roof and a second ring 0.9 m vertically below. The full layout is shown in Fig. 4. Distribution of points was uneven because the tank was found to be reinforced by eleven roof trusses. These provided convenient supports for equipment but re-design to modules of eleven was impracticable.

(3) Optical detectors: one set of five was suspended 1.2 m above the tank floor along a diameter to monitor foam movements. This was permanently attached to five channels of a 6-point rapid response recorder. A second set was mounted near the peak of the roof.

(4) Relay system: a bank of relays to regulate access to the pen recorder was provided for each detection system. The circuit arranged that as one relay switched off, its successor was switched on until the cycle was completed. The cycle was initiated by closure of the switch of one of ten cams on the master timer. This switching led to successive monitoring of the outputs from the three oxygen meters, ten pairs of conductivity plates (which, inclusive of cross-linking of plates, led to eighteen outputs) and five optical detectors.

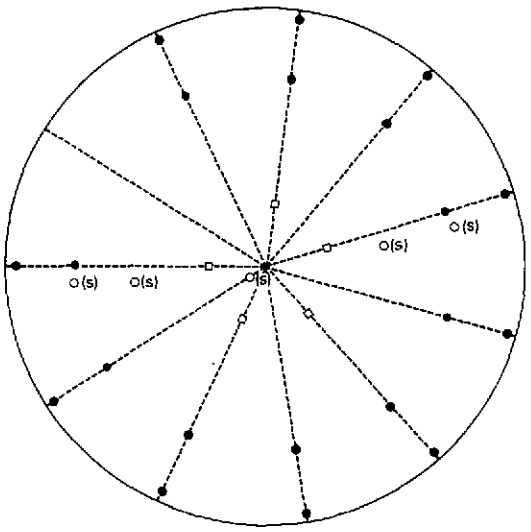


Fig. 4. Plan view of conductivity plates and optical detectors.

Results and discussion

Gas inerting: Test 1

Nitrogen was introduced via a diffuser near the base of the tank. Owing to the difficulties with a heat exchanger, flow rate was not constant throughout the period. However, the obvious feature of the results was the virtual absence of a concentration gradient within the tank. The extremes found for two sampling positions are shown in Fig. 5. Because of nitrogen supply problems the purge was not completed to normal operating levels. The volume of nitrogen used was quoted as 1270 m^3 (45000 ft^3) i.e. almost two tank volumes.

Using the relationship for ideal mixing $c = c_{max} \exp(-tv/V)$, (where c = final oxygen concentration, c_{max} = initial oxygen concentration (21%), t = time (h), V = tank volume (m^3), v = purge rate (m^3/h). The ideal mixing curve shown in Fig. 5 was calculated. From this the final oxygen concentration is expected to be 3.0% (c.f. 4.9% average for eight sample points). Although inlet temperature fell to an estimated $-10°$ C there was no obvious stratification.

Foam inerting: Test 2

Top filling with the 12-inch generator was used with a target fill time of

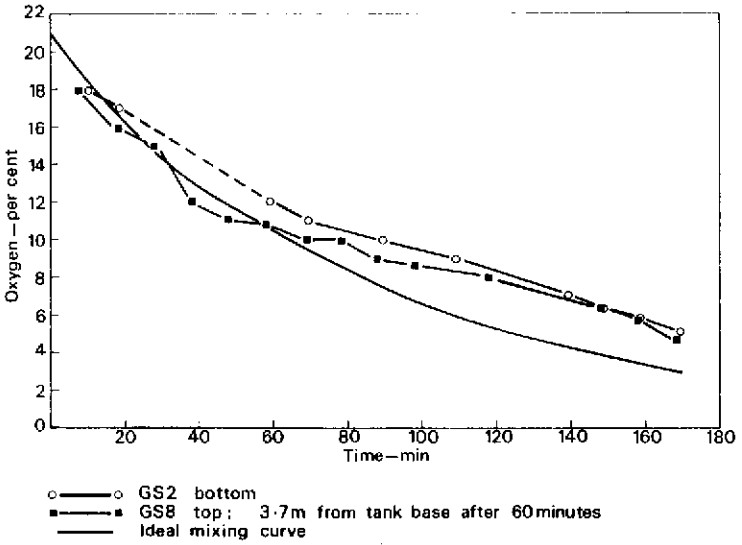


Fig. 5. Test 1: nitrogen gas inerting.

2 h. The stream of foam was continuous and spread rapidly and evenly across the tank. The repose angle of fresh foam was 10—15° from horizontal with a leading edge 0.6 m (2 ft) high of rather steeper angle (30—60°). As the gas analysis shows, in Fig. 6, very little air diffused into the foam and there was only slight dilution of the air above the foam by nitrogen.

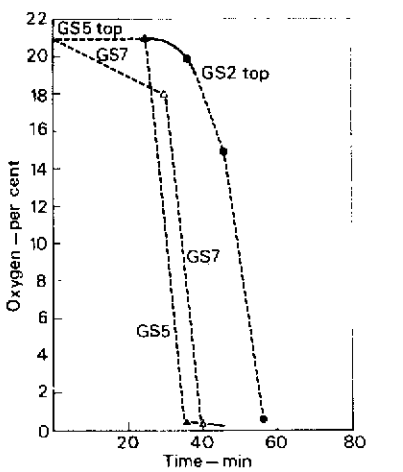


Fig. 6. Test 2: top fill.

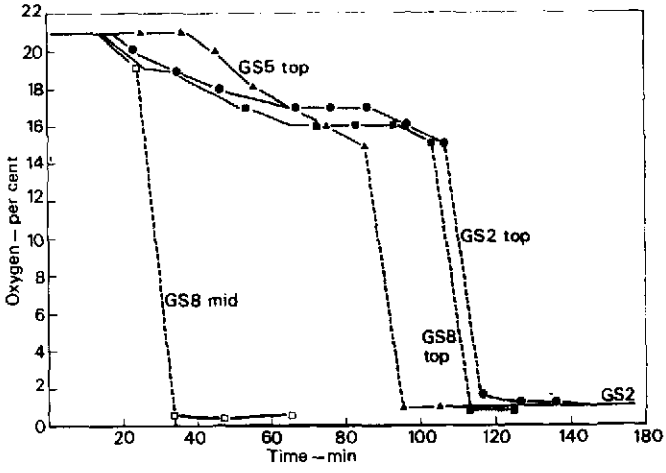
Foam inerting: Test 3

Base filling with the 12-inch generator was used with broadly comparable results to the first fill. (Test 2). Simulated columns with hardboard surfaces 230 mm (9 inch) square cross-section were installed and as can be seen from Fig. 7 foam flowed round them to leave an almost indiscernible "valley" in one case and a visible but shallow valley in the second.

Fig. 7. The flow of foam around a simulated column.

There was a failure of water supply for 20 min during the fill and a subsequent instability of foam supply for a time. Typical gas analyses are shown in Fig. 8.

When the tank was full of foam after a total period of 145 min, an oxy-acetylene torch was used to cut the tank. This was synchronized as far as possible with the gas analysis system. At the analysis point close to the cut, oxygen concentration rose to a level of 6% and may have been still rising when the analysis cycle moved on. However, the other sampling points to either side and those 1.8 m from the wall showed no perceptible rise and, at the next cycle, the oxygen concentration was again close to zero at all points. As can be seen, (Fig. 9), the foam moved quite closely behind the flame to purge any void. To ensure safe conditions the foam generator was used to maintain the foam level within the tank.



GS2 top: 2·4m from tank base
GS5 top: 2·4m from tank base
GS8 top: 2·7m from tank base
GS8 mid: 0·9m from tank base

Fig. 8. Test 3: base fill.

Fig. 9. Hot cutting showing foam purging.

Foam inerting: Test 4

The foam provided from the 4-inch generator for this top fill test did not descend as a continuous stream. This would be undesirable in practice because (a) descending, separated clouds of foam may generate electrostatic charges; and (b) tank atmosphere may be occluded in the mass of foam.

As the fill progressed, foam breakdown increased correspondingly. After 3 h a layer 1.2 m (4 ft) had formed across most of the tank but progress had become very slow. The repose angle of the bulk of the foam was again only a few degrees but the leading edge was high and steep (60°).

The 4-inch generator was removed and the 12-inch generator in base fill position was used briefly with the intention of pushing the old foam to the main gas analysis system. The oxygen concentration for three analysis points showed 1.5% oxygen while the fourth, which was probably most susceptible to sample channelling, showed 3—4% oxygen. The results are summarized in Fig. 10. In view of the unfavourable conditions, these analyses are more clearcut than might have been expected.

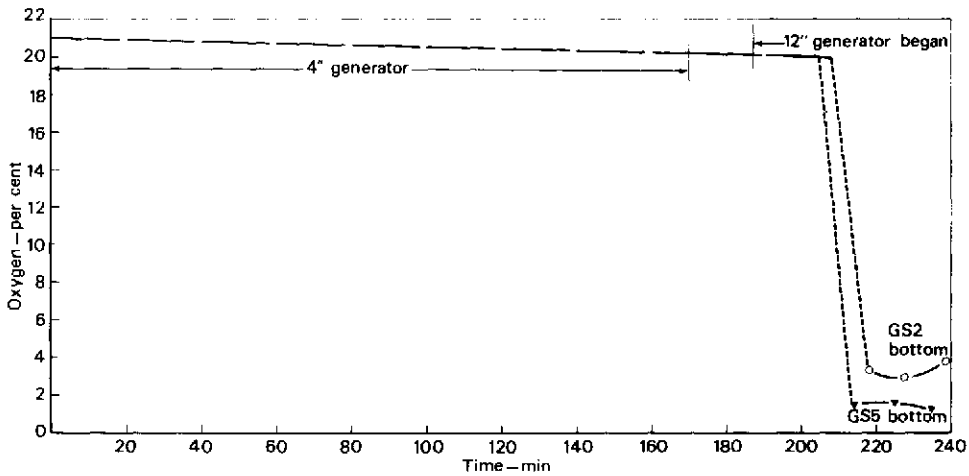


Fig. 10. Test 4: slow top fill.

Foam behaviour: general

(1) The output from the suspended optical detectors showed a continuous ripple indicating foam movement while foam generation proceeded but with relative quiescence when foam supply ceased.

(2) The conductivity plates showed that: (a) while the wettest foam was most frequently found near the bottom, it could also be found half-way up the mass of foam; and (b) foam near the top or, for the slow fill, near the outside edge, might lose at least 95% of its electrical conductance. Despite this it appeared still to offer a useful barrier to oxygen diffusion.

Foam mobility round the columns has been described above.

Future requirements

Weighing estimated costs against benefits a future programme might include the following progression:

(1) more detailed examination of oxygen introduction and foam breakdown by a cutting torch;

(2) measurement of diffusion of volatile and gaseous hydrocarbons through foam;

(3) development of a simple method to describe foam mobility;

(4) examination of potential void situation;

(5) correlation of variables in foam properties. (This section is a considerable programme in itself).

Conclusions

(1) Tests with the 500-tonne tank, under practical conditions, showed that it could be satisfactorily filled with high-expansion foam containing nitrogen without forming large voids which could present a hazard if flammable vapour and air were present. Filling either at the top or the base of the tank gave satisfactory results.

(2) Foam breakdown did not present a significant problem during a filling period of 2 h. The results of the third foam test suggest that longer filling times may be acceptable. However, in general, faster filling is preferable for both technical and economic reasons.

(3) Sampling of the gas within the tank showed that there was a relatively sharp change in composition when the foam arrived at the sampling point. There was some evidence of nitrogen entering the air immediately above the foam, particularly with the filling at the base of the tank, but not sufficient to give protection. Once the foam reached the sampling point, the oxygen concentration dropped to a low value.

(4) The rapid decrease in oxygen concentration at the foam surface indicated that, on a practical scale, the visible presence of the foam at a point implies a low oxygen concentration in the foam.

(5) When hot cutting of the wall of the tank was in progress, the concentration of oxygen adjacent to the cut increased. The gas pocket was however purged rapidly, and visibly, by the foam which emerged through the cut. As the cutting proceeded, the foam emerged progressively through the cut, indicating that the void inside the tank which was not filled with foam was confined to the immediate vicinity of the hot cutting.

(6) When the tank was purged by introducing nitrogen alone, good mixing occurred with the air initially in the tank. The oxygen concentration dropped steadily but even after about two tank volumes of nitrogen had been introduced the oxygen level was still above that readily obtained when foam was used. In practice, continuous monitoring of the atmosphere at many points would be necessary, without the benefit of the visual presence obtained using foam.

(7) Although the tests covered only some of the aspects which would be examined in a full assessment of the technique, the clear outcome of the tests encourage further serious consideration of its use where flammable materials may be present in a tank which is to be demolished or repaired.

Acknowledgement

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Reference

1 S.G. Wilson and N. Wilson-Smith, British Patent No 1 441 258, British Patents Office, 1976.