Harpur Hill, Buxton, SK17 9JN
Telephone: +44 (0)1298 218000
Facsimile: +44 (0)1298 218218

HEALTH & SAFETY LABORATORY

Evaluation of the Workbook on Gas Accumulation in a Confined and Congested Area

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Project Leader: **Dr M Ivings**
Author(s): **Dr C J Lea & Dr A Kelsey**
Science Group: **Fire & Explosion**

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EXECUTIVE SUMMARY

OBJECTIVES

In 1997 a JIP was undertaken on "gas build-up from high pressure natural gas releases in naturally ventilated offshore modules". As a consequence of the JIP, a workbook was created. The workbook aims to provide a quick, first pass, technique for estimating the flammable volume arising from the release of a material within a confined, and congested, naturally-ventilated offshore module.

However, the workbook has not, to HSE's knowledge, undergone independent assessment of its scientific basis. Neither does it appear that its performance has been evaluated against offshore measurements or the results of more detailed modelling. Hence its range of applicability and predictive capability are not well understood.

The objectives of the present project were to:

- examine the assumptions made in the workbook and comment on their likely effect on the results;

- compare the workbook predictions of ventilation velocity against offshore measurements;

- compare the workbook predictions of ventilation velocity and gas cloud size against an existing database of Computational Fluid Dynamics (CFD) results;

- review BS EN60079-10:2003 and compare the methods described for estimating ventilation rates and flammable volumes.

MAIN FINDINGS

The workbook combines correlation of large-scale trials data with extrapolation to other scenarios based on simple - and in parts uncertain - physical reasoning.

Application of the workbook involves two steps: calculation of the ventilation velocity in a module and use of that velocity in a correlation to determine flammable cloud volume. The ventilation velocity is based on the ambient velocity multiplied by correlation factors: f_4 (module geometry and orientation with respect to the wind), f_5 (confinement) and f_6 (congestion).

There is no demonstration of the validity of the expression for ventilation velocity in the workbook. The method for determination of factor f_4 is based on pragmatic estimates, rather than a well-defined scientific basis. The value of f_4 is particularly prone to uncertainty caused by interpretation of the workbook approach by the user. As an example, in the application of the workbook to a real offshore installation, values for f_4 of either 1.0 or 0.1 could be obtained based on two differing, but equally-reasonable, assumptions. As a consequence the ventilation velocity differs by a factor of 10. The workbook contains an error in the expression for factor f_5. If this error is not corrected by the user, the value of f_5, and hence the ventilation velocity, will be over-predicted by 40%. The main expression for factor f_6 is only strictly valid for levels of congestion similar to the large-scale trials on which the workbook is based.

The expression for flammable cloud volume is a correlation of large-scale trials data. However, this data is limited to a single module, single level of congestion, and a restricted set of wind conditions. The extent to which the correlation is valid for other modules is unknown. Application of the workbook thus relies on the assumption that the gas cloud behaviour seen in the JIP trials is representative of that in all offshore modules for which it might be applied.

The definition of flammable cloud volume in the workbook –the volume contained between the 5% and 15% concentration levels (i.e. lower and upper explosive limits) – leads to the correlation producing a maximum cloud volume of 0.6 of the module volume, based on the limited JIP data set. Recent data[4] shows that ignition of realistic releases can, in some cases, produce overpressures which are comparable to or exceed those from full fills of a module with stoichiometric gas. Whether truncating the cloud volume at 0.6 of the module volume affects predicted overpressures will depend on the assumptions made. If it is assumed that the full fill overpressure will occur beyond a specified value of fractional fill then the calculated overpressures may not be affected. If overpressure is assumed to vary with fill for all values then the overpressure distribution may be affected. The former assumption would appear to be a better match to the experimental data. A truncated maximum cloud volume could also affect calculated probabilities of ignition, if these depended on the fraction of a module occupied by a cloud.

The workbook does not consist of a set of well-defined unambiguous procedures to follow: in some areas application of the workbook requires considerable user interpretation. As a consequence different offshore operators may well have interpreted and extended the workbook methodology in different ways.

Application of the workbook to a real offshore installation shows large differences when predictions for ventilation velocity are compared against both offshore measurements and CFD results. The workbook consistently produces far lower ventilation velocities. However, there is no evidence to suggest that this might be a general conclusion.

The workbook predictions of flammable volume have been compared to CFD results for potential gas releases in this offshore installation in the range of 0.1 to 5.0 kg/s. Again there are large differences seen in the outcomes from the two approaches. Given the uncertainties in the workbook approach, as well as those in the CFD modelling, it is unfortunately not possible to draw firm conclusions on the performance of the workbook for prediction of flammable volume.

It has been demonstrated that a large difference in flammable volume can be obtained using the workbook approach purely as a consequence of differing, yet reasonable, assumptions when applying the methodology.

The methodology for prediction of flammable volume in BS EN60079-10:2003 has been examined. This standard does not provide a means to estimate ventilation velocity: it assumes that this is known. The definition for flammable cloud volume differs significantly to that in the workbook; BS EN60079-10:2003 adopts a more conservative definition. Overall, BS EN60079-10:2003 is far simpler than the workbook, but is based on the even more sweeping assumptions of fully-mixed conditions and a known ventilation rate.

RECOMMENDATIONS

The uncertainties in the workbook methodology and present lack of evidence of its wider applicability suggest that while the workbook is suitable for its intended use, to provide first pass estimates, it should not generally be used as the sole means to provide estimates of flammable cloud volumes for use in QRA for offshore safety cases.

An alternative method for calculating ventilation velocity was mentioned in the workbook. This alternative is a zonal approach used in ARAMAS, Advantica's risk assessment tool. It was not clear whether this approach is in use as part of the workbook approach. Little detail on the method was given so the approach was not reviewed in this work. A review of this approach to for the calculation of the ventilation velocity should be considered.

1 INTRODUCTION

In 1997 a JIP was undertaken on "gas build-up from high pressure natural gas releases in naturally ventilated offshore modules". As a consequence of the JIP, a workbook was created[1]. The workbook aims to provide a quick, first pass, technique for estimating the flammable volume arising from the release of a gas within a confined, and congested, naturally-ventilated offshore module.

This workbook is closely based on the results of the JIP experiments, together with physical reasoning to extend its applicability to other situations. It provides a quick and relatively easy approach for analysing a large number of dispersion scenarios. The originators of the workbook envisaged that it might be used as part of a QRA, where statistical analysis is required for many possible release scenarios, or, as a screening technique to determine whether more detailed analysis is necessary.

It is believed that the workbook has been used by some operators not just as a first pass technique, but rather as the sole technique for generation of a statistical distribution of flammable volumes. However, the workbook has not, to HSE's knowledge, undergone independent assessment of its scientific basis. Neither does it appear that its performance has been evaluated against offshore measurements or the results of more detailed modelling. Hence its range of applicability and predictive capability are not well understood.

The objectives of the present project were to:

- examine the assumptions made in the workbook and comment on their likely effect on the results;
- compare the workbook predictions of ventilation velocity against offshore measurements;
- compare the workbook predictions of ventilation velocity and gas cloud size against an existing database of Computational Fluid Dynamics (CFD) results;
- review BS EN60079-10:2003[2] and compare the methods described for estimating ventilation rates and flammable volumes.

This report describes the outcome of the project. In Section 2 the workbook methodology is outlined. The basis and consequences of the assumptions in the workbook are discussed in Section 3. Section 4 describes the outcome of a comparison of the workbook predictions for ventilation velocity, against offshore measurements and CFD results. In addition, Section 4 contains a comparison of the workbook predictions for gas cloud size against CFD results. Section 5 contains a brief review of the methodology in BS EN60079-10:2003 for prediction of gas cloud volume, together with a comparison against the workbook approach. Conclusions are drawn in Section 6.

2 WORKBOOK METHODOLOGY

The workbook is based on several key assumptions:

- a representative ventilation velocity, U_v, can be determined for the module;
- dispersion and gas build-up are strongly dependent on this ventilation velocity;
- a correlation of the JIP data for flammable volume can reasonably be assumed to represent gas build-up and dispersion in other modules;
- this correlation can be expressed in terms of a mass flux parameter, defined as the ratio of the volume flow rate of released material to the volume flow rate of air ventilating the module.

The workbook methodology is essentially as follows:

$$\frac{V}{L^3} = \min\left\{150\left(\frac{\dot{m}/\rho_s}{U_v L^2}\right)^{3/2}, 0.60\right\} \tag{1}$$

V is an upper estimate of the flammable volume contained between the upper and lower flammable limits (taken as 5% and 15% by volume).

L^3 is the module volume.

$\dot{m}$ is the mass flow rate of the release.

ρ_s is the density of the released material at ambient conditions.

U_v is the ventilation velocity through the module.

$\frac{\dot{m}/\rho_s}{U_v L^2}$ is the mass flux parameter.

Expression (1) could be expected to be used when screening for cases needing more detailed analysis[3].

For estimating a 'typical' flammable volume, rather than an upper bound, the following expression is proposed in the workbook:

$$\frac{V}{L^3} = \min\left\{ 75\left(\frac{\dot{m}/\rho_s}{U_v L^2} \right)^{3/2} , \quad 0.50 \right\} \tag{2}$$

Expression (2) could be expected to be used when the workbook is used to give information on the statistical distribution of flammable volumes within a QRA[3].

The representative ventilation velocity, U_v, is determined as follows:

$$\frac{U_v}{U_a} = f_4(geometry\_and\_orientation) f_5(confinement) f_6(congestion) \tag{3}$$

U_a is the ambient wind speed upwind of the module.

f_4, f_5 and f_6 are correlation factors, with values that range between 0 and 1.

3 DISCUSSION OF WORKBOOK METHODOLOGY

The workbook is based on rather sweeping assumptions. The most significant of these are discussed below.

3.1 A REPRESENTATIVE VENTILATION VELOCITY

Firstly, the workbook relies on the assumption that a ventilation velocity can be found which is representative of flow throughout a module.

In reality a module can be well-ventilated in some areas, whilst in other regions the flow may be near-stagnant. This type of flow could be described as ‘short-circuiting’: the ventilation flow does not uniformly sweep all parts of the module. A release in the well-ventilated area may be dispersed very rapidly, whilst one occurring in a confined stagnant region may build-up to form a substantial flammable volume. Releases in the latter region should be of most concern and could form a substantial contributor to the overall explosion risk. If poorly ventilated regions are present then dispersion and gas build-up will not be strongly dependent on a representative, i.e. some form of average, ventilation velocity, but will instead be more dependent on the location of a release in relation to the poorly-ventilated regions.

Although the workbook deals only with a representative ventilation velocity effects, such as those outlined above, may be partially taken into account. This is because it is based on a correlation derived from a large number of releases from the JIP trials. Some of these releases were in sheltered, i.e. poorly-ventilated, regions. The correlation for flammable volume is formulated in terms of either an upper estimate for flammable volume or a typical flammable volume. If the upper estimate correlation is used, then this can be expected to be bounded by releases that, for whatever reason, lead to the largest flammable volumes, for example, those in near-stagnant regions.

However, we then have to consider whether the data from the JIP could be considered to be representative of all other modules, releases, wind conditions, etc. Obviously there is no reason to think this would be the case, nor is it demonstrated to be the case in the workbook.

The workbook is based on a calculation of ventilation velocity prior to a leak occurring, or alternatively one assumed to be independent of the release. In reality large leaks have the potential to substantially modify the ventilation flow through a module. The ventilation can be enhanced if the release is oriented in the wind direction, or reduced if oriented into the wind. This effect will not be captured by expression (3). Some of the JIP large gas releases were found to modify the ventilation flow. The effects of this modification to the ventilation, and hence gas dispersion, will be included in the correlation for flammable volume, since this covers all the experimental releases. The flammable volume correlation is, in effect, tailored to include the influences of these changes in ventilation velocity. However, this means that the applicability of this correlation is reduced – to the range of scenarios examined in the JIP.

3.2 DETERMINATION OF VENTILATION VELOCITY AND CORRELATION FACTORS

If a representative ventilation velocity exists, its value will depend on a wide range of factors. Expression (3) attempts to take the most important of these into account in a simple fashion.

However, there is no demonstration of the validity of expression (3) in the workbook. It is particularly surprising that there is no comparison in the workbook between the ventilation velocity as given by expression (3) and measurements from the JIP data. It should be noted that the prediction of ventilation velocity is a key part of the overall approach.

The absence of such a comparison could be because the range of module configurations and wind directions during these trials was quite limited. There is also a degree of calibration of the correlation factors in expression (3) using the JIP data, particularly for factor f_6 and somewhat less so for factor f_5. Hence it could be that such a comparison would merely confirm that the calibration was appropriate for the limited range of JIP configurations and wind conditions. Even so, it would have been useful to see whether this is the case.

Turning now to the estimation of factors f_4, f_5 and f_6:

3.2.1 Factor f_4 – geometry and orientation

Correlation factor f_4 is dependent on the module type and the wind direction relative to the module.

As an example, if the module is roughly rectangular in shape and has two opposite vertical faces closed, with the other two vertical faces nominally open, then f_4 is defined to be 1.0 for the wind direction normal to the open faces, and 0.1 for a direction normal to the closed faces. For other wind directions f_4 varies as the cosine of the angle between the wind direction and the normal to the open faces. Such a module is classed in the workbook as Type 1. This is illustrated below.

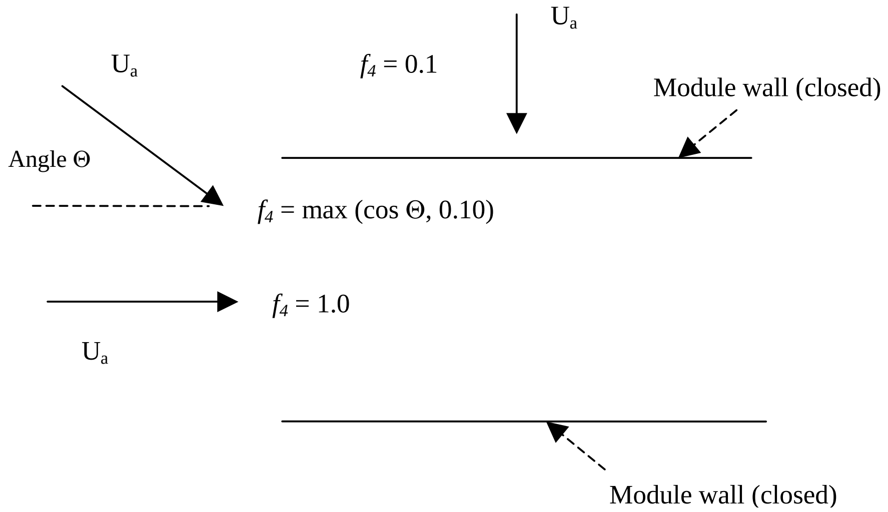

Figure 1 Factor f_4 for a module designated as Type 1

Note that for wind normal to the closed faces, f_4 is not defined to be zero, but is instead set to 0.1. This is to account for the effect of fluctuations in the wind direction. The argument is that even a wind direction which is nominally normal to a closed face will exhibit natural variation, so driving some flow through the module, assumed to be 0.1 of the ambient velocity. However, no such effect is considered when the wind direction is normal to the open faces. If it was included, it would presumably have the effect of reducing f_4 to a value somewhat less than 1.0.

Two other module types are also defined, Types 2 and 3. In these cases the classification depends on the two most open faces being adjacent to each other, with either one or both of these faces being open to atmosphere. The value of f_4 again depends on the wind direction relative to the faces of the module. Further details are given in the workbook[1].

For modules of all types the values assigned to f_4 are in fact largely based on pragmatic estimates, rather than a well-defined scientific basis.

In all cases the determination of factor f_4 relies on the user of the workbook deciding which of the faces of the module have the most open area. However, this is not always an obvious decision and its consequences can be profound. This potential problem is illustrated in Section 4. However, in brief, the decision made can result in factor f_4 taking a value of either 1.0, or 0.1. That is, the ventilation velocity in the module could be ten times larger, or smaller, depending on the judgement of the user as to which two faces of the module are the most open.

The workbook does not cover all, or possibly even many, types of module arrangement. For example it does not cover situations in which the floor of the module is one of the most open faces. It states that extension of the method for determination of f_4 to cover such configurations is straightforward, but this is not illustrated and does not seem to be the case.

The workbook does not take account of sheltering from other platforms in an installation in the determination of f_4, or, that flow through a module may be affected by the presence of other modules above and below the module in question.

Therefore for some, possibly many, module configurations, a considerable degree of user interpretation is required to allow determination of values for factor f_4.

3.2.2 Factor f_5 - confinement

Correlation factor f_5 represents the reduction in ventilation velocity caused by confinements (such as wind walls) on the nominally 'open' faces of the module. It is based on physical reasoning and calibration against the JIP data. To determine f_5 requires the ratio of the open area on a face to its total area. Determination of f_5 will depend on less user interpretation than needed for factor f_4. Overall we judge that uncertainty and variability in f_5 will be less than that found for f_4. Note, however, that the workbook contains an error at this point: the multiplier '2' in the expression for f_5 should in fact be $2^{1/2}$. If the user does not take this error into account when applying the workbook, then factor f_5, and hence the ventilation velocity, will be over-estimated by $2^{1/2}$, or about 40%.

3.2.3 Factor f_6 - congestion

The correlation factor f_6 represents the reduction in ventilation velocity as a result of obstacles in the module. The main expression for f_6 in the workbook is based on calibration against one of the sets of JIP trials. Hence this expression is only strictly appropriate for congestion equivalent to that found in these JIP trials.

An alternative, more general, expression for f_6 is also described during the workbook's derivation of this correlation factor. However, this alternative expression is not highlighted. It is therefore possible that the cursory user could employ a correlation factor for f_6 which is inappropriate.

This alternative expression is based on the ratio of the frontal area of all obstacles in the module, to the cross-sectional area of the module. It has its roots in a simplified equation for the pressure drop across a single obstacle. However, its extension to the multiplicity of obstacles found in an offshore module does introduce uncertainty. For example, its use implies that the pressure drop from a single obstacle of diameter D, is the same as that from 100 randomly oriented obstacles of diameter D/100, which in general is not the case. In addition, quantification of the frontal area of all obstacles may require considerable effort. In practice it seems likely that the effort used in the estimation for frontal area would be consistent with the overall level of effort required to apply the workbook. Hence if this alternative expression for f_6 is used, it could be that further uncertainty is introduced as a consequence of estimation of the frontal area.

3.2.4 Summary

Clearly there are numerous assumptions contained within the workbook approach for calculation of ventilation velocity. The general validity of both expression (3) and the methodology for determination of factors f_4, f_5 and f_6 is not demonstrated by the workbook. We feel that most uncertainty attaches to the determination of factors f_4 and f_6. This uncertainty will be directly reflected in the ventilation velocity, and hence flammable cloud volume, via expression (1). There is no reason to suggest that the ventilation velocity returned from expression (3) would in all cases be a cautious under-estimate.

3.3 ALTERNATIVE METHOD TO CALCULATE VENTILATION VELOCITY

The workbook as it appears in reference 1 also outlines a further method for determining U_v, in Appendix A, which is different to that of expression (3) above. This alternative method is instead based on a zonal approach apparently used in ARAMAS, Advantica's risk assessment tool for offshore modules. This method is also mentioned in the FABIG Newsletter[3] which outlines the workbook. However, the alternative method is not described in sufficient detail that it could be readily applied; only a description of the basic methodology is given.

Hence it is not fully clear whether a QRA received by HSE and said to be based on the workbook would imply the use of expression (3), above, to determine module ventilation velocity, or, the use of an alternative zonal method as, for example, embodied in ARAMAS.

This could be significant, because the zonal method of calculating ventilation velocity appears to be more soundly-based than that in (3), although its details are not given. In addition, the workbook contains a comparison between measured ventilation rates from the JIP trials and those predicted using the zonal approach, thereby giving a measure of confidence in the zonal model. There is, as already mentioned, no such comparison provided in the workbook for the expression given in (3).

Although this alternative zonal approach for the estimation of ventilation velocity exists, references 1 & 2 both imply that expression (3), above, constitutes the 'workbook approach'. This being the case, no further consideration will be given to the contents of Appendix A of the workbook and the zonal approach.

3.4 FLAMMABLE CLOUD VOLUME

The central question about the predicted flammable cloud volume is to what extent are expressions (1) and (2) representative of the behaviour that could be seen from releases in modules other than that used for the JIP trials? No answer can be given: these expressions are purely correlations based on the JIP data. The extent to which these expressions are valid, or invalid, for other modules, is unknown. Application of the workbook thus relies on the assumption that the gas cloud behaviour seen in the JIP trials is representative of that in all offshore modules to which it might be applied.

Whilst the JIP data is reasonably comprehensive, it is still limited. For example, in these trials the wind was mostly from a single (West) direction. Only one obstacle arrangement was investigated. Low wind speeds were not covered.

Therefore, for applications which are not similar to the JIP trials, there must be considerable uncertainty in the validity of predictions for flammable cloud volume.

For cases similar to the JIP trials, the workbook proposes an uncertainty of +/- 20%. However, this is only a subjective estimate.

The definition of flammable volume in the workbook, namely that volume between the upper and lower flammability limits, is also of significance. Gas at concentrations above the upper flammable limit has not been counted as part of the flammable volume, i.e. it is assumed that this would not participate in an explosion.

It is the use of this definition which limits the maximum cloud volume to be no more than 0.6 times the module volume, based on the limited JIP data. The limit is applied irrespective of mass release rate or ventilation velocity, see expression (1). This could be imposing an artificially low limit to the cloud size. In reality the explosion hazard from very large releases may be the same as that arising from a full fill of the module with flammable gas. This is supported by the outcome of the Phase 3B large-scale explosion trials, in which realistic, high pressure, gas releases were ignited in the JIP rig. Johnson et al[4] report:

> *'Though considerable variation in flammable cloud size and concentration was observed in the experiments, under some release and weather conditions, significant portions of the module were filled with near stoichiometric natural gas-air mixture. These conditions were generally produced by impacting releases where the confinement, release rate and weather conditions resulted in recirculation and gradual accumulation of the natural gas-air mixture within the rig.*
>
> *The overpressures generated in the realistic release experiments were in general lower than those produced in equivalent base case experiments. However, in experiments where there were significant proportions of the test rig filled with near stoichiometric mixture, the overpressures produced were comparable to or exceeded those generated in the base case experiments.'*

In this context the base case experiments comprised complete fills of the module with a quiescent stoichiometric gas mixture. It is clear from the above work that some high pressure gas releases in a module are capable of producing an explosion hazard which is equivalent to a full fill of stoichiometric gas, not 0.6 of the fill as embodied in the workbook. Treatment of the overpressure based on cloud volumes must recognise this fact. A truncated maximum cloud volume could also affect calculated probabilities of ignition, if these depended on the fraction of a module occupied by a cloud.

3.5 ADDITIONAL REMARKS

The workbook does not consist of a well-defined unambiguous set of procedures to be followed. Instead it is more in the nature of a detailed methodology, which in some areas is open to considerable interpretation by the user. This is particularly the case with respect to factor f_4. This factor represents the effect of module geometry and orientation on the ventilation velocity. In practice there is a huge variation in the design and location of modules with respect to other parts of an offshore installation. Hence what the workbook seeks to do is to identify a number of scenarios and set out how f_4 is to be determined for these cases (which are in fact closely related to the JIP configurations) and then suggest that extension to other scenarios could be made along similar lines.

What this means is that different operators may well have interpreted and extended the workbook methodology in different ways.

To be fair, the authors of the workbook are open about its limitations. For example, they point out that the JIP trials, although extensive, were still limited in several respects; single module congestion, limited wind directions, etc. They state that:

> *'This workbook..……is intended to provide the user with a quick first pass technique for estimating the flammable volume.….'*

That is a first pass technique, not the only technique used to estimate flammable volume.

The article on the workbook in the FABIG Newsletter[3] states:

> *'…it is most likely that the workbook would be used at the early stages of a new development when some idea of the overall level of risk is required.………….as more details of the module layout are produced it is likely that more detailed analysis would be warranted, using a range of more sophisticated models.…'*

It seems clear that the authors of the workbook never intended it to be widely used as the sole means of estimating gas cloud volume.

The extent to which the workbook could be used in support of compliance with standards[5,6] could also be in doubt. Adequate ventilation as defined in IP15 requires, for sheltered or enclosed areas, a uniform ventilation rate of 12 air changes per hour and no stagnant areas. ISO 15138 notes that the distribution of air within the area/module is considered to be at least as important as the quantity of air supplied. However, the workbook gives no information on the distribution of ventilation in a module, or the presence/absence of stagnant areas.

4 COMPARISON AGAINST DATA

4.1 OVERVIEW

In this section the workbook is applied to the prediction of ventilation velocity and gas cloud volume for one of the three installations, Installation C, investigated in HSE project JR41.110. A comparison of workbook predictions of ventilation velocity is made against offshore measurements and CFD results. In addition, workbook predictions for flammable volume are compared to the output of CFD simulations for postulated gas releases in this same installation.

As a source of data for comparison against the workbook, this installation is by far the most valuable of the three installations examined in JR41.110. This is because there is not only a comprehensive dataset of offshore velocity measurements, but also because there are CFD predictions available as well, which give added insight into the performance of the workbook.

Originally it was envisaged that comparison would be made against offshore measurements on all three installations covered by JR41.110. However, as will be seen, comparison for just one installation is already revealing of the performance of the workbook.

The final report[7] from JR41.110 was studied to establish what data could usefully be extracted to form the basis for comparison against workbook predictions.

In brief, the offshore measurements of ventilation velocity, and the CFD simulations, can be used to support the validity, or otherwise, of expression (3). The CFD simulations of gas releases can be used to examine the applicability of expressions (1) and (2).

It should be recognised that these offshore measurements and CFD data also have their limitations. The CFD data is based on modelling, although at a more fundamental level than that of the workbook. The measurements, whilst comprehensive, do not allow for a complete mapping of the flow throughout the module. Neither was it found possible to determine a volumetric ventilation rate by measurement.

Nevertheless, a comparison between this data and the predictions of the workbook will enhance understanding of the applicability and accuracy of the workbook. In addition, the process of applying the workbook to these scenarios is revealing, particularly of the amount of interpretation required to use the workbook and the resulting uncertainty.

Information to be extracted from the offshore measurements and CFD was defined. This in itself requires some interpretation. For instance, the workbook does not define 'ambient velocity' in detail. However, it is reasonable to assume that what is meant is the flow speed at the module height, although most measurements of flow speed which are available practically will not be at this height; they will instead be from the heli-deck (i.e higher and hence faster), or a standby vessel (lower and hence slower) or MET data (say at a standard 10m above sea level). This could be another source of uncertainty when the workbook is applied by operators: has the correct ambient velocity been used?, also has this information been recorded. In the processing of the offshore measurements and CFD results, the measured wind speed (typically at 5 m or 10 m above sea level), has been corrected to give a velocity at the module height. This can be done with knowledge of the variation of wind speed with height.

4.2 SCENARIOS

For Installation C, offshore measurements were gathered during 21 tests. Velocity measurements were made using ultrasonic anemometers, at between 18 and 88 locations per test. The majority of the tests had at least 66 velocity measurement locations. Measurements were made throughout the plan area of the module, at three different heights above the solid floor; 1 m, 2 m and 2.82 m. Some measurements were also made on the mezzanine level, the same measurement heights were used on the mezzanine as above the solid floor, giving heights above the solid floor of 5.5m, 6.5m and 7.32m. Flow data from the upper regions of the module is, however, much more limited than at lower levels. Attempts were also made to measure global quantities, such as air change rate, but these were unsuccessful.

The CFD data covers a smaller number of test cases, but has the advantage that gas releases were simulated in addition to the ventilation flows. Flammable volumes can be extracted from this data and compared to the predictions of the workbook.

CFD simulations were undertaken in two phases. Initially the windfield external to the five platforms in the Installation was computed. From this, the surface pressure distribution was extracted and used as a boundary condition for simulation of flow inside the cellar deck module of the production platform.

CFD simulations were carried out for three of the conditions at which offshore experimental measurements were made; tests 12, 7, 15 & 19. The last two tests are measurements made on the cellar deck and mezzanine at the same condition and can be treated as a single test. These CFD simulations are referred to as cases V1, V2 and V3. In project R41.110 the computed velocity field for V1, V2 and V3 was compared to the experimental measurements. Here predictions of the workbook value for U_v for these cases are compared to values for U_v extracted from both the measurements and CFD results. By using both sources of data, bias in the conclusions – arising from uncertainty in each source – should be reduced.

CFD simulations were also undertaken for eight wind directions at compass points, and two wind speeds. Whilst this data could be used to provide a further source for U_v, there are no directly comparable offshore measurements. Hence there would be additional uncertainty in conclusions reached on the workbook if reliance were placed on this CFD data in the absence of measurements. Hence this velocity data will not be used.

Finally, CFD simulations were undertaken for gas releases in the module for some of these eight wind directions and two wind speeds. A single release location and direction was used, judged as leading to ‘worst case’ conditions, i.e. conducive to gas build-up. Three wind directions, two wind speeds, and three mass release rates, were simulated. All simulations were transient, one for a release duration of five minutes, the remainder for a release duration of two minutes.

In the absence of any other data on gas cloud volumes, it is proposed to compare the predictions of the workbook against a sub-set of these gas release simulations. There will, of course, be uncertainty in the CFD data for gas cloud volume, which unfortunately cannot be quantified here. The specific cases used for comparison are as follows:

- SE wind, 6.5 knots, 0.1/1.0/5.0 kg/s release rate (cases D7, D3 and D9 respectively). These allow the effect of release rate on flammable volume to be examined.

- N wind, 6.5 knots, 5.0 kg/s release rate, and W wind, 6.5 knots, 1.0 kg/s release rate (cases D10 and D1 respectively). These cases allow – to some extent - the effects of wind direction on flammable volume to be examined.

- W wind, 14 knots, 1.0 kg/s release rate (case D5). This allows the effect of wind speed on flammable volume to be examined.

In summary, the scenarios used for comparison against the workbook are as follows:

- three offshore measurement tests (12, 7, 15/19) providing data for U_v for comparison with the workbook;

- the corresponding CFD simulations (V1, V2, V3) provding results for U_v;

- the CFD data for six gas release simulations (D7, D3, D9, D10, D1 and D5) providing results on flammable cloud volumes for comparison with the workbook.

4.3 DATA EXTRACTED

An overview of the data which has been extracted from the offshore measurements and CFD simulations is given below.

4.3.1 Geometric

The module width, length and height.

The open area of each of the N, S, E, W – facing walls of the module.

The volume occupied by obstacles in the module. This has been achieved by analysis of the CFD geometry, but taking care to ensure that those obstacles represented as porous media in the CFD model are also included. This volume is needed for calculation of f_6 using the main expression for this parameter in the workbook.

4.3.2 Ambient velocity

The ambient wind speed upwind of the module (U_a), calculated at the module height, based on the reference wind speed at its reference height (5 m above sea level for cases V1, V2 and V3, and 10m above sea level for cases D7, D3, D9, D10, D1 and D5) with knowledge of the boundary layer profile, taking into account surface (sea) roughness.

4.3.3 Ventilation velocity

The ventilation velocity through the module (U_v).

The workbook does not define this velocity in any more detail. However, the workbook implies that it is that velocity which if applied uniformily throughout the module would give the same volume flow rate through the module as found in reality.

For the offshore measurements, only spot values of velocity are available. Hence a simple average of measurements for velocity magnitude at all locations for each of tests V1, V2 and V3 was made. The same method was used to calculate a ventilation velocity from the CFD results, i.e. an average of spot values for computed velocity magnitude at the same locations at which the offshore measurements were made. This measure does not account for any effects of flow recirculation on the velocity magnitudes.

In addition, for the CFD results, the computed total volume flow rate through the module was extracted from the simulations.

4.3.4 Flammable volume

The workbook defines the flammable volume, *V*, to be the volume with a concentration between 5% and 15% by volume of the released gas.

However, this definition assumes that gas at concentrations above 15%, the upper flammability limit, will not contribute to the explosion. For the JIP data this leads to the expression for the upper bound of flammable volume having a maximum value of 0.6.

In other areas of HSE's work a concentration of half of the lower explosion limit is often used to define the outer boundaries of the cloud, i.e. 2.5%. Note that the CFD simulations show (Table 9.1 in ECO/02/15) that the 2.5% iso-surface can be two orders of magnitude larger than the 5% iso-surface. That is, there can be an extreme sensitivity of cloud volume to the concentration used to define the outer extent of the cloud.

The workbook provides, p25 – 26, an expression for computing the flammable volume for concentrations other than those between 5% and 15%.

In view of the above, the CFD data was examined to extract flammable volume for the following concentrations:

- total volume contained within the 15% concentration by volume iso-surface;
- total volume contained within the 5% concentration by volume iso-surface;
- total volume contained within the 2.5% concentration by volume iso-surface.

Unfortunately the CFD data for gas releases is transient, whilst the workbook assumes steady-state conditions. Even more unfortunately the CFD does not necessarily reach a steady-state gas cloud size before the release is switched-off. A comment is made in the next section on the extent to which the CFD results for gas cloud size are at steady-state.

4.4 COMPARISON OF VENTILATION VELOCITY

The module is outlined in Figures 1 to 4, in the Appendix. These Figures are derived from the CFD geometry of the module. The shaded areas are openings in the faces of the module as defined in the CFD geometry. The East face of the module comprises a solid blast wall, in which there are no openings.

The first step in application of the workbook is the determination of the two faces with the largest open area. This is not quite as straightforward as it seems, because of the presence of the 'annex' – see Figure 4. Thus it is not clear whether to include the open areas in the annex with those of the corresponding main face of the module (i.e. add the West-facing open area in the annex to the open area on the main West-face), or whether to ignore these annex areas altogether. The decision is crucial, since depending on which areas of the annex are included determines whether the module will be classed as Type 1, or Type 2 in the workbook terminology. This could mean the difference between a value for factor f_4, of 1.0, or 0.1. Expression (3) shows that this would have a direct influence on the calculated ventilation velocity.

For the present, choosing to ignore the open areas on the North and South faces of the annex, but including the open area on the West face of the annex, results in the North and West faces of the module as having the most open area. These two faces are adjacent to each other and open to the atmosphere, so the module is defined as Type 2 in workbook terminology.

The detailed calculation of factors f_4, f_5 and f_6 is not presented here. Instead, Table 1 provides a tabulation of these factors, together with the workbook value for ventilation velocity. Table 2 contains the workbook ventilation velocity, along with the measured ventilation velocity, based on an average of all offshore velocity measurements, the corresponding CFD value, and finally a range of CFD-derived values for ventilation velocity based on the volume flow rate through the module. In the latter case the range of values occurs as a result of averaging the volume flow across either the North-South, or East-West cross-sectional area of the module.

Table 1 Calculation of workbook ventilation velocity – module Type 2

Parameter	*Offshore test 12, Simulation V1*	*Offshore test 7, Simulation V2*	*Offshore tests 15 &19 Simulation V3*
Wind direction, degrees from North	199	92	208
Ambient velocity U_a at module height, m/s	16.85	4.8	9.05
f_4	0.33	0.1	0.47
f_5	0.21	0.21	0.21
f_6	0.37	0.37	0.37
Workbook ventilation velocity U_v, m/s	0.43	0.037	0.33

Table 2 Comparison of ventilation velocity – module Type 2

Parameter	*Offshore test 12, Simulation V1*	*Offshore test 7, Simulation V2*	*Offshore tests 15 &19 Simulation V3*
Workbook ventilation velocity U_v, m/s	0.43	0.037	0.33
Measured average ventilation velocity, m/s	2.05	0.21	1.57
CFD average ventilation velocity, m/s	3.62	0.41	2.1
CFD ventilation velocity based on volume flow, m/s	2.7 to 3.3	0.22 to 0.26	1.4 to 1.7

Note that factor f_6 above is determined from the main expression for this correlation in the workbook, a correlation which is strictly only applicable to the JIP geometry. Estimates were made of the frontal area of all obstacles in the module, in an attempt to apply the more general form of this correlation. In this case f_6 was estimated to have a value of between 0.53 and 0.7, compared to the main expression value of 0.37.

It is immediately apparent that the workbook prediction for ventilation velocity is far lower than the measurements or values derived from the CFD. It is interesting to note that the measured value for ventilation velocity and the CFD derived values are similar. This tends to suggest that the actual ventilation velocity is indeed far higher than that predicted by the workbook, even taking into account the crude method used to obtain average measured ventilation velocities, not to mention uncertainties in the CFD modelling. It is not clear why the workbook prediction for ventilation velocity is so low. Note that from application of the workbook to this one installation it cannot be inferred that ventilation velocity will always be predicted to be lower than found in reality. There is no reason to suspect that this should be the case.

If, however, all the open areas in the annex are ignored, then the North and South faces of the module have the most open area. In this case, the module now becomes classed as Type 1. The effect on the values of factors f_4, f_5 and f_6 is illustrated in Tables 3 and 4, below, by the additions in parentheses to Tables 1 and 2.

Table 3 Calculation of workbook ventilation velocity – workbook module Type 1 values in parentheses

Parameter	***Offshore test 12, Simulation V1***	***Offshore test 7, Simulation V2***	***Offshore tests 15 &19 Simulation V3***
Wind direction, degrees from North	199	92	208
Ambient velocity U_a at module height, m/s	16.85	4.8	9.05
F_4	0.33 (0.95)	0.1 (0.1)	0.47 (0.88)
F_5	0.21 (0.16)	0.21 (0.16)	0.21 (0.16)
F_6	0.37 (0.4)	0.37 (0.4)	0.37 (0.4)
Workbook ventilation velocity U_v, m/s	0.43 (1.0)	0.037 (0.031)	0.33 (0.51)

Table 4 Comparison of ventilation velocity – workbook module Type 1 values in parentheses

Parameter	***Offshore test 12, Simulation V1***	***Offshore test 7, Simulation V2***	***Offshore tests 15 &19 Simulation V3***
Workbook ventilation velocity U_v, m/s	0.43 (1.0)	0.037 (0.031)	0.33 (0.51)
Measured average ventilation velocity, m/s	2.05	0.21	1.57
CFD average ventilation velocity, m/s	3.62	0.41	2.1
CFD ventilation velocity based on volume flow, m/s	2.7 to 3.3	0.22 to 0.26	1.4 to 1.7

The effect of this slight change in what is regarded as the open area of the module faces is large for test 12/simulation V1, increasing the predicted ventilation velocity from 0.43 m/s to 1.0 m/s. The effect for the other two scenarios is relatively small. This illustrates the point that the way in which the user applies the workbook can potentially have a significant effect on the predicted ventilation velocity. This will feed through into the prediction of flammable volume.

4.5 COMPARISON OF FLAMMABLE VOLUME

The CFD value for flammable volume, *V*, is in all cases compared against the upper bound estimate for *V* from the workbook, i.e. expression (1). This is because the CFD release is chosen so as to be directed into a relatively sheltered location, i.e. it is not representative of a 'typical release', in the workbook terminology.

The same methodology is used as above, that is, the module is initially classed as Type 2, and the workbook is used to calculate ventilation velocity and flammable volume – using expression (1). Then the module is classed as Type 1, with the workbook again used to predict ventilation velocity and flammable volume.

These results are shown in Table 5. The detailed calculation of factors f_4, f_5 and f_6 is again not presented. Instead, Table 5 provides a tabulation of these factors. Table 6 shows the calculated workbook flammable volumes, along with those extracted from the CFD simulations. For cases where the cloud volume at a particular concentration did not reach steady-state, the entry in the table is listed as '> numerical value', to indicate that the cloud size is still increasing. Values in parentheses are again those obtained assuming that the module is Type 1, rather than Type 2.

Table 5 Calculation and comparison of workbook flammable volumes – module Type 2, with module Type 1 values in parentheses

Parameter	***D1***	***D5***	***D10***	***D7***	***D3***	***D9***
Wind direction, from….	West	West	North	South East	South East	South East
Ambient velocity U_a at module height, m/s	3.65	7.85	3.65	3.65	3.65	3.65
Release rate, kg/s	1.0	1.0	5.0	0.1	1.0	5.0
f_4	1.0 (0.1)	1.0 (0.1)	1.0 (1.0)	0.1 (0.71)	0.1 (0.71)	0.1 (0.71)
f_5	0.21 (0.16)	0.21 (0.16)	0.21 (0.16)	0.21 (0.16)	0.21 (0.16)	0.21 (0.16)
f_6	0.37 (0.4)	0.37 (0.4)	0.4 (0.4)	0.4 (0.4)	0.4 (0.4)	0.4 (0.4)
Workbook ventilation velocity U_v, m/s	0.28 (0.02)	0.61 (0.05)	0.31 (0.23)	0.03 (0.17)	0.03 (0.17)	0.03 (0.17)
Workbook flammable volume, V, (between 15% & 5%), m^3	735 (6528)	229 (6528)	6528 (6528)	664 (49)	6528 (1555)	6528 (6528)

Note that 6528 m^3 is $0.6L^3$. This means that the calculated flammable volume from the mass flux part of expression (1) is greater than $0.6L^3$, so the volume has been set to be 6528 m^3.

Table 6 Comparison of flammable volumes – workbook module Type 2, with workbook module Type 1 values in parentheses

Parameter	***D1***	***D5***	***D10***	***D7***	***D3***	***D9***
Workbook flammable volume, V, (between 15% & 5%), m³	735 (6528)	229 (6528)	6528 (6528)	664 (49)	6528 (1555)	6528 (6528)
CFD flammable volume (between 15% & 5%), m³	3.8	1.75	>1661	0.05	>3.9	>4216
CFD flammable volume (above 2.5%), m³	>3630	>297	>3817	0.38	>1547	>6300

The flammable volume as predicted by the workbook is generally very much larger than that extracted from the CFD. The main reason for this is that the workbook predicts low ventilation velocities, which results in a large mass flux parameter in expression (1).

For cases D9 and D10, covering releases at the largest release rate, 5 kg/s, the CFD-derived flammable cloud volume is not at steady-state; it was still growing when the simulations were stopped. Hence it is possible for these cases that the workbook prediction of flammable cloud volume may not be very different to the steady state CFD flammable cloud volume.

However, when the cloud volume as defined by 2.5% concentration is examined, the workbook and CFD predictions become comparable – with the exception of case D7 (lowest release rate)

There is a marked sensitivity in the CFD simulations: the cloud volume increases very rapidly as its defining concentration reduces. For instance, for case D1, the CFD-derived cloud volume is 3.8 m^3 for concentrations between 5% and 15%, but 3630 m^3 for a concentration of 2.5%. In all cases, the CFD-derived volume at concentrations greater than 15% is negligible.

This sensitivity, coupled with other uncertainties in the CFD modelling for gas releases and dispersion, mean that it is unfortunately not possible to draw firm conclusions on the performance of the workbook for prediction of flammable volume.

Nevertheless, it appears as though the workbook prediction of flammable cloud volume may be very conservative when the release rate is small (i.e.~ 0.1 kg/s) and the ventilation velocity is low (i.e. less than 0.1 m/s). Conversely, when the release rate is larger (i.e. ~5 kg/s) and the ventilation velocity is not too small (i.e. greater than ~0.3 m/s), the workbook prediction of flammable volume may be comparable with that from other, more sophisticated, techniques – such as CFD.

Given the uncertainties in the workbook approach, as well as those in the CFD modelling, it would however, be unwise to assume that this is a firm conclusion which is generally valid.

Finally, Table 5 shows that the effect of a slight change in what is regarded as the open area of the module faces can be very substantial. So, omitting the West-facing open area in the annex, from the total open area of the West face, means that the North and South faces now have the most open area. This results in a change from a Type 2 to a Type 1 module. Factor f_4 can then be very different and this feeds through into the prediction of flammable volume via the mass flux parameter in expression (1). In case D7, the flammable volume is reduced by a factor of about 14. This further highlights the point that the way in which the user applies the workbook can potentially have very significant effects on both the predicted ventilation velocity and flammable volume.

5 REVIEW OF METHODOLOGY IN BS EN60079-10:2003

BS EN60079-10:2003[2] is a standard for:

> *'…..the classification of hazardous areas where flammable gas or vapour risks may arise, in order to permit the proper selection and installation of apparatus for use in such hazardous areas.'*

Annex B of this standard provides a means to assess the degree of ventilation. In particular the standard provides a method to determine the type of zone by:

> *'…..calculating a hypothetical volume, V_z, which allows determination of the degree of ventilation..…'*

The hypothetical volume V_z, represents:

> *'...the volume over which the mean concentration of the flammable gas is either 0.25 or 0.5 times the lower explosive limit (LEL), depending on a safety factor, k. This means that, at the extremities of the hypothetical volume estimated, the concentration of gas would be significantly below the LEL, i.e. the volume where the concentration is above the LEL would be less than V_z.'*

BS EN60079-10:2003 advises a safety factor, *k*, of 0.5 LEL, for releases which are not expected to occur during normal operation.

This volume is different from the workbook flammable volume in several key respects. The difference is that flammable volume is defined much more conservatively than in the workbook.

This conservatism arises partly through the use of 0.5 LEL, rather than LEL as the cloud boundary. Note that the workbook actually uses a volume which is potentially smaller even than that defined at LEL, being based on the volume between LEL at 5%, and 15% - the upper explosive limit.

The conservatism also arises from use of a hypothetical volume at a mean concentration, rather than the actual flammable volume bounded by that concentration: the former volume will always be larger than the latter.

BS EN60079-10:2003 does not, in fact, provide a method to predict the ventilation velocity. It is assumed that this is known, or can be estimated. The method in BS EN60079-10:2003 for computing the flammable volume is simply based on the assumption that releases are instantaneously and homogeneously mixed in the (known) through-flow of air. To account for the efficiency of the ventilation, i.e. some areas being more poorly ventilated, a factor is applied to the flammable volume. The factor has a value of one for ideal ventilation and five for 'impeded' air flow.

This being the case, it is not possible to compare the workbook and BS EN60079-10:2003 methodologies for the prediction of ventilation velocity. A direct comparison of flammable volumes from the two approaches is not meaningful, since their definition is quite different.

In summary, BS EN60079-10:2003 adopts a more conservative definition of flammable cloud volume than is the case with the workbook. However, unlike the workbook, the standard assumes that the ventilation rate is known or can be estimated. Instead of using a correlation of data to determine flammable cloud volume, as in the workbook approach, the standard simply assumes that releases are well-mixed in the ventilation flow. Overall, BS EN60079-10:2003 is far simpler than the workbook, but is based on the even more sweeping assumptions of fully-mixed conditions and a known ventilation rate.

6 CONCLUSIONS

The workbook on gas build-up from high pressure natural gas releases in naturally ventilated offshore modules has been examined to evaluate its scientific basis and performance. Predictions of the workbook have been compared to offshore velocity measurements. In addition, a database of CFD simulations has been used to provide further insight into the performance of the workbook: predicted ventilation velocities and flammable cloud volumes have been compared against the CFD results.

It is concluded that the workbook combines correlation of large-scale trials data with extrapolation to other scenarios based on simple - and in parts uncertain - physical reasoning.

Application of the workbook involves two steps: calculation of the ventilation velocity in a module and use of that velocity in a correlation to determine flammable cloud volume. The ventilation velocity is based on the ambient velocity multiplied by correlation factors: f_4 (module geometry and orientation with respect to the wind), f_5 (confinement) and f_6 (congestion).

There is no demonstration of the validity of the expression for ventilation velocity in the workbook. The method for determination of factor f_4 is based on pragmatic estimates, rather than a well-defined scientific basis. The value of f_4 is particularly prone to uncertainty caused by interpretation of the workbook approach by the user. As an example, in the application of the workbook to a real offshore installation, values for f_4 of either 1.0 or 0.1 could be obtained based on two differing, but equally-reasonable, assumptions. As a consequence the predicted ventilation velocity would differ by a factor of 10. The workbook contains an error in the expression for factor f_5. If this error is not corrected by the user, the value of f_5, and hence the ventilation velocity, will be over-predicted by 40%. The main expression for factor f_6 is strictly valid only for levels of congestion similar to the large-scale trials on which the workbook is based.

An alternative method of calculating ventilation velocity is presented in Appendix A of the workbook[1]. This alternative is a zonal approach used in ARAMAS, Advantica's risk assessment tool. It was not clear whether this approach is in use as part of the workbook approach. Little detail of this method was given so it was not reviewed in this work. A review of this approach to calculation of ventilation velocity should be considered.

The expression for flammable cloud volume is a correlation based on large-scale trials data. However, this data is limited to a single module, single level of congestion, and a restricted set of wind conditions. The extent to which the correlation is valid for other modules is unknown. Application of the workbook thus relies on the assumption that the gas cloud behaviour seen in the JIP trials is representative of that in all offshore modules for which it might be applied.

The definition of flammable cloud volume in the workbook –the volume contained between the 5% and 15% concentration levels (i.e. lower and upper explosive limits) – leads to the correlation producing a maximum cloud volume of 0.6 of the module volume, based on the limited JIP data set. Recent data[4] shows that ignition of realistic releases can, in some cases, produce overpressures which are comparable to or exceed those from full fills of a module with stoichiometric gas. Whether truncating the cloud volume at 0.6 of the module volume affects predicted overpressures will depend on the assumptions used. If it is assumed that the full fill overpressure will occur for a fractional fill greater than a specified value then calculated overpressures may not be affected. If the overpressure is assumed to vary with fill for all values then the overpressure distribution may be affected. The former assumption would appear to be a better match to the experimental data. A truncated maximum cloud volume could also affect calculated probabilities of ignition, if these depended on the fraction of a module occupied by a cloud.

The workbook does not consist of a set of well-defined unambiguous procedures to follow: in some areas application of the workbook requires considerable user interpretation. As a consequence different offshore operators may well have interpreted and extended the workbook methodology in different ways.

Application of the workbook to a real offshore installation shows large differences when predictions for ventilation velocity are compared against both offshore measurements and CFD results. The workbook consistently produces far lower ventilation velocities. However, there is no evidence to suggest that this might be a general conclusion.

The workbook predictions of flammable volume have been compared to CFD results for potential gas releases in this offshore installation in the range of 0.1 to 5.0 kg/s. Again there are large differences seen in the outcomes from the two approaches. Given the uncertainties in the workbook approach, as well as those in the CFD modelling, it is unfortunately not possible to draw firm conclusions on the performance of the workbook for prediction of flammable volume.

It has been demonstrated that a large difference in flammable volume can be obtained using the workbook approach purely as a consequence of differing, yet reasonable, assumptions when applying the methodology.

The authors of the workbook are open about its limitations. They state that:

> *'This workbook..……is intended to provide the user with a quick first pass technique for estimating the flammable volume…..'*

The authors state in an article on the workbook in the FABIG Newsletter[3]:

> *'…it is most likely that the workbook would be used at the early stages of a new development when some idea of the overall level of risk is required…………..as more details of the module layout are produced it is likely that more detailed analysis would be warranted, using a range of more sophisticated models….'*

It seems clear that the authors of the workbook never intended it to be widely used as the sole means of estimating gas cloud volume. However, the concern is that gas cloud volumes calculated from the workbook or results derived from these may be been used in this way in practice.

The uncertainties in the workbook methodology and present lack of evidence of its wider applicability suggest that it should not generally be used as the sole means to provide estimates of flammable cloud volumes for use in QRA for offshore safety case.

The methodology for prediction of flammable volume in BS EN60079-10:2003 has been examined. This standard does not provide a means to estimate ventilation velocity: it assumes that this is known. The definition for flammable cloud volume differs significantly to that in the workbook; BS EN60079-10:2003 adopts a more conservative definition. Overall, BS EN60079-

10:2003 is far simpler than the workbook, but is based on the even more sweeping assumptions: fully-mixed conditions and a known ventilation rate.

7 APPENDIX - FIGURES

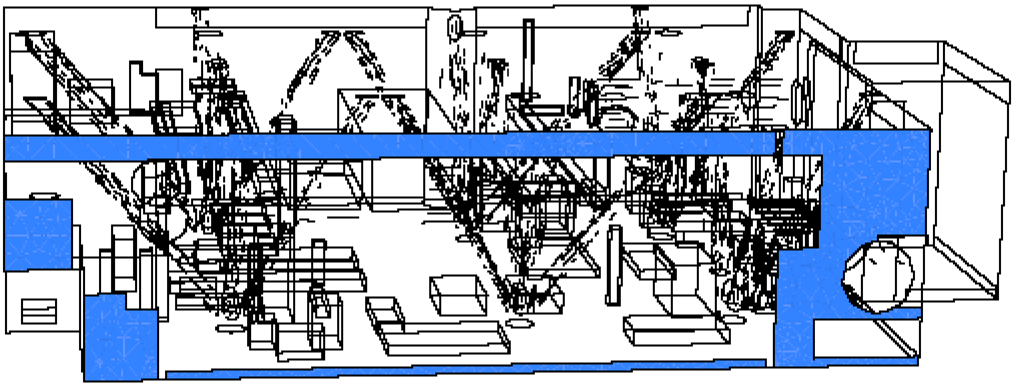

Figure 1 View onto the North face of the module, i.e. looking South

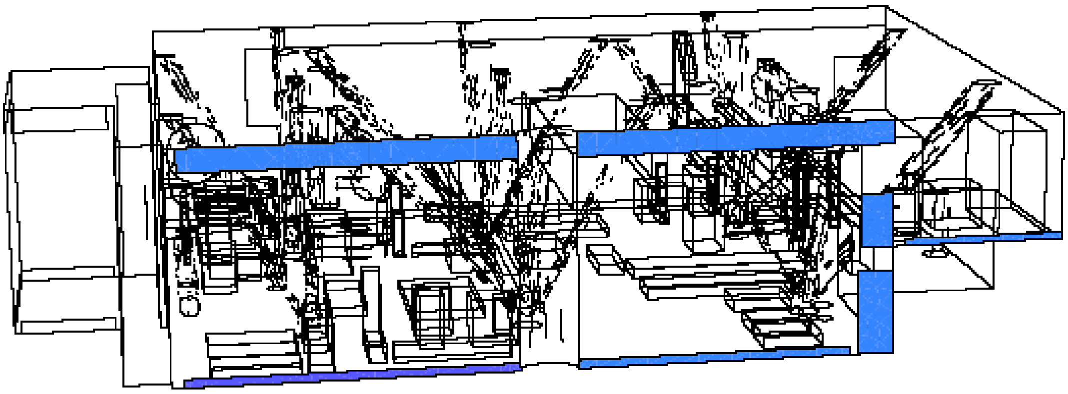

Figure 2 View onto the South face of the module, i.e. looking North

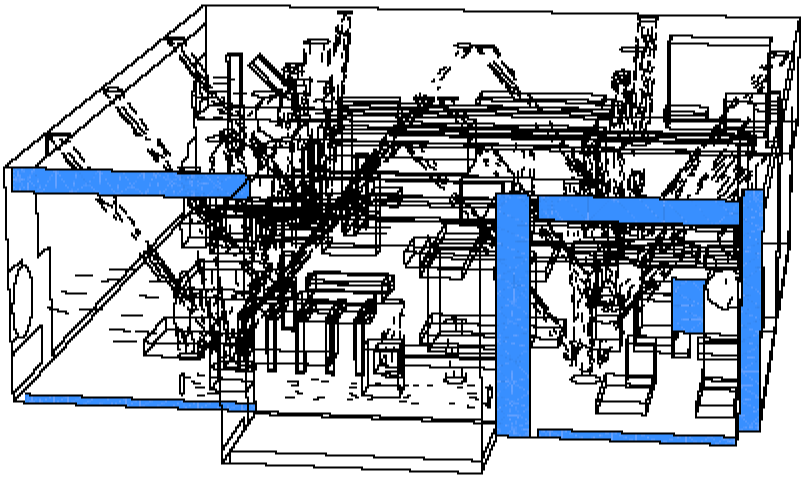

Figure 3 View onto the West face of the module, i.e. looking East

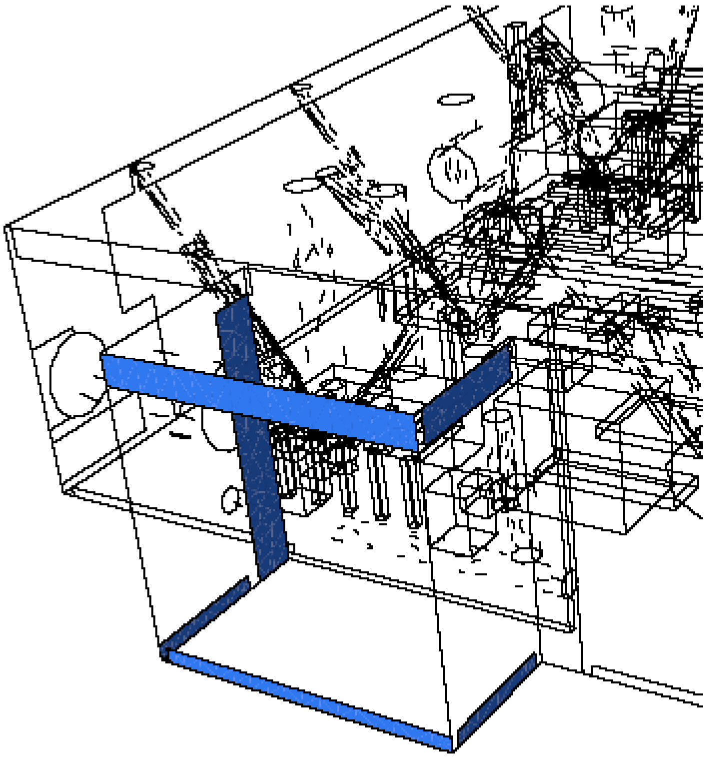

Figure 4 Close up view onto the West face of the module, i.e. looking East, showing the 'Annex'.

8 REFERENCES

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