REQUIREMENTS FOR VALIDATION OF MATHEMATICAL MODELS IN SAFETY CASES ©

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The Offshore Installations (Safety Case) Regulations 1992 require operators (or owners) of offshore installations to prepare a Safety Case that shows, among other things, that risks from a major accident have been reduced as far as is reasonably practicable. Such a hazard is that of a gas explosion. To show that effective measures have been taken to prevent or mitigate the consequences of a major accident it is first necessary to identify the sources of the hazard and then determine their consequences. This requires the prediction of the effects of gas explosions. Several mathematical models are available and used for this purpose. This paper describes some of these models and their inherent uncertainties. It explains the need to validate the models, the methods used to effect such validation and difficulties met in trying to validate models for use on offshore installations.

INTRODUCTION

On 6 July 1988 an explosion on the Piper Alpha platform started a chain of events that led to the destruction of the platform and the loss of 167 lives. This prompted a public inquiry under Lord Cullen[1] who, as a result of his findings, recommended sweeping changes to the way health and safety were administered in the North Sea. One of his recommendations was the introduction of legislation requiring the operators (or owners) of offshore installations to prepare a Safety Case showing, among other things, that risks from a major accident had been reduced as far as is reasonably practicable. This recommendation was implemented in the form of the *Offshore Installations (Safety Case) Regulations 1992*

An obvious major accident hazard is that of a gas explosion. Before it can be shown that effective measures have been taken to prevent or mitigate the consequences of such a major accident it is necessary to identify the sources of the hazard and then determine their consequences. This requires the prediction by mathematical models or otherwise of the effects of gas explosions.

There has long been an interest in predicting the effects of gas explosions, and mitigating their consequences. Much research has been carried out in this field, starting with the work of Cubbage and Simmonds[2] in the 1950s and continuing to this day. Recently a review of the applicability of the predictive methods to gas explosions in offshore modules has been carried by British Gas on behalf of the Department of Energy[3]. A review of prediction methods has also been carried out by the Steel Construction Institute (SCI)[4] as part of a joint industry project on blast and fire engineering for topsides structures and they have subsequently published guidance based on their findings^5.

Although it is comparatively easy to predict the effects of an explosion in a confined and relatively uncongested space such as an oven it is much more difficult to do so for a large and congested space such as a module on a typical offshore installation and there are still many areas of uncertainty. This paper is concerned with the particular problems met when trying to predict the blast loadings of a gas explosion in a typical offshore module. It does not deal with how plant or the structure of the module will respond to these loadings.

EXPLOSION MODELS

To model a gas explosion it is necessary to know the extent and composition of the gas cloud. This can be achieved by identifying leak sources and modelling the leak and dispersion. Mathematical techniques are available for such modelling but often the conservative assumption is made that the module is filled with a stoichiometric mixture of gas and air.

Owing to their highly congested nature, offshore modules do not lend themselves to simple methods for calculating blast loadings. Whereas unconfined hydrocarbon gas clouds do not generally cause large explosion pressure impulses, where the gas flow generated by an explosion passes through an obstacle array the turbulence generated can cause the flame front to accelerate leadibng to very large pressure impulses. Turbulence can also be generated by the momentum of a jet of escaping fluid. Several methods have been developed for simulating these effects. These include small-scale simulations, using a gas mixture with enhanced reactivity to compensate for the reduced scale, and mathematical modelling. The former offer interesting possibilities but still rely on mathematical scaling arguments. This paper, therefore, concentrates on mathematical modelling techniques.

Mathematical models for predicting the behaviour of gas explosions fall into 3 categories:

1 Empirical: these simple models extrapolate to the real problem from a set of small-scale experimental data in a range of geometries, usually idealised. The relative importance of the variables measured in the experiments is then assumed to hold for the real conditions of interest. At best these models can only give rough answers since without some fundamental modelling of the combustion and turbulence processes there is no reliable way of predicting what will happen at larger scales, in different geometries and for different fuels from those studied in the underlying experiments.

2 Phenomenological: these models use a set of equations to describe the bulk behaviour of the explosion, taking account of the dominant physical processes. The models are calibrated against experimental data, both on individual physical

processes (eg turbulent burning velocities) and from idealised or realistic module geometries. Because they are based on a model of the physics of combustion processes, they can be used to extrapolate from experimental data more safely than can empirical models (if the model is good enough) and, because only a few simple equations have to be solved, they do not require a great deal of computing power. However owing to the simplifying assumptions made, and because the models are based only on the dominant physical processes, there may be some doubts about the reliability of these models in predicting behaviour beyond the range of experimental data unless the extrapolation can be supported by a demonstration that different physical effects do not become dominant.

3 Numerical: these models are usually based on computational fluid dynamics. The field in which the explosion occurs is divided by a grid and the behaviour in each cell within the grid calculated in turn. This type of model demands a great deal of computing power and, to enable it to run on even a very powerful computer, requires the use of a coarse grid (about $1m^3$) and, to take account of turbulence effects of a smaller scale than the grid size, sub-grid turbulence models are employed. Thus simplifying assumptions have to be made although to a lesser extent than with the phenomenological models. As with phenomenological models it is necessary for these models to be calibrated and validated against experimental data.

Table 1. is a list of models typical of those used to predict blast loadings in offshore modules.

EXPERIMENTAL DATA

As already discussed even the most sophisticated models have uncertainties in them. These uncertainties become greater when the models are used to extrapolate beyond the range of the experimental data against which they were calibrated, particularly because the simplifying assumptions made may not hold true at the larger scale.

There is a large body of experimental data which has been generated by organisations working in this field against which models can be calibrated. However not all models will necessarily have been calibrated against the same set of data and none of them have been calibrated against full-scale experimental data because of the sheer size of typical offshore modules. Hitherto no experimental data have been obtained on rigs of greater than about one fifth linear scale.

VALIDATION

Models can be validated against existing data other than those against which they were calibrated and, as stated above, these data exist. Models can also be validated by a model comparision exercise. However no full scale experiments have been carried out yet and when extrapolating beyond the range of existing experimental data there will be large uncertainties because there may be some assumptions common to all the models that do not hold true at the larger scale. To rectify this situation there are plans to carry out tests at full scale. There is a joint industry project managed by the Steel Construction Institute to build a 3000m^3 model of a typical offshore module and carry out a series of tests in it to obtain data that it will then be possible to use to validate models at full scale.

It is unlikely that the results from full-scale experiments will be available for some time yet. In the meantime it has to be recognised that there is a high degree of uncertainty in all the models and this should be taken into account in applying them. When uncertainties in passing to different geometries at full-scale are taken into account one may well suppose that the error could be in the order of a factor of two or more. The models will not necessarily produce conservative results.

When using a physical or mathematical model for predicting blast loadings for the purposes of a Safety Case the degree of validation expected will depend on the extent to which the Case relies on the predictions. For example the assumption that an explosion would cause major damage would be acceptable if the frequency of such events were shown to be both tolerable and as low as is reasonably practicable: this would not require any validated predictions. In other cases the degree of certainty sought in the predictions should increase with the frequency of the events leading up to an explosion and the size of the risk from the explosions in relation to the total risk. In any case it will be necessary to take account of the uncertainties in any risk assessment based on the predictions.

The SCI Interim Guidance Note[5] advises that with the current *state of knowledge it would not be prudent to rely on any single* predictive method where the predicted values of explosion pressures are of critical consequence.

APPLICATIONS

Although all models have a high degree of uncertainty they are nonetheless of practical value. Apart from their application in risk assessments they can be used to show how passive inherent features of design such as layout and venting paths influence the effect of explosions. They can also show where improvements need to be made such as the provision of vents and the construction of blast walls or measures taken to reduce the probability of unacceptably severe explosions. They may well be better at showing the relative effect of such changes than in predicting absolute values.

CONCLUSIONS

1 There is a large body of data based on experiments on the effects of explosions in models of offshore modules.

2 Although these experiments have been carried out over a wide range of scales none have been carried out on rigs of greater than about one fifth scale. It has therefore not been possible to validate these models at full scale.

3 Confidence in these models could be improved by validating them against data from a wide range of sources, by carrying out a benchmark exercise and by carrying out experiments in a full-scale rig.

4 In the meantime the models can be put to good use in risk assessments provided that allowance is made for the inherent uncertainties. They can also be used in comparative studies of the influence that passive design features such as plant layout have on explosions. Models may be better at showing the relative effect of changing such features than in predicting absolute values.

REFERENCES

1 The HON. LORD CULLEN, *The Public Inquiry into the Piper Alpha Disaster.* HMSO London, November 1990.

2 Cubbage, P.A., Simmonds, W.A. *An Investigation of Explosion Reliefs for Industrial Drying Ovens - I Top Reliefs in Box Ovens,* Trans. Inst. Gas Engrs., 105, p470, 1950.

3 OTH 89 312 *Review of the Applicability of Predictive Methods to Gas Explosions in Offshore Modules.* Prepared by British Gas for the Department of Energy.

4 OTH 92 591 (BL1) *Gas/Vapour build-up on offshore structures.*
OTI 92 592 (BL2) *Confined vented explosions.*
OTH 92 593 (BL3) *Explosions in highly congested volumes.*
OTI 92 594 (BL4) *The prediction of the pressure loading on structures resulting from an explosion.*
OTI 92 595 (BL5) *Possible ways of mitigating explosions on offshore structures.*

5 *Interim Guidance Notes for the Design and Protection of Topside Structures against Explosion and Fire.* Published by the Steel Construction Institute.

Model Name	Model Type	Ease of Use	Comments
EXPEL1	Empirical	Quick; personal computer	Subject to the limitations of empirical models, possibly a practical tool albeit for rough calculations.
ComEX	Empirical	Quick; personal computer	Subject to the limitations of empirical models, possibly a practical tool albeit for rough calculations.
VENTEX	Empirical	Quick; personal computer	Validated against a wide range of data.
CLICHÉ	Phenomenological	Half-hour run on desk top work station	Validated against a wide range of data. This model is incorporated into CHAOS, which also models dispersion and blast response. Not accurate above 1 bar.
SCOPE	Phenomenological	Quick; personal computer	Based on experimental data on rigs up to 500 m^3.
FLACS	Numerical	Hours on a powerful computer	Most extensively developed numerical model. A simplified form called μ-FLACS that uses a coarser grid and can be run on a personal computer is available as a screening tool.
REAGAS	Numerical	Hours on a powerful computer	Being developed by TNO for off-shore use.
EXSIM	Numerical	Hours on a powerful computer	Validation unknown at present but continuing. Has the potential to become a useful tool for simulating offshore explosions.

Table 1.. Typical Models used to Predict Blast Loadings in Offshore Modules