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HEALTH & SAFETY LABORATORY

Outstanding safety questions concerning the use of gas turbines for power generation –

Summary report

CM/04/09

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EXECUTIVE SUMMARY

This report presents a summary of the work carried out by a Joint Industry Project (JIP) that set out to address outstanding safety questions concerning the use of gas turbines for power generation. The project focuses on the potential explosion hazard from gas leaks in acoustic turbine enclosures.

This report is one of a number of reports produced during the course of the JIP. The purpose of this report is to briefly summarise the programme of work that has been carried out and to introduce a new safety criterion for the ventilation of gas turbine enclosures.

1 INTRODUCTION

This report presents a summary of the work carried out by a Joint Industry Project (JIP) that set out to address outstanding safety questions concerning the use of gas turbines for power generation. The project focuses on the potential explosion hazard from gas leaks in acoustic turbine enclosures.

1.1 BACKGROUND

Most commonly, the current basis of safety in the event of a gas leak in a gas turbine enclosure is dilution ventilation. The current safety criterion given in HSE's Guidance note, PM84[(1)], is believed to be both conservative and attainable. This research project therefore set out to define the criterion more accurately and less stringently.

The ATEX Directives as they apply to gas turbines in acoustic enclosures - that is in relation to the design and manufacture of such equipment and to the health & safety of workers potentially at risk from explosive atmospheres - have profound implications for the industry. Since it is not feasible to exclude the possibility of ignition of a potential fuel leak to comply with the regulations made to implement the ATEX Equipment Directive, the chosen basis of safety may demonstrate that explosive atmospheres do not arise. Dilution ventilation is still seen as the preferred basis of safety for compliance with the regulations made to implement ATEX.

It has also been recognized that a harmonized European Standard should be produced to provide definitive and precise guidance that can be used as a general means of compliance with the regulations made to implement the ATEX, Machinery and Pressure Equipment Directives. The results of the present research have been used to inform, and are used within, the draft standard ISO/CD 21789[(2)].

The aims of the JIP therefore were to:

1. Establish the degree of conservatism in the HSE dilution ventilation criterion when used as a basis of safety, with the possibility of defining the criterion less stringently.

2. Provide a well substantiated means to comply with the regulations made to implement the ATEX Directives.

3. Use the outcome of the research to inform a proposed harmonised European Standard produced to provide definitive and precise guidance that can be used as a general means of compliance with the regulations made to implement the ATEX and Machinery Directives.

HSE guidance note PM84[(1)], "Control of safety risks for gas turbines used for power generation", provides advice on means of identifying and controlling hazards due to a gas leak. It also refers to ASME 98-GT-215[(3)] which proposed a criterion to be met by dilution ventilation design; the 50% LEL enclosed iso-surface volume of leaked gas under alarm conditions to occupy no more than 0.1% of the enclosure volume. Whilst these documents contained the best guidance available, refinement was seen as possible and desirable, to provide an enhanced basis for safety and to provide the means to comply with the regulations made to implement the ATEX Directives.

Specifically, the criterion is based on an allowable size of flammable volume. The criterion is informed by explosion trials. These provide a relationship between the over-pressures generated from the ignition of flammable clouds and their volumes. One of the main objectives of the present project is thus to map out this relationship, focusing on clouds which fill up to 1% of the net enclosure volume, for a range of different levels of congestion and release conditions. Note that no other work has been undertaken for clouds which fill such a relatively small percentage of a total enclosure volume. Even so, the over-pressures generated from a 1% fill can approach one tonne / m^2.

The effectiveness of the dilution ventilation can be assessed through the use of Computational Fluid Dynamics (CFD) and this is the approach recommended in PM84 for enclosures larger than 50 m^3 in volume. However, although the technique is reasonably well established for this application its use is subject to some uncertainty. An advantage of CFD is that it is able to take into account the momentum of the jet, which some other techniques ignore, and it permits a quantitative assessment of the ventilation effectiveness against a criterion such as that described above.

1.2 OBJECTIVES

To meet the above aims a detailed set of project objectives were set out and these have been met through a combined programme of experimental tests and CFD modelling. The objectives evolved throughout the duration of the project and were all agreed by the project's Steering Committee (see Section 1.4 below). The objectives are summarised below:

1. To establish the effect of congestion – supply pipe work, supporting structure, etc., on over-pressure generated from ignition of a range of cloud sizes which partially fill enclosures. This will provide information on the degree of conservatism in the present HSE dilution ventilation criterion, presently unknown.

2. To establish the effect of absolute cloud size, as well as its percentage fill of an enclosure, on over-pressure generation.

It is not certain that the safety criterion in PM84 (the 50% LEL volume of leaked gas under alarm conditions to occupy no more than 0.1% of the net enclosure volume) is valid for all sizes of enclosure. That is, there may be an absolute upper limit to the size of cloud needing to be controlled or viewed as acceptable in the context of compliance with ATEX. Conversely, it may be that there is an absolute lower limit below which over-pressure generation is minimal.

3. To review the likely effects of overpressure on people and gas turbine enclosures. To ensure compliance with the regulations made to implement the ATEX Directive, a risk assessment is required which should demonstrate that explosive atmospheres do not arise. This will require definition of an acceptable over-pressure, below which ignition of a flammable cloud is deemed not to have resulted in an explosion.

4. To define limits for the potential minimum and maximum leak sizes to be considered in a risk assessment.

The HSE guidance does not presently advise an acceptable lower or upper bound on the size of release required to be controlled. A combination of low ventilation rates and low detection levels could lead to unrealistically small releases being considered. Conversely, there has to be an upper bound on leak size, to avoid patently unsafe releases being viewed as acceptable. Both alarm and trip levels of gas detection also need to be taken into account.

5. To establish the accuracy bounds on Computational Fluid Dynamics (CFD) predictions of gas cloud size, in particular for high pressure releases into congested regions.

6. To establish guidelines for best practice in the application of CFD to the prediction of ventilation flows and gas build-up in gas turbine enclosures.

7. To establish the range of validity of in-situ experimental tests, such as smoke or tracer gas, and provide guidance on how they should be carried out.

8. To inform a proposed harmonised European standard produced to provide definitive and precise guidance that can be used as a general means of compliance with the regulations made to implement the ATEX and Machinery Directives.

1.3 DELIVERABLES

The main deliverables from this project are:

- A report[(4)] presenting new experimental data on explosion over-pressure and an interpretation of this data in light of the project objectives. This report remains confidential to the members of the Sponsor Group until 17th May 2005.

- A CFD report[(5)] assessing the modelling of high pressure gas leaks, gas build-up and dispersion in congested regions. The influence of a porous media approach for modelling congestion was compared to methodologies in which the obstacles were fully resolved by the computational mesh. Results are presented for three different commercial CFD codes: CFX-5, FLUENT and STAR-CD. This report remains confidential to the members of the Sponsor Group until 17th May 2005.

- Best practice guidelines[(6)] on the range and validity of in-situ experimental tests, such as smoke or tracer gas. These guidelines have been published on HSE's web-site: www.hse.gov.uk.

- Best practice guidelines[(7)] for the application of CFD to the assessment of ventilation effectiveness and gas build-up in gas turbine enclosures. These guidelines have been published on HSE's web-site: www.hse.gov.uk.

- An Executive report[(8)], including recommended minimum and maximum hole sizes for leak evaluation and a more soundly-based safety criterion to supersede that appearing in PM84. This report summarises the work programme carried out for this JIP and includes a description of all of the results. The report remains confidential to the members of the Sponsor Group until 17th May 2005.

- The present report summarising the project work programme and introducing the new safety criterion. This report is to be published on HSE's website: www.hse.gov.uk.

1.4 PROJECT SPONSORS

The proposal for this project and an invitation to contribute was sent to all known OEMs, UK suppliers, packagers, users, and other interested parties for comment and indications of interest in participation. The work was part funded by the UK Health and Safety Executive, with the bulk of the research being undertaken by its in-house research Division; the Health & Safety Laboratory. Additional CFD simulations were undertaken by FLUENT Europe Ltd., ANSYS CFX and RWE Innogy at their own expense and made available to the project. A full list of the sponsors of this project is listed at the end of this Section.

The project was managed by a Steering Committee consisting of a sub-section of the Sponsor Group. The Steering Committee met approximately three-monthly to review the progress of the project against the original objectives and agree any changes that were deemed necessary. The Steering Committee also reviewed the project reports as they were produced providing extensive feedback and therefore influencing the content of the final reports. The new criterion was also discussed at length by the Steering Committee and Sponsor Group to ensure that, based on their experience, it would distinguish between good and poor ventilation, and be practical and achievable.

The Sponsors of this Joint Industry Project were:

- Alstom Power Generation Ltd
- ANSYS CFX
- Centro Elettrotecnico Sperimentale Italiano
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- Deeside Power
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- RWE Innogy
- Siemens AG
- Scottish Power
- Thames Power Services Ltd
- Transco National Transmission System
- WS Atkins

2 PROJECT PROGRAMME

2.1 EXPERIMENTAL PROGRAMME

A series of explosion tests has provided data on over-pressure generation from gas clouds which partially fill an enclosure, including the effects of congested regions. High pressure gas releases into a congested region were also undertaken providing data on the build-up and dispersion of gas clouds in congested regions. A detailed description of the work is reported by Pritchard *et al.*[(4)] and this report remains confidential to the members of the JIP Sponsor Group until 17th May 2005.

2.2 CFD PROGRAMME

The CFD modelling programme investigated different approaches for modelling the source of a high pressure under-expanded gas release. An assessment was also carried out of the capabilities of CFD for modelling high pressure gas releases in congested regions by comparison of model predictions against experimental data. A detailed description of the work is reported by Ivings *et al.*[(5)] and this report remains confidential to the members of the JIP Sponsor Group until 17th May 2005.

2.3 CFD BEST PRACTICE GUIDELINES

Best practice guidelines for the application of CFD to the assessment of ventilation and gas dispersion in gas turbine enclosures have been presented based on the results of the CFD modelling programme. The guidance draws attention to the key modelling issues that need to be addressed. The guidelines have been published on the HSE website (www.hse.gov.uk) in the report by Ivings *et al.*[(7)].

2.4 IN-SITU TESTING BEST PRACTICE GUIDELINES

Best practice guidelines have also been presented for making in-situ measurements within a gas turbine enclosure. Such measurements can be used to help demonstrate the effectiveness of the ventilation system and provide valuable data for CFD model set-up and validation. These best practice guidelines have been published on the HSE website (www.hse.gov.uk) in the report by Saunders[(6)].

3 DILUTION VENTILATION CRITERION

In this Section a new safety criterion for the ventilation of gas turbine enclosures is described to supersede that found in PM84[1]. This new criterion is based on the experimental and CFD programmes of work from this JIP. The new criterion places a limit on the allowable volume of a flammable gas cloud resulting from leaks that are not large enough to initiate the trip condition of the gas turbine.

The new safety criterion states that the ventilation of a gas turbine enclosure should ensure that a gas leak, smaller than that required to trip the gas turbine, should not form a gas cloud which, if ignited, would pose a significant hazard to people or the strength of the enclosure. The main differences between this new criterion and that in PM84 are the move to the 'trip' condition and the definition of the volume of the flammable gas cloud. The flammable gas cloud volume is now defined less conservatively and more robustly, as it is based on an 'equivalent uniform stoichiometric volume'.

The dilution ventilation safety criterion as appearing in PM84[1] is reproduced here:

> *"A quantitative criterion against which to assess dilution ventilation efficiency has been proposed by HSE and shown to be both conservative and attainable. It is based on the principle of limiting any foreseeable accumulation of flammable mixture so that its ignition would not present a hazard to the strength of the enclosure or to people. The criterion is such that the size of the flammable cloud - as defined by the iso-surface at 50% of the lower explosive limit (LEL), should be no larger than 0.1% of the net enclosure volume. This criterion has been developed to permit a common basis for assessment of ventilation effectiveness. It is primarily applicable to a CFD - based approach. The results of any research into this field should be taken into account as they become available.*
>
> *The leak rate to be modelled in CFD simulations should be the largest leak which would just pass undetected. This can be calculated as that gas release rate which, when fully mixed in the ventilating air passing through the enclosure, just initiates detection alarm for a detector located in the ventilation outlet. Larger leaks than this should be readily detected and appropriate action taken. Smaller leaks could pass undetected, but present a lesser hazard.*
>
> *A CFD approach should aim to demonstrate that the ventilation is effective for a credible 'worst case'. That is, the leak rate calculated using the above approach should be employed, with the leak location and orientation chosen such that the predicted flammable cloud is a maximum. This can be best achieved by an approach which identifies poorly-ventilated regions, i.e. recirculating or stagnant flow. Identification of poorly ventilated regions can be achieved by analysing simulations or measurements. Since it is not possible, a priori, to know which combination of factors will lead to the largest flammable cloud, a small number of alternative leak locations and orientations should be simulated. These leak scenarios should be investigated in turn to avoid interactions, rather than all modelled within a single simulation."*

The new safety criterion is outlined below and highlights the differences between the new criterion and the criterion in PM84.

NEW SAFETY CRITERION - SUMMARY

1. The modelled gas leak rate should be the largest gas release rate which, when fully mixed in the ventilation air passing through the enclosure, just initiates the automatic **trip** of the gas turbine.
2. In all cases the gas leak rate should be based on a hole size no smaller than 0.25 mm^2 and no larger than 25 mm^2.
3. A number of different worst-case leak scenarios should be considered and the *flammable cloud volume* should be less than 0.1% of the net enclosure volume.
4. The *flammable cloud volume* is defined to be the *100% LEL equivalent stoichiometric volume* which is the volume of a uniform stoichiometric mixture of gas and air containing the same volume of gas as that enclosed by an iso-surface at 100% LEL.
5. A safety factor should be applied, based on a risk assessment, to the allowable flammable cloud volume.
6. The *100% LEL equivalent stoichiometric volume* should additionally be less than 1 m^3 in all cases, irrespective of the enclosure volume.
7. The strength of the enclosure should be shown to be capable of withstanding at least 10 mbar static overpressure.
8. If the criterion cannot be met, and the enclosure can be demonstrated to be capable of withstanding 15 mbar, then the 100% LEL equivalent stoichiometric volume should be less than 0.15% of the net enclosure volume.

4 CONCLUSIONS

This report presents a summary of the work carried out by a Joint Industry Project (JIP) set out to address outstanding safety questions concerning the use of gas turbines for power generation. The project focuses on the potential explosion hazard from gas leaks in acoustic turbine enclosures.

A new safety criterion based on the results of the experimental and CFD modelling programmes of work has been introduced to supersede that appearing in PM84. Although much conservatism in the old criterion has been removed, the new criterion is now more soundly based on the gas detector setting that trips the gas turbine.

5 REFERENCES

1. HSE Guidance note PM84: Control of safety risks at gas turbines used for power generation. 2003, 2nd Edition, HSE Books

2. ISO/CD 21789 'Gas Turbines – Safety'

3. Santon R.C. 1998 'Explosion hazards at gas turbine driven power plants' ASME 98-GT-215

4. Pritchard D.K., Hedley D. and Eaton G.T., 2003, 'Outstanding safety questions concerning the use of gas turbines for power generation – Final report on the experimental programme of work' Health and Safety Laboratory Report EC/03/19, (Confidential report until 17th May 2005)

5. Ivings M.J., Azhar M., Carey C., Lea C.J., Ledin H.S., Sinai Y., Skinner C., Stephenson P., 2003, 'Outstanding safety questions concerning the use of gas turbines for power generation – Final report on the CFD modelling programme of work' Health and Safety Laboratory Report CM/03/08 (Confidential report until 17th May 2005)

6. Saunders, C. J., 2004, 'Outstanding safety questions concerning the analysis of ventilation and gas dispersion in gas turbines enclosures: Best practice guidelines on in-situ testing' Health and Safety Laboratory Report ECO/03/06

7. Ivings M.J., Lea C. J., and Ledin H. S., 2004, 'Outstanding safety questions concerning the analysis of ventilation and gas dispersion in gas turbines enclosures: Best practice guidelines for CFD', Health and Safety Laboratory Report CM/03/12

8. Ivings M.J., Lea C.J., Ledin H.S., Pritchard D.K., Santon R. and Saunders C.J., 2004, 'Outstanding safety questions concerning the use of gas turbines for power generation – Executive report' Health and Safety Laboratory Report CM/04/02. (Confidential report until 17th May 2005)