EXPLOSION HAZARDS AT CHP AND CCGT PLANTS

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CHP (Combined Heat and Power) and CCGT (Combined Cycle Gas Turbine) plants have become larger and more popular in recent years for local power and heat generation, and for main stream power generation. Many are based on gas turbines within acoustic enclosures. Complex fuel supply pipework to the turbines at high pressure gives rise to an explosion hazard within such enclosures in the event of foreseeable small leaks if adequate ventilation is not provided. HSE investigations have exposed poor ventilation in some cases to the extent that explosion relief or significantly improved ventilation has been required. The paper describes the investigations, with reference to CFD, incident data, ignition probability, current relevant standards, ventilation performance and pitfalls. Suggested criteria for the evaluation of existing and new plant and risk reduction measures are described.

KEY WORDS : Gas Turbine, Gas, Explosion, Ventilation

BACKGROUND (Refs. 1 &2)

A combined heat and power (CHP) plant consists of an engine, normally a gas turbine or an internal combustion engine, connected to an electricity generator, and with a waste heat recovery system connected to the engine exhaust. The heat may be used for industrial process purposes, space heating, domestic hot water, etc. A combined cycle gas turbine plant (CCGT) similarly consists of a gas turbine driving a generator, but the recovered heat is used to generate steam which is used to drive a conventional turbine and generate further electrical power. The concepts are not new, and systems based on reciprocating engines have been used for many years. The most common larger systems now being installed in UK comprise a gas turbine, usually driven on natural gas and, in some cases, with a liquid fuel available for stand by purposes. Overall efficiency rises to 80%, compared with around 50% for the separate generation of heat and power. The Energy Act 1983 and the reduced regulatory burden on utilities have supported an enormous increase in activity over the last few years. Most off-shore rigs contain one or more gas turbine based plants.

There are over 1050 on-shore UK plants, of which about 10% are gas turbine based, with a total installed generating capacity of 2800MW. A number of new large gas turbine based plants and CCGT based Power Stations are under construction or recently completed and not included in these figures. As part of its carbon dioxide emission reduction strategy, the government has a CHP goal of 5000MW by the year 2000. Over 500 of the existing land based units are rated at less than 100kW, and are installed in schools, hotels, hospitals, and leisure centres etc. Any site with a large and fairly steady consumption of heat and electricity is likely to be suitable for CHP. Thus large industrial units, including over 150 plants rated at over 1MW, are located in the oil and chemicals, food and drink, paper and board, and iron and steel sectors. This paper is concerned with gas turbine driven plant, but many of the matters discussed are relevant to plant driven by internal combustion engines.

HAZARDS

The fuel supply to a gas turbine is required at high pressure. Whilst typically a 6MW unit requires gas at from 8 to 20 barg, a 40 MW unit uses 10 tons per hour at up to 30 barg. The pipework supplying the fuel to the turbine combustion chambers is convoluted. Its complexity increases with the size of the machine. The complexity is due to the supply from annular distribution pipes to the individual combustion chambers. Each chamber may require up to 4 main fuel supplies, and alternative fuel supplies. For a 40MW machine the pipework may include 30 flanges or flexible pipes; for a 250MW machine it may include over 200 flanges, 90 flexible hoses, 18 valves, and 8 bellows, all operating at 20 barg. Liquid fuel supplies may operate at up to 60barg.

A particular problem associated with gas turbines arises from the absence of isolating valves on the fuel supply systems. The pipework is invariably connected to the combustion chambers without an isolating valve so that, whilst a blank can be inserted at this point for pressure testing of all upstream pipework, this final connection cannot be tested. In practise, whilst pipework is pre-assembled and tested by suppliers, it is often not tested at all when assembled on site, or following maintenance, because of the difficulty of access. This is contrary to normal gas supply industry, chemical, or petrochemical plant practice, where any such complex pipework carrying hydrocarbon at such pressure would be rigorously tested whenever disturbed.

A fuel leak from the fuel supply pipework is foreseeable. It may arise following assembly, either when new or following maintenance. The fuel pipework is routinely dismantled for turbine maintenance at intervals of one to three years. It is predictable that a joint failure following incorrect assembly will arise approximately one to ten times a year in UK. Gas turbines should operate without excessive vibration, and vibration detectors are often, but not always, fitted to larger units to detect bearing failure etc. Such vibration could also cause fuel pipe joint failure. Catastrophic, e.g. sudden guillotine pipe failure is very improbable, but a fuel leak from a flange, control valve, or welded pipe joint is a hazard against which appropriate precautions should be taken.

Gas turbines are fundamentally a significant noise source and environmental pressures often dictate their installation within acoustic enclosures. The release of fuel within the enclosure is potentially hazardous if the release results in a volume of flammable fuel/air mixture within a significant fraction of the chamber volume. The release may be of gas, such as natural gas, flashing liquid such as propane, or liquid such as naphtha or fuel oil, or lubricating oil. Even the release of liquids at temperatures below their flash points can create an explosion hazard since releases from high pressures can generate fine mist which behaves as if it were a flammable gas. The ignition of such a gas or liquid mist fuel release would result, depending upon the construction of the chamber and its location, in explosion blast, fire ball, and missile effects which could seriously injure or kill persons nearby. The commercial implications of such an event are also likely to be very significant.

The ignition of a fuel release would require the presence of a source of ignition. Electrical equipment within the enclosures is normally installed to appropriate zoning standards by the application of relevant codes of practice against ventilation data. This concept may provide inadequate protection however if ventilation is not properly designed. Furthermore it is also impractical to exclude other sources of ignition entirely. Ignition may result from static discharges, from mechanical means such as moving parts in the event of a major pipe failure (pipewhip) or blade enclosure failure, from mechanical disruption of electrical equipment, from backflowing combustion gases in the event of a fuel pipe failure close to a combustion chamber, or from hot surfaces. The fuel is being burnt in turbine combustion chambers and the exhausts of some smaller units based on aircraft engines glow. The exhaust diffusers of larger units do not reach such high temperatures but are nominally at 450°C to 500°C. Thermal imaging techniques have been used to measure such surface temperatures and have identified hot spots of over 520°C. Auto ignition is the most probable source of ignition of a fuel release. Auto ignition temperature is not an absolute property of a fuel, and is a function of surface roughness, orientation, contamination and size, and of fuel purity, stoichiometry, velocity and turbulence. The literature values quoted for relatively common materials vary widely even for results obtained under standard conditions. Such values are unreliable for use with small margins in this application.

Whilst it is clearly appropriate to take relevant precautions to minimise the presence of sources of ignition, it is not possible to eliminate them in these circumstances, and in the event of a fuel release within an acoustic enclosure the probability of ignition should be assumed to be very high, and in effect unity for practical purposes and risk assessment.

Apart from the hazard of an explosion within the acoustic chambers, there are other explosion hazards, characteristic of any gas fired plant. In particular there is the possibility of the accumulation of a flammable gas/air mixture within the turbine and associated inlet and exhaust systems, and its ignition by the combustion process itself, e.g. at startup This hazard is relatively easier to mitigate, with adequate purging and reliable gas safety shutoff arrangements.

INCIDENTS

Following Lord Cullen's enquiry into the Piper Alpha incident, a hydrocarbon release data base has been set up by the Offshore Division of HSE. Reports are mandatory and, as a result, this database represents an accurate picture. Most offshore installations include gas turbines and the data base thus records incidents relating to them. Data for the initial 18 months of operation has been analysed, and show that there were 36 incidents within this period associated with turbines in general. Of these 7 related to gas releases at turbines, and in 3 incidents there was ignition resulting in turbine enclosure doors being blown off by the explosion. One incident in particular was classified as of major potential.

By comparison, taking into account the larger onshore population, the number of onshore incidents has been relatively low, perhaps reflecting the less arduous environment. There was a major explosion at a large CCGT plant in NE England in mid 1996. Naphtha released from a pipe joint ignited at fuel changeover, and one man was seriously injured by the explosion which lifted the $600m^3$ acoustic chamber from its foundations. There have been a number of less serious incidents. Blade failure, resulting in casing rupture and a small fire, was reported at one site. A fuel release on first start up at another was traced to a loose flange. Other releases elsewhere have occurred at fuel changeover. Many fires have occurred within compartments, and a survey by Insurers reported 64 worldwide over 20 years, but the discrepancy between the onshore and offshore explosion incident frequency suggests that other non reportable incidents may have arisen onshore. It is also possible that there is a level of under-reporting as many companies are unaware of the importance of reporting dangerous occurrences.

Apart from an incident in Paris in 1991, which killed 1 and injured 59, possibly related incidents in Indonesia and Pakistan, and a gas explosion in Holland in 1996 in which an acoustic chamber was damaged, no data has come to light about other relevant explosion incidents overseas. The author would be grateful for any information about these or any other incidents that can be supplied.

It is however concluded that the potential for explosions as a consequence of the identified hazards has been realised often enough in practice to make these hazards foreseeable.

STANDARDS

There are a number of standards which refer to gas turbines specifically, as well as those of general relevance. The following review only summarises the codes insofar as they deal with the acoustic chamber and fuel supply explosion hazards.

NFPA 37 (Ref. 3) is a fire protection standard but recognises the explosion hazard and recommends the provision of explosion relief for turbine enclosures, or the provision of "ventilation adequate to prevent a hazardous accumulation of flammable vapours or gases..." Adequate ventilation is not defined further. In the case of an engine handling hazardous material other than its own fuel supply, i.e. a gas turbine driven gas compressor, there is no alternative to the recommendation of explosion relief. The scope of this code is limited to engines and turbines not exceeding 7500HP, i.e. 5.6MW.

API 616 (Ref. 4) is essentially a purchasing specification but includes some relevant recommendations. It requires exhaust system purging, an automatic vent on any gas fuel supply, the minimum of flanges and flexible pipework, and insulation, or guarding, so that no exposed surface exceeds 74°C. (Since guards are permitted, this requirement is probably directed towards protection for operators rather than ignition risks.) It makes no specific reference to ventilation or other explosion mitigation means. A later similar code (Ref. 9) is directed specifically at packaged plant. It refers to acoustic enclosure ventilation as having a purging duty but gives no safety specific guidance on it, and it extends the fuel gas supply shutoff requirement to two valves and an automatic vent.

IM/24 (Ref. 5) is a broad code covering the whole installation from fuel supply to instrumentation. It refers to the need to provide adequate ventilation, and quotes $1m^3$/sec as the minimum for gas leakage ventilation. It refers to gas detection for some circumstances, but stresses that it should not be regarded as a substitute for good ventilation.

IP 15 (Ref. 6) is a general area classification code for Petroleum Installations. It contains extensive discussion on the adequacy of ventilation, and a specific section on the ventilation and classification of turbine enclosures, or hoods, and the relevance of this ventilation to the prevention of the accumulation of flammable mixtures. Significantly it permits the enclosure to be classified as safe (unclassified) during normal operation if *dilution ventilation* is present, recognising the effectiveness of properly designed ventilation in preventing accumulation.

The concepts of *Adequate Ventilation* and *Dilution Ventilation* are well recognised in area classification. *Adequate ventilation* is intended for applications where the probability of release is limited and unlikely to be sustained for a prolonged period, whilst *dilution ventilation* is intended to be high enough to dilute below the Lower Explosive Limit (LEL) any reasonably foreseeable leak. The concepts are discussed further in Refs. 6 and 7. In both cases it is essential that there are no stagnant regions. *Adequate ventilation*, as defined, is not appropriate for releases that may be prolonged or where the probability of ignition is high, as is the case in both respects in an acoustic enclosure. Ref. 6 notes, in respect of *dilution ventilation* that "The design of the ventilation system must ensure that there are no stagnant regions and that the immediate mixing and dilution are as required."

THE VENTILATION ISSUE

All of the standards noted above contain much sound guidance, slanted towards their source, but have been applied at various CHP and CCGT installations to varying extents. Serious shortcomings have been found in some cases in the ventilation design and gas detection systems.

Turbine enclosure ventilation rates are specified by turbine suppliers on the basis of the turbine cooling requirement. These rates are relatively high, as suggested by Ref. 5, and may be typically $20m^3$/sec for a 40 MW turbine. In a $100m^3$ acoustic chamber, this exceeds by a factor of 8 the 90 air changes per hour as suggested by Ref. 6 as equivalent to *dilution ventilation*". However it has been found that in many cases the distribution of this quantity of ventilation air is such that the air velocity in the vicinity of the fuel pipework is low, in the order of 0.1m/sec, and the "immediate mixing and dilution" requirement of Ref. 6 has not been met. In smaller enclosures the ventilation may be studied effectively with the use of smoke combined with CCTV, but in larger enclosures it is best shown by Computational Fluid Dynamics (CFD) modelling, which HSE commissioned at one such installation with the ventilation characteristics noted above.

Fig.1 shows the computational grid set up for the acoustic chamber. Modelling of the ventilation gave adequate agreement with velocity measurements carried out on site. A small gas release was postulated as a leak from a hole of $2.5mm^2$. This size of hole was chosen from Refs. 7 and 8, and is also the size used by British Gas for ventilation specification in similar cases. Fig. 2 shows the 50% LEL iso-surface which arose after the leak and remained stable. (50% of LEL was chosen as a representation of the flammable volume, since the actual concentrations within the iso-surface will fall from 100 % gas at the leak. In later modelling the choice was shown to be appropriate, in particular at larger release rates, by integrating the gas inventory within the iso-surface.) The leak represents a gas concentration in the total air flow of 1.8% of LEL, and would thus not activate the gas detectors although a significant volume of flammable gas/air mixture would be present within the chamber. A larger gas release was postulated representing a concentration of 25% of LEL in the air flow, equal to the gas detector setting. Fig. 3 shows the 50% LEL iso-surface arising from this release after 17 seconds. Flammable gas/air mixture nearly fills the chamber before gas detection. In both cases it can be seen that mixing in the vicinity of the leak is poor, and that flammable mixture would accumulate. Any leak up to the larger size would go undetected, and flammable mixture would fill an increasing proportion of the chamber. Large leaks are often said to arise from smaller ones, but in this case there would be no indication of the smaller leak to give cause for investigation. Essential requirements of dilution ventilation, immediate mixing and dilution, have not been met. Gas detectors under these circumstances are deceptive, giving a false sense of security and only able to indicate, at best, the imminent probability of an explosion.

Fig. 4 shows the results of modelling at a different installation. The 50% of LEL iso-surface shown has been produced following a simulated release in a 600 m^3 enclosure, sufficient to produce 11% of LEL if fully mixed. The gas detector setting in this enclosure was 20%. It is again apparent that mixing is poor and therefore gas detection is of little value. Whilst it is recognised that CFD modelling is an approximation that may not represent true conditions with precision, it is an appropriate technique to confirm major effects as in these examples.

CHP and CCGT plants are constructed in a wide variety of configurations, and only a small number have been examined in detail. In addition to CFD studies, some work has been carried out with tracer gas to simulate leaks and establish mixing efficiency. Relatively simple velometer and smoke generator tests have been used at other plants, and the problem of inadequate ventilation has been found to exist in many, but not all of those seen. Generally, as might be expected, it appears to be relatively easy to distribute ventilation air effectively within smaller enclosures and within those in which equipment is tightly installed so that there is relatively high velocity and high turbulence around the fuel pipework. In some cases it has been found to be practicable to modify the air inlet arrangements in a simple way so as to achieve adequate mixing. **However many larger installations appear to require substantial further improvement to reduce the explosion hazard. At these installations the ventilation design is such that a small gas release would go un-noticed and would not trigger a gas detection alarm because the overall ventilation rate is high, but a significant proportion of the acoustic enclosure volume can quickly fill with an accumulation of flammable gas/air mixture because the ventilation velocities are so low.**

The discussion has concentrated on the accumulation of gas/air mixtures but many plants use liquid fuel as an emergency standby, and as their main fuel in a few cases. Liquid fuel supplies to gas turbines may be at pressures of 60barg, and the release of fuel in such circumstances may lead to a mist with explosive potential. Release rates would be very much higher for equivalent hole sizes, and the physics of the mixing and dilution of such a cloud is not well documented. The auto ignition temperatures of such fuels may be particularly low and the risk of ignition enhanced.

SUGGESTED SOLUTIONS

Depending on circumstances, reduction of the foreseeable risk of an explosion can be achieved by the adoption of a combination of solutions. Different solutions will be appropriate at different plants, depending upon design, size, location etc. Improvements may be made to both the hardware and to the software, i.e. the safety management systems. In most cases consideration should be given to improvements in both categories, although the options for changes to hardware will always be greater in the design of new installations. Software improvements could include attention to a formal safety management system, quality assurance procedures, written operating and maintenance procedures, alarm testing, emergency procedures, change control and audits, for example.

The following are not suggested as a complete or exclusive list of possible relevant improvements, but for consideration. A risk assessment should be carried out in each case and the appropriate solution(s) selected if indicated.

SITE SELECTION

1) Site plant so that noise reduction measures are not required, or can be satisfied by insulation or less enclosed noise reduction measures. Turbines within very spacious halls do not present an explosion hazard, since flammable mixtures are not enclosed, but ignition following a leak would result in a fire which could only be detected and fought in conventional ways. Natural thermal convection has been found to approximate to *Dilution Ventilation* in some such cases. *Adequate ventilation* should be provided as a minimum.

ACCESS

2) Access should be restricted to the minimum and only permitted in exceptional circumstances for authorised personnel under a permit to enter/work system. Routine visits once per shift probably tell the operators nothing that cannot and should be detected by instrumentation. Entry under any on-going emergency condition should be banned.

VENTILATION

3) Design to achieve *dilution ventilation* as defined, i.e. with no stagnant regions. In larger units it may only be possible to achieve this by introducing air at high velocity locally to regions containing potential leak sources. There are no

established numeric criteria against which to assess ventilation mixing efficiency. Pure fuel at the leak source is inevitable and any criterion should take dilution into account. For an enclosure of $100m^3$ a criterion of $0.1m^3$ at 50% of LEL iso-surface, i.e. dilution from pure gas to 50% LEL within a volume of $0.1m^3$, from a leak equivalent to that which would trigger gas detection, has been suggested, and is under trial as a design limit, on the basis that the ignition of a cloud within this limit would create an overpressure no greater than 10mbarg. For other enclosures a similar criterion of 0.1% of the enclosure volume is suggested. CFD or tracer gas trials could be used to confirm achievement of this type of criterion.

4) Set gas detectors to operate at the lowest practicable acceptable level. This reduces the leak size that they will detect, and thus the leak size which the ventilation has to be shown to be capable of diluting rapidly. In larger units this may only be possible by the use of on-line analysers. Gas detectors should be sited in the ventilation outlet duct. Other positions, such as the enclosure roof, may be appropriate in addition, but not as the sole position. Additional piped gas sampling systems from probable key leakage positions may be appropriate, but cycle times must be low for such systems to be of value. External gas detector calibration points should be considered.

5) Consider the use of a second fan as an emergency addition to the normal levels of ventilation in the event of a gas detection alarm, to allow the plant to be shut down safely. Alternatively or additionally trip the turbine to idle in the event of an alarm, reducing fuel supply pressure, prior to shut down. It is essential that any gas alarm is investigated properly however, and that the effect of the additional ventilation, if it causes the alarm to be cancelled, does not result in a failure to carry out such an investigation.

6) Arrange ventilation to pass from exhaust towards compressor, i.e. so that fuel releases are less likely to ignite. This may have a small effect on cooling efficiency, but the effect would be insignificant at plants with low ventilation velocities. It may not be possible to change those that are efficiently ventilated from cool to hot regions.

7) Interlock ventilation with fuel supply, so that the unit cannot start without ventilation and pre-purging, and will shut down on ventilation failure.

8) Consider the use of a recirculating fan within the acoustic enclosure, to create better mixing and dilution without increasing the overall ventilation rate.

FUEL PIPEWORK

9) Avoid liquid fuels, if possible, since the flow patterns and dilution efficiency of ventilation of liquid fuel mist releases is not known. If liquids are essential, take additional precautions, as noted below, to minimise leaks and their consequences.

10) Reduce the risk of a leak. Use the minimum number of joints. Very high standards of Quality Assurance should be applied to the assembly, and every re-assembly of fuel supply pipework, requiring the individual identification and duplicate signing for each bolt, or joint. Consider all welded pipework for liquid fuels. Consider double sealed flanges; i.e. flanges with pressure testable interspace between double seals. Consider vibration monitoring of pipework.

11) Fit manual valves to each fuel entry at each combustion chamber. If such valves were an integral part of the combustion chamber, the fuel supply systems could be safely tested using tracer gases, reducing the risk of a leak at start up and enabling the positions of leaks to be safely identified when they have arisen. The increased number of potential leak sources would be more than compensated by the ability to test after assembly or the detection of a leak. The proposal may not be practicable for smaller turbines, where there is insufficient space for valves and their mass associated with thin wall fabrications, would be unacceptable

12) Consider double containment fuel supply system. Although more likely to be practicable for smaller turbines or liquid fuels, this has been proposed at one large application.

13) Fit a valve proving system to fuel supply safety shut off valves. This requires double safety shut off valves with a pressure proving system, or proof of closure switches fitted to each valve and to the vent valve. Full details are given in Ref. 10, pages 557-563. It is a normal requirement for large gas-fired plant, and should be fitted to turbines of equivalent capacity.

EXPLOSION RELIEF AND SUPPRESSION

14) If *dilution ventilation* cannot be shown to be practicable, and risk assessment indicates need for reduction measures, fit explosion relief. Easier and less costly to fit to new plant than to retrofit , relief has the advantage of proven reliability. Strengthening of the enclosure reduces the vent area required, and existing roof panels may suffice. Relief has now been, or will be fitted to a number of on-shore plants. Whilst relief should, if possible, discharge to a safe place outside, if this is not possible it may be necessary to discharge into a building, towards the roof, rather than risk the more disruptive effects of an explosion without any designed relief. The operation of relief panels that remain open may effect the efficiency of fixed fire fighting equipment, if fitted, but such equipment would be of little value if the enclosure were more substantially disrupted by the explosion in the absence of relief, and the operation of relief can be used to trigger an emergency shutdown with fuel shutoff to minimise subsequent fire damage. Relief panels that close after use would be advantageous in this respect.

15) As an alternative to relief, consider explosion suppression techniques, probably more likely to be cost effective at smaller units. Most suppressants will preclude access during operation.

LEGAL POSITION

Manufacturers and suppliers are subject to The Health and Safety at Work etc. Act (HSWA) 1974, section 6(1)(a) which places a duty on them to ensure, so far as is reasonably practicable, that equipment is designed and constructed so that it will be safe and without risks to health at all times when it is in use or being cleaned or maintained by a person at work. They are also likely to be subject to the Supply of Machinery (Safety) Regulations 1992 (as amended) which implement The Machinery Directive, and require safety by design and manufacture, and to the Equipment and Protective Systems Intended for Use in Potentially Explosive Atmospheres Regulations 1996 which implement the Article 100A ATEX Directive and also require safety by design and manufacture.

Owners and operators are subject to HSWA 1974, sections 2 and 3 in particular, the Provision and Use of Work Equipment Regulations 1992, and The Management of Health and safety at Work Regulations 1992, all of which impose relevant duties.

CONCLUSIONS

It has been found that the ventilation systems in many gas turbine based CHP and CCGT plants are inadequate, and have been designed for turbine cooling without proper consideration of the implications of a fuel release. The need to avoid stagnant regions to achieve *dilution ventilation* has been overlooked, with the result that a serious explosion hazard exists at many of these plants. Gas alarms, if fitted, would give no indication of the existence of large accumulations of flammable mixture in the event of a leak, and ignition is probable. A wide range of improvements are possible to reduce the risk, or mitigate the consequences. Risk assessment and plant modifications to existing plant should be carried out, where necessary, as soon as practicable. Similarly, risk assessment should be used to determine appropriate safeguards for new plant.

Similar considerations may also apply to CHP plants driven by internal combustion engines, and to other applications where the basis for safety is ventilation supported by gas detection.

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Figs 1-4 are taken from work carried out under contract to HSE by W S Atkins Ltd and AEA Technology plc, and by the Health and Safety Laboratory (HSL)..

Figs 1-4 were originally derived in colour, but may have been reproduced in B/W. Coloured versions may be obtained from the author on request .

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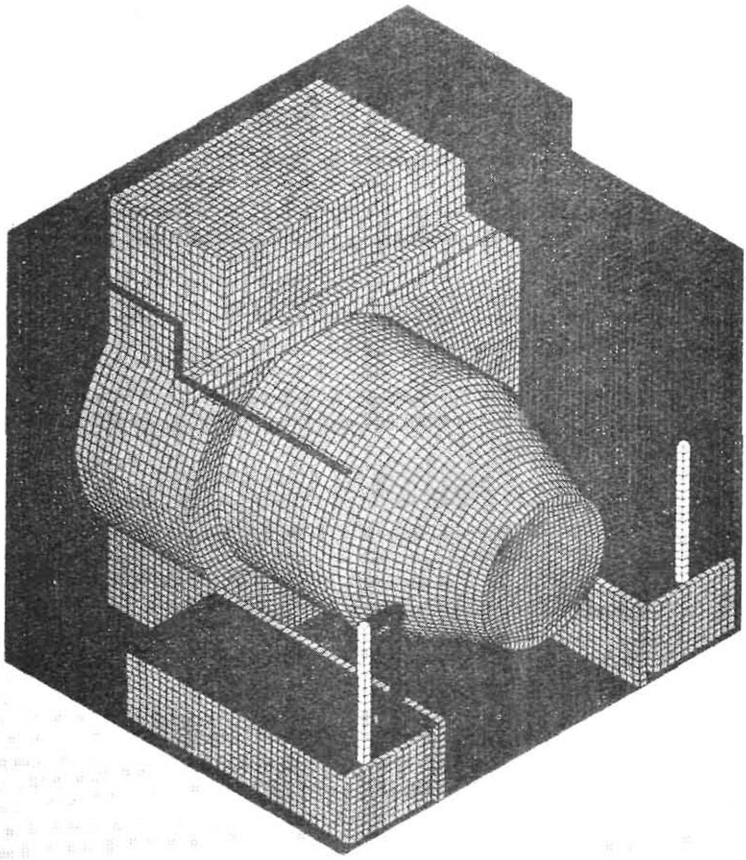

FIG 1

$100m^3$ ACOUSTIC ENCLOSURE, COMPUTATIONAL GRID

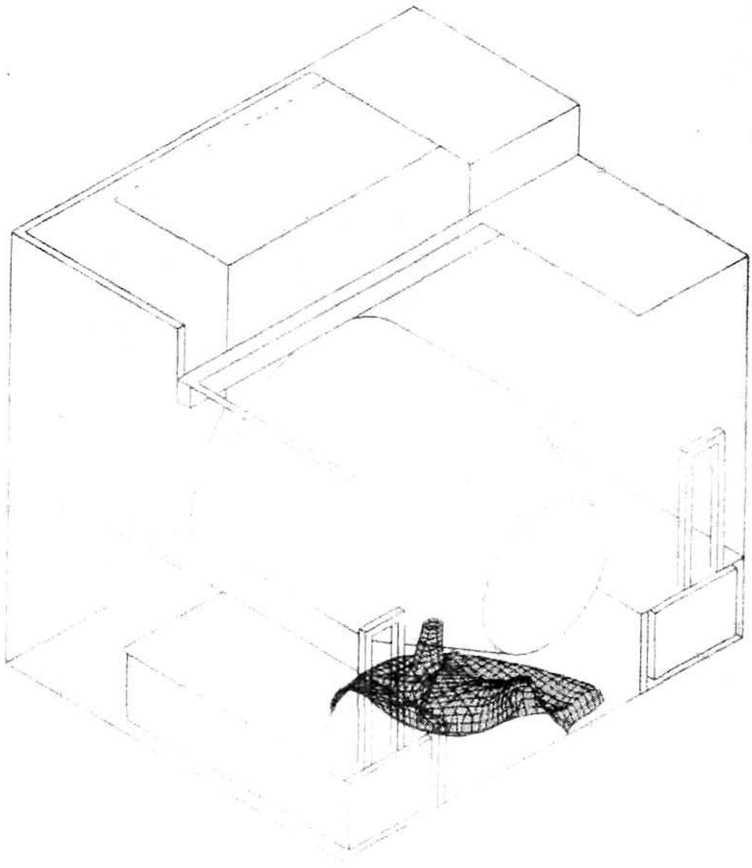

FIG 2

100m³ ACOUSTIC ENCLOSURE

SMALLER GAS RELEASE, 50% LEL ISO-SURFACE

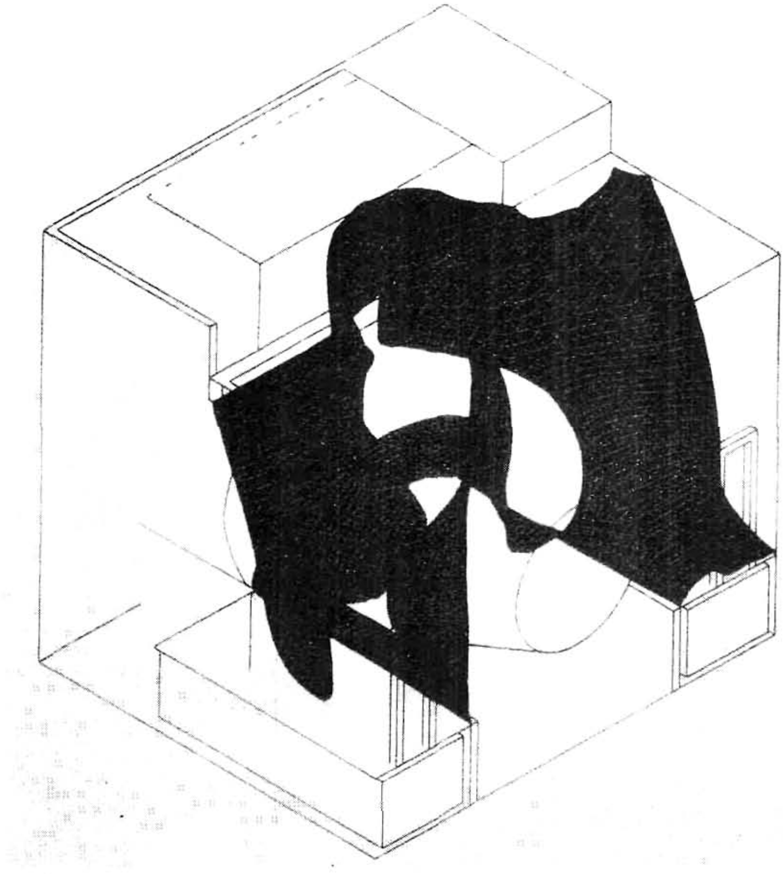

FIG 3

100m³ ACOUSTIC ENCLOSURE

LARGER GAS RELEASE, 50% LEL ISO-SURFACE

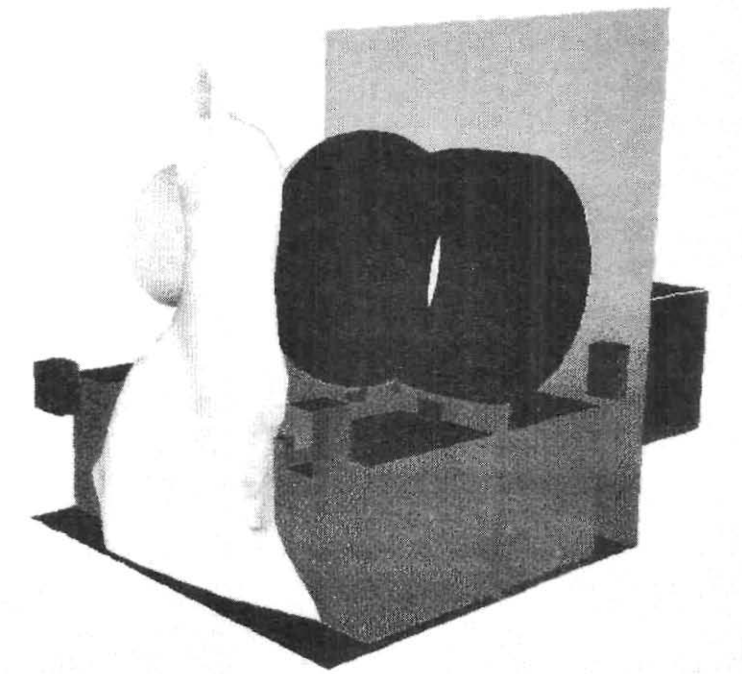

FIG 4

600m³ ACOUSTIC ENCLOSURE

GAS RELEASE, 50% LEL ISO-SURFACE