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STEAM EXPLOSIONS AND REACTOR SAFETY

A.J. BRIGGS
United Kingdom Atomic Energy Authority

September 1982

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

OECD NUCLEAR ENERGY AGENCY
38, boulevard Suchet, 75016 Paris, France

NUCLEAR SAFETY DIVISION

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The main CSNI activities cover particular aspects of safety research relative to water reactors and fast reactors; probabilistic assessment and reliability analysis, especially with regard to rare events; siting research; fuel cycle safety research; various safety aspects of steel components in nuclear installations; and a number of specific exchanges of information.

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Requests for additional copies should be addressed to:

Nuclear Safety Division
OECD Nuclear Energy Agency
38 boulevard Suchet
F-75016 Paris
France

FOREWORD

In November 1981, CSNI decided to set up a small Group of Experts to explore the possible significance of fuel-coolant interactions (FCIs) to reactor safety. In particular, the Group was to see if it was now possible to reduce the conservatism regarding FCI phenomena in recent US and German risk studies on light water reactors, where the dominant accident sequence considered was that involving pressure vessel and containment failure.

NEA commissioned Mr A.J. Briggs of the UKAEA Atomic Energy Establishment at Winfrith to prepare this report as a background and stimulus to the Group's discussions. It reviews the history of the concern over hypothetical FCIs in reactor core melt accidents. It is focussed on LWR applications because of the Group's interest in risk assessments for this type of reactor, and because of several recent attempts to resolve remaining uncertainties about the impact FCIs could actually have on severe LWR accidents.

The report was well received by the Group of Experts, and is now being issued as a CSNI report to make it available to a broader technical audience.

Mr Briggs prepared the report as a consultant to the NEA. Thus it expresses his own personal views and in no way represents the official views of the UKAEA or OECD, or their respective policies on these matters.

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A J Briggs

1. INTRODUCTION

The design of every nuclear power plant includes diverse systems to ensure that the reactor core is effectively cooled, both in normal operation and in a very wide range of fault conditions. Nevertheless there has always been some concern that circumstances could arise in which part of a reactor core might overheat to the point at which the fuel melted. Studies of the behaviour of molten fuel have been pursued as part of the industry's programme to evaluate the probability and consequences of unlikely but severe accidents. One aspect has been investigation of the possibility of an explosive generation of vapour, often referred to in this context either as a Fuel Coolant Interaction (FCI), or as a Steam Explosion when the coolant is water.

The concern of the Nuclear Industry with FCI stemmed originally from two considerations. Firstly, steam explosions have been involved in a number of serious industrial accidents, for example the Quebec Foundry Incident in which 100lbs of steel fell into water producing an explosion which severely damaged the building. (1) (2) Such steam explosions also occurred in some early reactor incidents eg SPERT (3). Secondly, because of its high temperature, the amount of thermal energy stored in molten power reactor fuel is very large. Simple calculations show that it is thermodynamically feasible for a significant fraction of this thermal energy to be converted to mechanical energy if the fuel is mixed with a liquid coolant which then expands to relieve the high pressure of the mixture. Such calculations for a fast reactor cooled by sodium were published by Hicks and Menzies in 1965. (4) However, even though it is the case that damaging steam explosions have occurred with some materials, and that large explosions in some reactor situations cannot be ruled out on solely thermodynamic grounds, continuing studies have indicated a number of reasons why the role of FCI may be relatively minor in severe reactor accidents.

This paper reviews progress which has been made in understanding the nature of FCI, and discusses the significance of FCI in accident analysis and risk assessment. Attention is focused on LWR applications because of the current interest in risk assessment for this system. Issues on which there are differences of opinion or emphasis are identified, in the hope that they may be clarified or resolved at the meetings to be arranged by CSNI to discuss steam explosions and reactor safety.

2. BACKGROUND

Early work on FCI was largely related to LMFBR safety. In this system the high rating of the fuel implies that in some local faults fuel can overheat to its melting point rather rapidly. The possibility that material movements within the core can increase reactivity and result in a prompt critical transient implies that rapid melting of a significant fraction of the core inventory is also a possibility. For these reasons early studies of FCI were largely focused on evaluation of Sodium Fuel Interaction either locally within a sub-assembly, or following more widespread melting of the core. International meetings on Sodium Fuel Interaction were held at Grenoble in 1972, at Ispra in 1973, and at Tokyo in 1976. (5,6,7).

In an LWR a concern is that however, if a loss of primary cooling is followed by failure of emergency core cooling systems then melting of the core may eventually occur. Such low probability accidents were considered by Rasmussen in 1975, (8) who drew attention to the possibility of a large steam explosion damaging the reactor containment. Interest in steam explosions in water reactors led to the fourth CSNI specialist meeting at Bournemouth in 1979 having wider terms of reference than the earlier meetings to include this topic as well as fast reactor considerations.(9)

In addition to organising periodic meetings of specialists the CSNI has also sponsored meetings of a small Group of Experts in the Science of FCI, (10), and a Joint Interpretation Exercise on Selected FCI experiments, which was reported in 1981 (11). The continuing CSNI interest in this topic is an indication that assessment of the role of FCI is still considered important, and that some technical questions have yet to be fully resolved.

3. EXPERIMENTAL STUDIES

Experimental investigations relevant to FCI assessment can be of two kinds. Firstly there are experiments in which features of a specific reactor situation are simulated, and the nature of any energetic molten fuel coolant interaction directly observed. Such experiments may be called 'prototypic', and to the extent that they are representative, their results may be of direct value in reactor assessment. Alternatively, experiments may investigate vapour explosion characteristics possibly with different materials in simplified geometries. Such experiments provide a basis for development of physical models of vapour explosions, which may be relevant to the assessment of FCI in specific reactor conditions. Such experiments may be termed 'scientific' in the sense that the immediate objective is to advance the science of vapour explosions. Review of past studies indicates that practical difficulties have severely restricted the range of 'prototypic' experiments. In the LMFBR some data are available on FCI immediately following fuel failure from in-pile experiments, but very few other data

data of this kind are available for other LMFBR situations, or for the LWR situation of main interest. In the latter cases, the large mass of fuel potentially involved, effectively precludes 'prototypic' experiments until scaling effects have been established.

The type of data available from 'scientific' experiments extends from studies of the behaviour of single drops of fluid to observations of explosions involving at least 20 Kg of material. Materials studied cover a range of physical properties, and included molten refractory oxides, molten metals, oils, water and cryogenic fluids. References may be found in review papers e.g. (12) (13) (14) (15) (16) (17). On the basis of these data, the most recent meeting of experts arranged by CSNI, (Karlsruhe December 1980) (11), agreed on a description of the necessary stages for a vapour explosion to occur, although with some reservation with regard to the specific description of the early stages. This description included the following major stages, as well as more detailed comments.

(i) Initial coarse pre-mixing without large heat transfer, generally implying stable film boiling for the pre-mixing period

(ii) Destabilisation of film boiling either spontaneously or from an external pressure pulse

(iii) Micro scale mixing and rapid heat transfer in a local region

(iv) Propagation of a zone of rapid heat transfer through the coarse mixture, which may develop into fully fledged propagating detonation

Although based on observation of interaction between a range of material pairs, such evidence as is available for reactor materials, including simulants of LWR materials, is consistent with the description (18) (19) (20). Hence there are now strong grounds for assessing steam explosions, and other FCI, in terms of the essential stages involving premixing, a trigger event and propagation through the system.

4. THEORETICAL MODELS

The identification of a series of necessary stages in a vapour explosion suggests that calculation of the loading on surrounding structures may require different models for each stage. For example, four separate models could be needed, dealing with the following topics:-

(i) The extent of mixing as the liquids come together

(ii) The timing and nature of possible trigger events

(iii) The extent and nature of the propagation, following each possible trigger, given the mixture characteristics at that time

(iv) The loading of key components resulting from the steam explosion.

Such models are necessary because of the need to extrapolate from experimental conditions to a wide range of possible reactor accident situations. Safety analysis can involve establishing some upper bound, or worst case, in distinction to calculating a best estimate for a particular process, for which more detailed models may be required. In the case of steam explosions, some bounds can be established but fully predictive models are not yet available for all the processes involved. Modelling of each stage is discussed in turn.

(i) Mixing Stage

Energy losses resulting from drag forces were considered by Cho, Fauske and Grolmes, who concluded that initially separated fluids could not be fragmented and mixed on a fine scale on a millisecond time scale without a very large input of energy (21). Although different assumptions as to the mechanics of the mixing process lead to different energies (22), their approach does allow some bounds to be placed on the rate at which mixing can occur. More recently two papers have drawn attention to the increased difficulty of mixing large masses of liquids at different temperatures. Fauske and Henry draw attention to the importance of vapour production, and argue that the extent of mixing can be limited by considerations of hydrodynamic stability (23). Theofanous and Saito also point out that the mixing rate may be low, and a coarse mixture unstable because of gravitational separation.

(ii) Trigger Stage

Little analysis of the trigger process has been reported and this stage of a vapour explosion has generally been discussed in terms of experimental data. The report of the specialists meeting at Karlsruhe in 1980 identified destabilisation of the vapour film as the key process. More recently Corradini has discussed experimental data from Sandia in terms of a model of vapour film collapse, and concluded that the main features of this data can be explained in these terms (25). In particular he concludes that the observed suppression of explosions by increasing ambient pressure may be dependent on trigger strength, and this is consistent with recent experimental results, for example experiments at Ispra with salt and water. (26)

(iii) Propagation Stage

The concept of thermal detonation was first proposed in 1974 by Board, Hall and Hall. (27) The key physical assumption is that the arrival of a shock wave results in an increase of heat transfer to the coolant in the rear of the shock wave, which then expands to provide the energy necessary to sustain propagation of the wave. Hence calculations using this concept require

(i) a description of the initial configuration of materials, and

(ii) a physical model to describe the fragmentation produced by the shock front, and the subsequent heat transfer

Additionally the nature of events capable of initiating such a detonation has to be considered, as well as the effects of the constraints provided by the boundaries of the system.

Considerable progress with the development of the detonation model has been made, but this has been limited by the difficulty in establishing a model for the fragmentation process. The CSNI Group of Experts commented at their meeting in December 1980 that the fragmentation mechanism is complex and variable, and suggested that it might be sufficient to develop correlations rather than mechanistic models.

An alternative approach to the calculation of FCI characteristics has been to develop models in which the fragmentation and heat transfer rates are controlled by input parameters. Such models are useful in analysing experimental data, but their value for safety assessment is limited by the difficulty in establishing appropriate parameters for reactor conditions. Parameters derived from experimental data may not be appropriate if significant extrapolation is involved between experimental and reactor conditions. An example of this approach is provided by the SIMMER calculations discussed in Appendix 7 of reference 30.

(iv) Structural Response

Calculation of the effects of an in-vessel explosion involves first calculating the loading on the reactor vessel, secondly assessing the nature of vessel failure with special attention to production of high energy missiles, and thirdly evaluating any damage to the containment. For the first task transient hydrodynamic codes are available, which can in principle make some allowance for the interaction of fluid flows with deformable internal structures. However, in practice the dominant uncertainty is the characterisation of the steam explosion Codes such as SEURBNUK, CSQ and SIMMER have been used. Output from codes of this type can be used as input for more detailed finite element calculations of the stresses and strains produced in critical regions of the structure. Failure criteria may then be used to assess whether failure is likely, and to comment on the mode of failure.

Further details of methods of these kinds are given in (8), (29) (30) (31).

5. TECHNICAL ISSUES IN LWR SAFETY

The development of an accident in which the core of an LWR melts could follow a variety of paths, but the possible roles of steam explosions can be defined in rather simple terms.

(i) The original concern of Rasmussen was that if a large fraction of the core were to melt, it might suddenly drop into the base of the reactor vessel and interact with the water there in a single explosion which could fail both the vessel and the containment. Such a catastrophic event would result in a large release of activity from the plant with severe consequences.

(ii) Given core melt, a more probable sequence would be for the core to interact less violently with water in the base of the vessel, and subsequently melt its way out of the vessel into the containment, where it may again come into contact with water. During these stages, steam explosions may affect the steam production rate or the coolability of the core debris, either directly or by dispersal of the core debris.

The issues associated with steam production rate and coolability of core debris are important in any probabilistic risk assessment, but in this context, steam explosion is one of a number of phenomena which need to be assessed if likely containment loadings are to be evaluated.

This contrasts with the assessment of the possibility of a very large explosion causing early failure of the containment. Although it may be considered improbable, such an event would inevitably have very severe consequences. The dominant steam explosion issue is therefore considered to be whether on present information such an event should continue to be considered physically possible, and if so, how its probability can be related to available data. Since a sequence of events is involved, analysis of this issue involves consideration of the following processes:-

(i) Meltdown of the core, including the extent to which a large pool of melt accumulates, and the rate at which the melt flows down into the lower head.

(ii) The extent to which molten core material mixes with water as it flows down to the base of the vessel.

(iii) The timing and location of events capable of initiating a steam explosion, given an appropriate mixture of molten fuel and water.

(iv) The characteristics of any steam explosion, in particular the form of the pressure transient generated in the explosion, and the kinetic energy developed in the surrounding fluids.

(v) The loading of the reactor vessel resulting from the explosion, after allowing for the effect of internal components.

(vi) The response of the vessel to the loading, and in the event of vessel failure, the mass and velocity of any missiles emitted.

(vii) The response of the containment to vessel failure, which could result in release of steam, missile impact and possibly vessel movement.

6. PROBABILITY ASSESSMENT

The possibility of failure of the containment of an LWR by steam explosion has been mentioned in a number of reactor safety studies, and other recent publications. The conclusions of seven such studies are discussed, in order to compare the conclusions drawn from the data available at the time of each study.

(a) Reactor Safety Study (1975) (8)

The Rasmussen study was published in 1975. The models used were idealised in a way which is not now considered realistic, but the study introduced its estimate with the statement "a broad band of uncertainty must be associated with a quantitative evaluation of the likelihood of failure of the containment as a result of a steam explosion in the primary vessel." The probability of containment failure by steam explosion given core melt was $10^{-2(+1,-2)}$.

(b) <u>German Risk Study (1979) (29)</u>

The summary of this report states that "the investigations reveal that destruction of the containment vessel as a result of a steam explosion is very unlikely". It also states that the following preconditions for containment failure to be "rather unlikely":-

- fragmentation of the molten core to particles of a size up to a few millimetres,
- even dispersion of the molten core fragments in the coolant,
- sufficient duration of these special heat transfer conditions,
- excessive loads on reactor pressure vessel and containment vessel,

However, pending the results of further research, it adopted the same median value as the Reactor Safety Study, but with a log normal distribution, that is $10^{-2\pm1}$.

(c) <u>Swedish Government Report (1980) (30)</u>

This report was produced by a committee which endorsed the view of the committee's technical consultants that steam explosions do not provide any threat to the integrity of the reactor vessel or the containment building. The conclusion of the report was that "in the overall opinion of the Committee, steam explosions and associated releases of radioactivity do not have to be taken into consideration in designing safety systems and emergency plans."

The technical reviews included in this report cover all aspects of containment damage by steam explosions; the major technical conclusions are summarised in an "additional statement". The principal arguments advanced include:-

- Mixing of large enough masses of fuel and water will not occur
- Steam explosion efficiency is low
- Instantaneous collapse of tens of tonnes of melt into water in the base of the vessel is not possible

- Generation of missiles capable of rupturing the containment by fluid impact on the vessel lid is not realistic

(d) Sandia Reports (31) (32) M L Corradini and D V Swenson (1981)

Two reports on steam explosions in LWRs by Corradini and Swenson were published in 1981. The first, (31), reviewed the phenomena and analysed the consequences of a steam explosion in a specific PWR design (Zion). It recognises that the physical mechanisms are not well understood, and analyses the consequences for the vessel and containment of two levels of explosion, 300MJ and 3000MJ. The larger value is an upper bound obtained by ignoring mitigation effects that are difficult to quantify. The smaller value is referred to as a best estimate, based on their analyses and subjective judgements. Their assessment of the probability of containment failure given core melt is made on the same basis, giving a best estimate of 10^{-4} and an upper bound of 10^{-2}.

One of the key assumptions in this work is the efficiency of the steam explosion. The best estimate case assumes that in a large system this has the same value as in experiments with kilogramme quantities. The probability assessment is similar to that in WASH-1400, in that a number of relevant factors are defined, and then quantified again on the basis of analyses and subjective judgement.

The second report, (32), used Monte Carlo analysis to quantify in a more systematic manner the combined effect of a range of mitigating factors, none of which can be accurately specified and which are therefore difficult to combine. A series of input parameters define the characteristics of the slug impacting the vessel head. Distributions are defined for each input parameter and a Monte Carlo technique used to calculate the frequency distributions of the output parameters. A simple structural analysis evaluates the vessel response to each slug, and hence allows the probability that a missile might damage the containment to be evaluated. In these calculations the uncertainty in the phenomena manifests as wide ranges on the nine input parameter values. Inevitably this results in most probable output values which are much below upper bound levels. The results of these calculations using "best estimate" input parameters are that the probability of containment failure is less than 10^{-4} for a PWR and of order 10^{-3} for a BWR. Sensitivity studies indicate the key quantities are steam explosion energy and the void fraction in the slug at the time of impact.

(e) Assessment of Class 9 (core melt) accidents for PWR dry containment systems. (24) T G Theofanous and M Saito (1981)

This paper reviews the phenomenology of core melt accidents in dry containments, and comments on both in-vessel and ex-vessel steam explosions. It emphasises the improbability of mixing large masses of molten core with water, on the grounds that given the reactor geometry a large flow of molten core would result in a layer of molten core, rather than extensive mixing. It also argues that for in-vessel situations, an effective trigger is improbable on the grounds that for the materials of interest a high resistance to vapour collapse would be expected, and that experimental data on corium water interaction supports this conclusion. An upper bound of 50% of the Hicks Menzies value is assumed for the yield of a large scale FCI. For in-vessel explosions, the maximum mass of mixed core melt is assessed at 2% of the core, to give an energy yield of up to 0.6 GJ. The final conclusion is that containment failure is essentially incredible, ie at least two orders of magnitude lower than the 10^{-2} estimate given in WASH-1400.

(f) 'Required Initial Conditions for Energetic Steam Explosions' (23) R E Henry and H K Fauske (1981)

Given that mixing of molten core with water must precede a major explosion, this paper investigates the consequences of assuming that globules of molten fuel are dispersed in the water. It argues that for cases of concern, the steam generated would disperse the system, driving the water out of the mixture, and dispersing any overlying liquid slug. It also argues that if an explosion were initiated, this would occur before a substantial mass of core had entered the water. The final conclusion is that steam explosions would not be a threat to either the reactor vessel or the containment.

(g) PWR Degraded Core Analysis (33)

This UKAEA report reviews the phenomenology of degraded core accidents in a PWR, and includes a section on steam explosions. This concludes that despite the additional information now available, the extrapolation involved in assessing the probability of a large scale in vessel steam explosion results in considerable uncertainty, and that there is no reason to adopt a narrower range than the 10^{-1} to 10^{-4} of the Reactor Safety Study.

The brief comments on seven studies are not intended to cover every view on steam explosions, and certainly do not develop the arguments in detail for which the reader must refer to the original documents. However, they do indicate the range of arguments that have been put forward, and the difficulty of relating the technical assessment of such a complex sequence of events to a statement on the probability of containment failure. All the studies quoted conclude that containment failure is not likely. They differ in the degree of certainty claimed for their conclusions, and in their best estimates of the containment failure probability given core melt. More specifically, two of these studies claim there is no threat to the containment, whereas others indicate probability ranges which extend from 10^{-1} to less than 10^{-4}.

Two separate factors contribute to the range of the overall conclusions. One results from differences in interpretation of available experimental data and analyses. Such differences are of a technical nature and can in principle, be resolved by further study. Issues of this kind are outlined in the next section.

The second factor involved is the process of relating the technical information available to a specific failure probability. The difficulty relates to the lack of complete and validated models for prediction of all stages of the complex sequence of events which would have to occur if a core meltdown were to be followed by a steam explosion which significantly damaged the containment. Such a model could be used to calculate a probability from the predicted frequencies of alternative end states. However, the situation becomes more difficult when there is a degree of uncertainty as to the physical modelling of important events. In this case, consideration of the analysts' confidence in a particular model becomes relevant, and this is difficult to quantify. Since a sequence of events is involved in failure of the containment, the importance of a particular model depends on other events in the sequence, and the method of combining assessment of different stages to give an overall evaluation also becomes important.

One method which has been used is to break down the overall probability into a number of factors, each of which is evaluated by exercise of technical judgement. The factors are often assumed to be independent, which can be an important assumption, especially if many factors are involved. The subjective element in this process may be expected to result in some variation if applied by different individuals or groups. An alternative method is the use of a Monte Carlo method to evaluate the overall effect of uncertainties on a range of factors which influence the probability of containment damage. This is a more elegant method of combining uncertainties, but the result depends on the realism, both of the physical models employed and of the distribution of input parameters. In this case the analyst had to define probability distribution for each input parameter, rather than point values and this can again introduce a subjective element into the analysis.

The difficulties in relating the results of analyses using models which entail some degree of uncertainty are likely to persist. More precise analysis of the relation between available data and probability estimated from consideration of that data is necessary if different studies are to be compared in detail.

In particular it is necessary to distinguish probability estimates which derive from an expectation of variation in the physical response of a system, from estimates which derive from uncertainty as to the validity of the physical models used.

7. DISCUSSION

The continuing study of fuel coolant interactions and their consequences has provided a firmer basis for safety assessment and there is now a broad measure of agreement on the nature of the processes involved in any large explosive interaction. However, the complexity of the detailed mechanisms involved leads to differences in interpretation and emphasis which can be significant in safety assessment. Some of the more important differences are discussed for each of the main stages of an interaction between molten fuel and water.

(i) Mixing Stage

The requirement for some degree of pre-mixing of fuel with coolant before any efficient coherent large scale explosion is widely accepted. It is clear that such mixing occurs spontaneously in many experiments, but quantification of either the necessary scale of pre-mixing or the actual dimensions in experiments is rather approximate. In the first case this follows from the diversity of possible fragmentation processes, and in the second, from the difficulties of measurement. However, there are some grounds indicating that dimensions of order up to 10mm are involved, and the upper limit of 100mm proposed in ref 24 provides a basis for assessment.

In order to predict the extent and nature of mixing a number of processes have to be modelled for example in the case of molten fuel and water:-

(a) Flow rate of molten fuel into water (or vice-versa)

(b) Break up of continuous zones (eg hydrodynamic effects)

(c) Heat transfer from fuel to water

(d) Effect of steam flow on flow patterns

(e) Settling rate of molten fuel into a lower layer

(f) Solidification rate of molten fuel in the mixture

(g) The timing and size of any FCI that occurs during the mixing process

Clearly these processes interact with each other, and in particular there are strong grounds for identifying steam flow as a major factor influencing other processes, especially in large systems. (23) Henry and Fauske argue that in a large system, a coarse mixture would be unstable because the steam flow would separate the molten fuel from the liquid water. Very rapid mixing is ruled out on the grounds that overcoming drag forces requires more energy than is available. Theofanous and Saito, (24), assess the probable extent of mixing as a stream of molten fuel drops through water onto a solid base. A key assumption is that the molten fuel accumulates on the base at the same rate as it flows into the water, which implies that steam flow upward does not hold up the downward flow of the molten fuel in this configuration.

A second major factor is the timing and size of any FCI which occurs before all the molten fuel has entered the water. If a series of FCIs were to occur very rapidly, then the size of each would be limited provided the mixing rate were not significantly enhanced. However, in (33), an FCI is suggested as one mechanism which could lead to an enhanced flow rate of molten core into water. It is also possible that such an event would tend to separate molten fuel from water, but the range of possible geometries makes firm conclusions of this kind dependent on detailed analysis.

A third factor is the system pressure. This is important because the probability of spontaneous FCI occurring rapidly will be reduced at high system pressure. Steam flow effects also depend in a more complex way on pressure, but the effect may be that the hydrodynamic stability limitation is less stringent.

In the context of possible severe damage in an LWR, very large masses of fuel would have to be involved. If a minimum mass of fuel of concern is defined then it is necessary to assess the probability of this mass of fuel mixing with water. Although there are reasons why mixing very large masses of molten fuel with water should be much less probable than for smaller masses, there is a case for further investigation of the following specific points:-

(a) The extent to which the critical heat flux proposed in (23) is appropriate for the geometry of molten fuel in a reactor vessel, in the time scale of interest, which may be short if the flow rate of molten fuel is high

(b) The extent to which heat transfer effects, especially steam production, delays the settling of molten fuel on the base of a water filled vessel

(c) The effect of FCI, early in the mixing process on the subsequent mixing process, either by altering the flow rate of molten fuel, or by ejecting the water, or directly by causing rapid flows in confined spaces.

(d) Evaluation of the likely flow rate of molten fuel from the core, and the configuration at the time when mixing is in progress, as this is relevant to assessing the effect of an FCI on subsequent mixing.

(ii) Trigger Stage

The importance of the trigger process is that it can strongly influence the timing of any FCI, and indeed can also influence whether an FCI occurs at all. On the basis of experimental data obtained at Sandia using simulated molten fuel, and the likely stability of the vapour film, it has been suggested that even near ambient system pressure spontaneous triggering may not often occur when molten fuel pours into water. (24). However, experiments at Winfrith have shown that a modest impact can effectively trigger interaction of molten fuel simulants with water. (20).

In (31) an estimate is made of the peak pressure that could arise from an impact, but it is also pointed out that the mechanisms involved in spontaneous triggering have not been identified. In (23) it is argued that spontaneous triggering is to be expected when the molten fuel contacts a wetted steel surface. It is clear that numerical assessment of the probability of an effective triggering occurring in reactor accident conditions depends on the interpretation placed on experimental data. The experiments with Corium at Sandia can be taken to indicate a low probability for the particular materials involved in-vessel, whereas other information indicates a higher value for similar materials.

At higher system pressure, there is a growing volume of experimental data to indicate that it becomes more difficult to trigger any interaction. If an external trigger is applied there is considerable evidence that a more energetic trigger is needed for higher system pressures, although some anomalies have been observed for small mass, (single drop), experiments. (34). Two interpretations can be put on this data. On the one hand it can be interpreted as indicating a pressure threshold, above which no FCI could occur. (30). Alternatively, it can be interpreted as resulting from the increasing stability of the vapour layer surrounding the hot liquid, in which case there is no obvious reason for any threshold effect. (25).

Since there is no reason to suppose that the trigger process depends on system size it is possible that further experimental work could provide a firmer basis for the assessment of this phenomena. This could test the frequency of triggering on contact with appropriate surfaces, as well as the variation of trigger strength over an extended pressure range. The value of such work would be greatly enhanced if it could also be used to validate a physical model of the trigger process, for example by demonstrating that variation in the stability of the vapour layer could explain the whole range of data.

For water reactor situations at present the balance of evidence is that an effective trigger is quite probable at near ambient pressure, but rather improbable at high pressures. Quantification of these statements depends on more detailed specification of the conditions, and involves the difficulties discussed in section 6. In view of the strong effect of system pressure and the diversity of possible trigger events it seems likely that safety assessments will continue to have to consider a range of frequencies for effective trigger events, especially for low system pressures (say less than 2MPa). For higher pressures, the situation is clearer, and further work should make it possible to resolve the question as to whether very energetic events could be effective triggers at high pressure, and if so, whether any such events are likely in reactor conditions.

(iii) Propagation Stage

The consequences of an FCI depend upon the kinetic energy imparted to surrounding fluids and the form of the pressure transient experienced by the vessel. If it is assumed that a large mass of molten fuel can mix with water then the principal issue involved in assessing the consequences of an FCI is the effect of scale. Experiments involving of the order of 10 kg of molten fuel simulant have generally resulted in efficiency of order 1% for conversion of the initial thermal energy to kinetic energy, and peak pressures measured to be of order 20 MPa eg (34).

A low conversion efficiency has also been observed in experiments with other materials, and deduced to be probable in a number of larger scale industrial accidents. The reason for this low efficiency is crucial when considering extrapolation. On the one hand if it is assumed that the initial mixture characteristics and heat transfer processes are independent of scale, and that the low efficiency is at least partly due to incomplete heat transfer, then the longer time scale resulting from the greater inertial constraint in a larger system could result in higher efficiency. In such a calculation, the peak pressure would also be higher in the large system. Alternatively, it is possible that one reason for the observed low efficiency is that much of the molten fuel does not participate because it is not mixed in a suitable configuration (eg particle size too large for fragmentation to be effective). In this case efficiency could effectively be controlled by the mixing process, in which case a reduction with scale is quite feasible. This point brings out the difficulty of separating arguments relating to mixing and efficiency from experimental data.

Calculation in terms of basic fragmentation mechanisms is possible in principle, but at the present time, knowledge of fragmentation limits the value of results, which of course also depend on the initial configuration of the mixture.

In this situation, judgement is involved in assessing the likely consequences of an FCI. There is a wide consensus for expecting a lower efficiency than would result from an idealised process such as that defined by Hicks Menzies, which ignored rate limitations. (4). Quantitative estimates of conversion efficiency range from 15% (half of Hicks-Menzies value) as an upper limit, (24), and 4 ± 4% as an upper limit (33) to 1 (+2, -1)% in (32) and 1% as an overestimate in (30). The two lower figures correspond to the values measured in experiments, whilst the higher figures allow for possible increase with scale. Progress with studies of the fragmentation process and of the mixing stage is required before likely conversion efficiency can be established more firmly, and such work could well justify considerable reduction in the higher values quoted above.

(iv) Structural Response

Studies of the damage resulting from an FCI in a water reactor initially concentrated on the impact of water on the upper head. (8). The importance of internal structures in dispersing the slug and reducing the slug energy on impact is now recognised (30) (32). However, the upward acceleration of a fraction of a molten core could increase the slug mass (31). A further factor is that a large enough FCI to threaten the upper head would almost inevitably involve pressures high enough to cause local failure at the site of the FCI, in the lower head. (31). For large explosions, the possibility of vessel movement has also been recognised. (31) (33).

The reported studies identify the capability of a typical PWR vessel as of the order of 1 GJ. (30) (31) (33). The question of containment failure is more difficult to assess. It requires calculation of the mass and velocity of any missiles ejected as the vessel fails, and of the consequences of vessel movement. The damage resulting from missiles generated by slug impact is assessed in (31), which concludes that large mass missiles are unlikely because a different failure mode is predicted, and that small mass missiles would not penetrate the containment. However, the difficulty in calculating the failure modes in a complex structure are emphasised in (33), and it is therefore difficult to establish that the containment would not be damaged for explosion yields exceeding 1 GJ. Further work on vessel failure would tend to be specific to a particular plant, and could at best establish a higher threshold value for containment damage (eg 5 GJ). This suggests that it may be more profitable to establish vessel capability, rather than to evaluate the consequences of vessel failure.

8. CONCLUDING REMARKS

This review has concentrated on the assessment of the possibility of a large scale steam explosion in an LWR. By comparing published studies in the light of available data it is clear that there are strong arguments indicating such an event is improbable. Numerical assessments of the probability of such an event vary, and two factors are identified as responsible. Firstly assessment of a number of aspects of such an event involves the exercise of judgement as theoretical models are as yet incomplete, and extrapolation from conditions studied in experiments is involved. Relating technical information to a probability value is particularly difficult when the event of concern has a low probability. The second factor is that there are technical differences, for example as to whether there is a pressure threshold above which FCI cannot be initiated.

In the context of risk assessment, it would appear that establishing more clearly the relationship between available technical data, the degree of confidence in modelling of the processes involved, and the probability of containment failure should be given high priority. This is important because the review does not indicate clear arguments that containment failure is physically impossible, rather that it is improbable.

The review also indicates that further studies on some aspects of the mixing and triggering stages could be expected to substantially reduce uncertainty. In particular, further study of the role of steam flows could establish limitations on the scale of mixing to be expected in various timescales of interest.

The structures present within a reactor vessel have been identified as being of major significance, particularly in reducing the loadings on the reactor vessel. This appears to be an area in which rather little published information is available, perhaps because it tends to be design specific. Further published work on this topic could help to establish the case for a low probability of containment failure.

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