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ENERGETICS OF LMFBR CORE DISRUPTIVE ACCIDENTS

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Summary

In general, in the design of fast reactor systems, containment design margins are specified by investigating the response of the containment to core disruptive accidents. The results of these analyses are then translated into criteria which the designer must meet. Currently, uniform and agreed upon criteria are lacking, and in this time while they are being developed, the designer should be aware of the considerations which go into the particular criteria he must work with, and participate in their development.

This paper gives an overview of the current state of the art in assessing core disruptive accidents and the design implications of this process.

Introduction

In the past, containment design margins for fast reactor systems have been specified by investigating the response of the containment to core disruptive accidents. The current approach in the U.S. is to consider the response of fast reactors to accident conditions in terms of four lines of assurance (LOAs). Thus, LOA-1 is to prevent accidents, LOA-2 is to limit core damage, LOA-3 is to control accident progression, and LOA-4 is to attenuate radiological consequences. Thus, the specification features to mitigate the consequences of core disruptive accidents fall under LOA-3. The objective of this paper is to give an overview of the current state of the art in assessing the energetics of core disruptive accidents within this context and to indicate the implications of this assessment for the reactor designer.

Overview

The first question we must ask ourselves in any discussion of core disruptive accidents is, should we consider them at all in the design of fast reactor systems. There is a point of view which says that if we are successful in LOA-1 and LOA-2, i.e., in preventing and limiting core damage, then we need not consider core disruptive accidents further. In this point of view it is believed that the probability of core disruption has been reduced to such a low level that further consideration of this type of accident is not required and a judgement that the risk is acceptable can be made without the consideration of mitigating features in the reactor design. In my view this approach is not entirely satisfactory in that I feel certain mitigating features should be provided and their effectiveness must be evaluated.

A better approach is that which was originally suggested by Graham [1]. In this approach the probability of core disruption is first reduced to a very low level (LOA-1 and LOA-2). Then provisions for design margins and features for accident mitigation are provided according to generally accepted standards. Any given reactor is then designed to these standards and then, based on an overall risk assessment, a judgement for a particular plant can be made as to whether the mitigating features provided in accordance with the standards are adequate or whether further features must be provided. Implicit in this suggestion is my belief that the majority of core disruptive accidents generally have low or mild energetics or can be made to have. In deriving such standards a spectrum of accidents should be considered such that the standards do provide reasonable margin. Obviously, as in the case of any other standard which we use in reactor design, if further knowledge requires a change then the standard can be modified.

If these standards are carefully developed then they should remove one of the greatest objections to the more traditional approach to fast reactor safety where designing to meet a source term directly derived from some specific accident analysis without considering the nature of that analysis, can lead to the inclusion of features in the design that do not significantly alter risk, but which can significantly affect plant costs. Because of this, in this period when uniform and agreed upon criteria for the design of fast reactor systems are lacking, the designer should be aware of the considerations which go into the particular criteria he must work with and participate in their development.

Work Energy Characterization

In the analysis of the response of fast reactor systems to core disruptive accidents the terms "work potential" and "work-energy" are often used to characterize damage potential. Marchaterre et al. [2] have given a review of the various methods of characterizing this damage potential. It is important to note the sensitivity of damage potential to ramp rate

... its implications in assessing risk. Table I below gives damage potential in terms of ramp rate for a loop reactor of the CRBR size based on fuel vapor expansion.

Damage Potential as a Function of Ramp Rate

	Ramp rate, $/sec	Damage Potential, MW/sec	
		Expanded to cover gas volume	Expanded to 1 atm
Case I	25-50	31	211
Case II	50-100	119	669
Case III	100-150	245	1306

Inspection of Table I shows two things: (1) damage potential from core disruptive accidents is very sensitive to the assumed ramp rates, and (2) for a given core damage potential a range of ramp rates is given. The reason ramp rate ranges are given is that the energetics of a prompt-critical excursion depends on the state of the core at the initiation of the excursion and this can vary depending on the nature of the initiating accident.

In view of the above we must ask ourselves whether, at the current state of the art, we can differentiate between accidents which lead to cases 2 and 3 above. The answer is, in general, that we cannot. That is, if we assume conditions that lead to the high end of category two above, we cannot assign a lower probability to conditions that would lead to category three. Thus with a change in design that accommodates category three energetics we would assign the same risk as one that is designed to accommodate the level of energetics in category two. True design margin comes from having the expected energetics well below the plant design point.

Thus, the approach outlined previously seems reasonable:

(1) Design the plant so that the probability of core disruption is very small.

(2) Provide margins in accordance with generally accepted standards.

(3) Verify by risk analysis that the design is acceptable.

It should be noted that the above process may or may not use formalized risk assessment techniques. In the end, sound engineering judgement and careful review must be applied to determine if a design is acceptable and defense in depth is provided.

Mechanistic Analysis of LMFBR Accidents

In view of the previous discussion, it is appropriate to ask "What is the role of mechanistic analysis of LMFBR accidents?" There appear to be two major roles for mechanistic analysis.

(1) Determine that the likely accidents lead to early termination or non-energetic core disruption or

(2) Define the reactor design changes that could be made so that initiators lead to non-energetic core disruption.

Implicit in the above is the belief that most initiators of core disruption lead, or can be made to lead, to non- or low-energetic core disruption. Early studies of core disruption, in an attempt to bound accident energetics, emphasized energetic excursions due to fuel collapse [3 - 5]. As further understanding of the processes inherent in the behavior of fast reactor cores under accident conditions grew, it was recognized that the assumptions in such analyses were much too conservative. As a result, it was attempted to analyze mechanistically the conditions leading to these excursions. As these analyses became more realistic it became apparent that many of the paths did not lead to the traditional energetic excursion. As a result, a comprehensive approach to mechanistic accident analysis was devised [6] which acknowledged paths that led to termination with limited core damage or with a gradual meltdown which did not necessarily lead to an energetic excursion. These results are, and continue to be, a major goal of mechanistic analysis.

In general, initiating phase analysis follows the following steps. First, the accident sequences which will be the most important contributors to risk are identified, then parametric analyses of the initiating phase behavior are carried out. Typically, these analyses are carried out utilizing large scale computer codes which enables the complex interaction of a large number of phenomena to be followed. A large number of codes have been developed for analyzing the initiating phase of an accident. The SAS (for Safety Analysis System) series of codes developed at Argonne are typical [7 - 8]. Wider et al. [9] has given a good perspective on the use of these large codes. This capability has both attractive features and dangers noted below.

A typical calculation, for example of a loss of flow with failure to scram, would proceed through the following steps. The calculation is first initialized taking into account the neutronics, the coolant flow of steady state, the fuel pin heat transfer and the characteristics of the irradiated fuel at the point in the fuel cycle where the calculation is performed. The transient calculation is then performed following the flow decay and computing the temperature changes up to the point of boiling initiation. Thus far, the calculation is comparatively straightforward. Following boiling initiation some subassemblies void, followed by cladding and fuel melting and motion, both of which can have significant reactivity effects. If the reactor has a large positive sodium void coefficient the voiding induced power burst can cause pin failures in partially voided or nonvoided subassemblies and material motions in these subassemblies and their effects on reactivity must be followed. Finally, if this initiating phase of the accident leads to core disruption, a disassembly analysis is carried out to determine the energy released.

The calculation of a complete scenario of this type is subject to a number of limitations. While some of the phenomena are well understood and adequately modeled, others are not. Even if they were adequately treated, it should be recognized that codes used for this type of accident analysis do not give any single "correct" answer. Rather, cases must be run varying the important model parameters to establish the sensitivity of the output to various input assumptions. In doing this it is important that the model assumptions be understood so that good judgement can be exercised in establishing the cases to be run. As Wider [9] points out, it is easy to create an illusion of certainty with the output of such codes which were never intended by its developers. Such codes are an important achievement in safety analysis and, properly used, are an important help in reaching an informed judgement on the safety of a plant. However, we should not believe that they can deliver precise point estimates of accident energetics which can be directly translated into design requirements.

In the absence of autocatalytic effects caused by adverse material motions in a power burst caused by, say, voiding in a core with a large positive sodium void coefficient the results of initiating phase calculations of the type described above generally have low or mild energetics. Further work is certainly needed to confirm this conclusion but this generally seems to be the trend.

This is an important conclusion as comparative risk studies of fast breeder reactors have shown that differences in hazard potential between LWRs and fast breeder reactors derive almost entirely from the possibility of an energetic core disruptive accident in which a substantial portion of the core is vaporized [10].

Thus far, we have only discussed the initiating phase of core disruptive accidents. If the initiating phase of core disruptive accidents leads to a gradual meltdown rather than to an energetic burst, we must address the question of how the core reaches a final subcritical configuration. Since LMFBRs are very sensitive to dimensional changes or relocation of core materials it is theoretically possible that compactions in the meltdown process and energetic bursts. This is indeed the type of core disruptive accident that was first analyzed in conjunction with core disruption [3]. This is the accident phase that is generally termed the transition phase in the generalized approach to mechanistic analysis of fast reactor accidents. At this point in the accident, however, it is perhaps better to think of the analysis as considering the mechanisms that might be important in the accident sequence rather than an attempt to model mechanistically the exact course of the accident. It is not possible at this point in time to trace sequentially the complex processes occurring in a meltdown sequence from initiating phase to final disposition. Rather, we must consider the controlling processes that could mitigate or prevent large energetics in such a scenario.

Considering these controlling mechanisms or "general behavior principles," as they are called by Fauske [11], allows us to draw conclusions about the course of the accident without necessarily being able to trace an exact path the accident will follow. It may never be possible or even desirable to do this detailed mechanistic modeling. Briefly put, these principles [11] are a belief that energetic fuel-coolant interactions are not possible with the UO_2-sodium system and that a self-heated liquid is dispersive. Again, at the present state of knowledge, consideration of these controlling mechanisms leads us to believe that the meltdown process would be non-energetic.

Conclusions

Consideration, by ourselves and others, of core disruptive accidents in fast breeder reactors seems to be leading us to the following conclusions:

(1) Comparative risk studies of fast breeder reactors and light water reactors have shown that differences in hazard potential derive almost entirely from the possibility of energetic core disruptive accidents.

(2) The trends in accident analysis lead me to believe that most accident scenarios do not lead to energetic core disruption.

(3) Consideration of a spectrum of accident types leads me to believe that design standards can be developed which provide adequate margin against the consequences of core disruption.

(4) In the absence of such standards the underlying sensitivity of accident calculations to assumed phenomena must be carefully considered so that designs are not compromised without a concurrent significant reduction in risk.

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