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A Reassessment of the Potential for an Alpha-Mode Containment Failure and a Review of the Current Understanding of Broader Fuel-Coolant Interaction Issues

Second Steam Explosion Review Group Workshop

U.S. Nuclear Regulatory Commission

Office of Nuclear Regulatory Research

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Second Steam Explosion Review Group Workshop

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ABSTRACT

This report summarizes the review and evaluation by experts of the current understanding of the molten fuel-coolant interaction (FCI) issues covering the complete spectrum of interactions, i.e., from mild quenching to very energetic interactions including those that could lead to the alpha-mode containment failure. The experts' review and evaluation took place in the form of a Second Steam Explosion Review Group (SERG-2) Workshop, held in Annapolis, Maryland, on June 15 and 16, 1995. The first such workshop (SERG-1) took place in 1985.

Extensive discussions took place at the SERG-2 workshop on the alpha-mode failure issue, based on the experts' responses to the questions raised, and consensus opinions on the status of resolution of the issue emerged from the discussions. Of the eleven experts polled, all but two concluded that the alpha-mode failure issue was resolved from a risk perspective, meaning that this mode of failure is of very low probability, that it is of little or no significance to the overall risk from a nuclear power plant, and that any further reduction in residual uncertainties is not likely to change the probability in an appreciable manner.

To a lesser degree, discussions also took place on the broader FCI issues such as mild quenching of core melt during non-explosive FCI, and shock loading of lower head and ex-vessel support structures arising from explosive localized FCIs. These latter issues are relevant with regard to determining the efficacy of certain accident management strategies for operating reactors as well as for advanced light water reactors. The experts reviewed the status of understanding of the FCI phenomena in the context of these broader issues, identified residual uncertainties in the understanding, and recommended future research (both experimental and analytical) to reduce the uncertainties.

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EXECUTIVE SUMMARY

A group of international experts from academia, industry, and research organizations was invited by the Office of Nuclear Regulatory Research of the U. S. Nuclear Regulatory Commission, to participate in the Second Steam Explosion Review Group (SERG-2) Workshop, held in Annapolis, Maryland, on June 15 and 16, 1995. The first such workshop (SERG-1) took place in 1985. The main objective of the SERG-2 workshop was to reassess the potential for containment failure arising from in-vessel steam explosions following a core melt accident (identified in the literature as the alpha-mode failure) by examining all the recently available information. A secondary objective was to review the current understanding of broader fuel-coolant interaction (FCI) issues such as mild quenching of core melt during non-explosive FCI, and shock loading of lower head and ex-vessel support structures arising from explosive localized FCIs. These latter issues are relevant with regard to determining the efficacy of certain accident management strategies for operating reactors as well as for the advanced light water reactors. The reassessment and review were to be benefited from the significant progress in FCI related research made in the U.S. and in other countries since the SERG-1 workshop.

To accomplish the stated objectives, the invited experts were requested to provide written responses to a number of questions and issues focussing on the major FCI-related topical areas such as premixing, triggering, and propagation phenomena, FCI energetics, damage consequences, and certain other phenomena like chemical augmentation, pressure suppression effect, etc., in the context of the alpha-mode issue and also, other FCI issues. The questions also covered the role and importance of accident progression and melt relocation in providing initial conditions for FCI, status and capabilities of analytical tools, and residual uncertainties in the understanding of various FCI phenomena in the context of broader FCI issues. Extensive discussions took place at the SERG-2 workshop on the alpha-mode failure issue, based on the individual responses to the questions raised, and consensus opinions on the status of resolution of the issue emerged from the discussions. To a lesser degree, discussions also took place on the broader FCI issues mentioned above with a view to identifying residual uncertainties in our current understanding of these issues. This report summarizes the presentations/discussions of the experts in three major categories: (1) improved understanding of the alpha-mode failure issue towards its resolution, (2) identification of residual uncertainties in the understanding of FCI phenomena, and (3) recommendations for future research.

Of the eleven experts polled, all but two concluded that the alpha-mode failure issue was resolved from a risk perspective, meaning that this mode of failure is of very low probability, that it is of little or no significance to the overall risk from a nuclear power plant, and that any further reduction in residual uncertainties is not likely to change the probability in an appreciable manner. The dominant overall judgement of the experts is that the combination of events leading to alpha-mode failure is highly unlikely. The quantification (i.e., the probability of alpha-mode failure given a core melt accident) provided by those SERG-2 experts, who also participated in the SERG-1 workshop, was generally an order of magnitude lower than the SERG-1 estimate and two orders of magnitude lower than the WASH-1400 best estimate (see

Table E.1 for details). Some experts did not provide quantitative probability estimates. Instead, they used qualitative measures such as "physically unreasonable" and "vanishingly small". Some other experts also provided qualitative estimates such as "very unlikely" and "probably low."

The strongest physical argument put forward to substantiate the quantification of the alpha-mode failure or to provide a basis for the qualitative estimate as discussed above is that the fuel mass, which is expected to participate in an energetic FCI, is limited. The argument is supported by substantial progress made in the area of premixing research since the SERG-1 workshop, specifically, experimental verification of premixing, steam voiding, and water depletion phenomena with saturated coolant at low pressures (~0.1 MPa). The limits-to-mixing argument is not appropriate at high pressures (>1-2 MPa), and the experts argued that at such pressures, it would be difficult to trigger an explosion. In the quantification of the alpha-mode failure probability by some experts, a conservative approach to triggering was taken whereby it was assumed that an explosion would be triggered at low pressures during a premixing transient. Also, a thermodynamic-based approach was taken to calculate expansion work (equivalently, thermal-to-mechanical energy conversion) in the same context. This approach is conservative and does not require the knowledge of propagation phase details. Other mitigative factors such as limited thermal-to-mechanical energy conversion and a range of dissipative phenomena involved in slug motion to the upper head are expected to reduce the energy conversion further in a prototypic reactor system. These factors were considered in arriving at the estimates of the alpha-mode failure probability.

While the main focus of the SERG-2 workshop was on the alpha-mode issue, the status of understanding of various related FCI phenomena and uncertainties therein were discussed briefly in the context of other issues such as localized FCIs leading to shock loading of lower head and cavity support structures, and non-energetic FCIs resulting in debris quenching and coolability. The experts acknowledged the underlying uncertainties in the late phase melt progression phenomena, and one of them stressed the importance of considering more realistic melt progression scenarios in setting up FCI initial conditions. The experts agreed, however, that for lack of a better knowledge of late phase melt progression, a bounding approach to initial conditions would be adequate for FCI analysis from a risk perspective. Most experts shared the view that triggering was a complex phenomenon not well understood and recommended a conservative approach to triggering (i.e., the assumption that triggering always takes place) at low pressures. Substantial progress was noted in the understanding of premixing. Some experts argued, however, that the dynamics of melt jet breakup was not properly understood. Further efforts to reduce residual uncertainties in jet breakup phenomena, while not necessary for resolving the alpha-mode issue, were deemed important by some of the experts for addressing broader FCI issues. Likewise, an improved understanding of the propagation phase details was deemed necessary for similar purposes. The experts agreed that the existing methods (analytical tools) were adequate to perform FCI energetics and damage calculations, but noted a need for further assessment of these tools against more representative experimental data. Some of the experts also noted a need to understand better the material and geometric scale effects in a prototypic reactor system.

Recommendations for future research were offered by the experts in various phenomenological areas. Some of the recommendations reflect national nuclear safety program policies and perspectives and, when implemented, will provide additional confirmation to the current resolution status of the alpha-mode issue. Other recommendations relate to broader FCI issues including, for example, experimental investigation of melt quenching and melt jet breakup, pressure suppression effect on triggering, explosivity of prototypic melts, and possible chemical augmentation of FCI energetics. On the analytical side, recommendations emphasized assessment of existing analytical tools and improvement of such tools, as necessary, to address the full spectrum of FCI phenomena.

Table E.1 - Alpha-Mode Failure Probability Estimates Given a Core Melt Accident

Participant	SERG-1 (1985)	SERG-2 (1995)	View on Status of Alpha-Mode Failure Issue
Bankoff (USA)	$< 10^{-4}$	$< 10^{-5}$	Resolved from risk perspective
Berthoud (France)	--	Very unlikely	No statement on resolution
Cho (USA)	< WASH-1400*	$< 10^{-3}$	Resolved from risk perspective
Corradini (USA)	10^{-4} - 10^{-2}	$< 10^{-4}$	Resolved from risk perspective
Fauske (USA)	Vanishingly small	Vanishingly small	Resolved from risk perspective
Fletcher (Australia)	--	$< 10^{-4}$	Resolved from risk perspective
Henry (USA)	--	Vanishingly small	Resolved from risk perspective
Jacobs (Germany)	--	Probably low	Not resolved from risk perspective; needs more quantitative evaluation
Sehgal (Sweden)	--	Physically unreasonable	Resolved from risk perspective
Theofanous (USA)	$< 10^{-4}$	Physically unreasonable	Resolved from risk perspective
Turland (UK)	--	$< 10^{-3}$	Resolved from risk perspective

*** WASH-1400 best estimate $< 10^{-2}$, SERG-1 consensus estimate $< 10^{-3}$**

Note: The SERG-1 column in this table shows the range of estimates to be 10^{-2} to 10^{-4}. The NUREG-1116 shows the range to be 10^{-1} to 10^{-5}. The latter document contains estimates from additional SERG-1 experts who are not listed here.

1. INTRODUCTION

This report summarizes the review and evaluation by experts of the current understanding of the molten fuel-coolant interaction issues covering the complete spectrum of interactions, i.e., from mild quenching to very energetic interactions including those that could lead to the alpha-mode (denoted henceforth as α-mode) containment failure. The review and evaluation took place in the form of a Second Steam Explosion Review Group (SERG-2) Workshop, held in Annapolis, Maryland, on June 15 and 16, 1995. The first such workshop (SERG-1) took place in 1985.

The Fuel-Coolant Interactions (FCI) process involves transfer of energy from molten fuel to a surrounding coolant. During a postulated core melt accident, the time scale for this mode of energy transfer may range from milliseconds to tens of seconds and even to hours. Interactions occurring in the milliseconds range could lead to energetic steam explosions which, if excessive, could challenge reactor vessel and containment integrity and, in turn, could create a potential leakage path for radiological releases. It is in this context that the FCI is considered a severe accident issue of potential risk significance and a more complete understanding of FCI is sought in the framework of severe accident research. Interactions occurring in the range of tens of seconds to hours are normally associated with quenching characterized by slow and partial fragmentation of melt and possible formation of a coolable debris bed. An understanding of the FCI issue associated with this form of interaction is important from the standpoint of debris coolability and subsequent arrest of accident progression.

Energetic interactions could threaten reactor vessel or containment integrity either in the form of shock loading of structures over a very short time (typically less than ten milliseconds) or in the form of missile generation over longer times (typically up to few hundred milliseconds). The failure mode induced by in-vessel steam explosion-generated missiles, identified in the 1975 Reactor Safety Study (WASH-1400)[1] as the α-mode containment failure, was the primary focus of NRC research in the early days. In 1985, the first Steam Explosion Review Group (SERG-1) workshop was convened by NRC to discuss and systematically evaluate the α-mode failure issue. At the conclusion of the workshop, there was a consensus among the experts that the occurrence of an explosion of sufficient energetics which could lead to an α-mode containment failure had a low probability (range of values between 10^{-1} and 10^{-5}, given a core melt accident). However, the experts also concluded that additional research would be necessary to develop a more complete understanding of the fundamental processes involved in FCI so that the α-mode failure probability could be estimated with a high level of confidence.

Much of the FCI research since 1985 has been aimed at enhancing the technical basis for understanding the α-mode failure issue, estimating the bounds of potential energetics, determining conditions under which energetic interactions could occur, and resolving residual uncertainties in our understanding of fundamental processes involved in energetic FCI. Significant new FCI programs (in addition to those in the U.S.) were initiated and progress made in other countries (e.g., France, Germany, Japan, and the United Kingdom) during this period as well. To share the benefit of the progress made internationally on the FCI issue, the

Committee for the Safety of Nuclear Installations (CSNI) Principal Working Group 2 (PWG2), through its Task Group on In-Vessel Degraded Core Behavior (IVDCB), organized a second Specialists' Meeting on Fuel-Coolant Interactions in January 1993 at Santa Barbara (the first such meeting held more than twelve years ago). Research results presented in the meeting (see NUREG/CP-0127)[3] confirmed the conservatism embedded in the assessment of the α-mode failure as documented in the first SERG report (NUREG-1116)[2]. The meeting concluded that there was a substantially reduced potential to intermix large quantities of molten fuel and water thereby limiting the steam explosion energetics and rendering the α-mode containment failure of no significance to risk. The meeting also concluded that significant progress was made in the understanding of fundamental aspects of FCI phenomena.

1.1 SERG-2 Workshop Objectives

Given the above body of knowledge on FCI and given that the ongoing FCI programs in the U.S. as well as abroad encompass broader FCI issues, the NRC convened the SERG-2 Workshop with the objectives of (1) reassessing the status of the α-mode failure issue towards its essential resolution, (2) reviewing the current understanding of broader FCI issues, (3) identifying residual uncertainties in our understanding of these broader FCI issues, and (4) providing recommendations for any future research efforts deemed necessary.

1.2 Experts' Review and Evaluation Process

To accomplish the SERG-2 Workshop objectives stated above, a group of experts from academia, industry, and research organizations in the U.S. and abroad was invited to form the SERG-2 panel. These experts have been formerly or are currently active in various aspects of FCI research, including experimental programs, modeling and analysis, and application of research results to integral plant safety assessments. Many, but not all, members of the SERG-2 panel also served in the SERG-1 panel. A number of questions were formulated for extensive discussion at the workshop. The questions focussed on major FCI-related topical areas such as premixing, triggering, propagation, FCI energetics, and damage consequence, as well as specific topics such as chemical augmentation, and pressure suppression effect. The questions also covered the role and importance of accident progression and melt relocation in providing initial conditions for FCI, residual uncertainties related to FCI issues, and status and capabilities of analytical tools. To facilitate discussion at the workshop, the panel members (henceforth referred to as experts) were asked to provide their written responses to the questions ahead of time. The invitation letter from Dr. T. P. Speis, the Deputy Director of the Office of Research at NRC, to the selected experts with an attached questionnaire, a list of experts, a second list of workshop attendees, and a schedule for the workshop are provided in Appendix A.

The workshop was chaired by Dr. Speis who summarized, in his opening remarks, the FCI related research and SERG activities to date, delineated the objectives of the SERG-2 workshop, and described the workshop format. The latter consisted of individual presentations by the experts followed by questions and answers on the presentations, and open discussions at the end of groups of presentations. Dr. D. Fletcher, a member of the SERG-2 panel, was not able to attend the workshop but provided his responses for discussion and dissemination at the workshop. Dr. Fletcher's presentation was given by Prof. Theofanous. Prof. I. Catton, a member of the Advisory Committee on Reactor Safeguards (ACRS) and a SERG-1 panelist, was invited to be a SERG-2 panel member. He elected to participate in the workshop as an ACRS member rather than as a panel member.

Following the individual presentations and subsequent open discussions among the experts, the major points brought up during these presentations/discussions were summarized in six topical areas. These are: (1) the α-mode failure probability (Dr. H. Fauske), (2) premixing (Dr. B. Turland), (3) triggering (Dr. D. Cho), (4) propagation (Prof. M. Corradini), (5) mechanical energy release (Dr. R. Henry), and (6) the issue resolution processes (Prof. T. Theofanous). At the conclusion of the workshop, the experts were given the opportunity to modify and/or supplement their individual responses based on additional information generated during the workshop. They were also invited to comment on the draft of this report.

1.3 Organization of the Report

The organization of this report is similar to that of the SERG-1 report (NUREG-1116). Presentations and discussions at the SERG-2 workshop are summarized in Chapter 2. Section 2.1 provides a summary of the experts' reassessment of the α-mode failure issue toward its resolution. Residual uncertainties in the understanding of FCI phenomena, identified by the experts, are summarized in Section 2.2, and recommendations for future research are summarized in Sections 2.3. The workshop objectives, schedule, and related items are delineated in Appendix A. Individual (unedited) responses of the SERG-2 experts are given in Appendix B, whereas the consensus results for each of the major FCI topical areas are given in Appendix C. Additional comments and contributions by the experts are given in Appendix D.

The draft version of the report was reviewed by the experts and their comments have been addressed, as appropriate, in the final report. The most significant comment was that the report should truly reflect the main focus of the SERG-2 workshop, which is reassessment of the α-mode failure issue, and should also strike a proper balance in documenting the discussion of residual uncertainties in relation to broader FCI issues noting that these issues were discussed only briefly at the workshop. The draft report was revised and restructured to address this significant comment. Specifically, the discussion of α-mode issue is elaborated in the final report with relevant supporting text on the status of understanding of various FCI phenomena. Residual uncertainties are discussed in Section 2.2 in the context of broader FCI issues. Finally, recommendations for future research are discussed in Section 2.3. Specific comments by the experts on the draft report have been addressed in the process. Also, the main body of the report has been made concise in the process, leaving out the details which can be found in the attached appendices.

2. SUMMARY OF THE SERG-2 WORKSHOP FINDINGS

2.1 Reassessment of the Alpha-Mode Failure Issue

The SERG-2 experts were asked (see Appendix A - attachment to Dr. Speis' letter) to express their views on the status of understanding of the α-mode containment failure issue. All but two experts concluded that the α-mode failure issue was resolved from a risk perspective, meaning that this particular mode of failure is of very low probability, that it is of little or no significance to the overall risk from a nuclear power plant, and that any further improvement in our knowledge of the various FCI phenomena and any further reduction in residual uncertainties are not likely to change the probability in an appreciable manner. Individual expert's deliberations on the issue are given in Appendix B, and a consensus summary is given in Appendix C-1.

Table 1 summarizes the experts' estimates of the probability of α-mode failure given a core melt accident, compares the same with the estimates arrived at the SERG-1 workshop and with the WASH-1400 best estimate, and presents the status of resolution of the issue from a risk perspective. The estimates of failure probability expressed by those SERG-2 experts, who also participated in the SERG-1 workshop, are generally an order of magnitude lower than the SERG-1 estimates. Note that the SERG-1 individual estimates range from 10^{-1} to 10^{-5} (see NUREG-1116), whereas the SERG-2 individual estimates range from 10^{-3} to 10^{-5}. Note also that the WASH-1400 best estimate failure probability is $< 10^{-2}$. Some experts suggested the probability estimate was vanishingly small so that there was no particular need to quantify the same. Some other experts expressed the view that the quantitative estimates of probability for such issues as the α-mode failure are not particularly meaningful. Rather, they used the term "physically unreasonable" as a qualitative measure of the failure probability. One expert was unwilling to provide any quantitative estimate suggesting that more information was needed, but gave a qualitative estimate as "probably low." Finally, one other expert initially offered a quantitative estimate, but later modified his position by providing a qualitative estimate as "very unlikely."

The dominant overall judgement of the experts is that the combination of factors leading to α-mode containment failure is highly unlikely. The factors, briefly, are: large coherent pour of melt into the lower plenum, large-scale fuel-coolant mixing in the lower plenum, and high thermal-to-mechanical energy conversion during the propagation and expansion phase.

A typical melt release scenario considered by the experts in rendering their judgement is associated with the release of melt from the core region through one or more pathways, leading to one or more molten jets penetrating (not necessarily simultaneously) into the water in the lower plenum. A massive single, large diameter coherent pour is generally not considered credible, but if it occurred, the experts argue that it would likely produce a vapor chimney thereby effectively separating the melt from the coolant, limiting further mixing, and possibly inhibiting any triggering. Further, the experts generally agree that the melt mass participating in FCI at any particular instant of time is limited to the pour stream (single or multiple), and that any previously accumulated melt at the bottom of the pool does not participate to any significant extent in the interaction. These arguments provide the basis for setting up initial conditions for FCI. Variations in melt mass, jet diameter, temperature, and composition are considered so as to encompass the full spectrum of FCI initial conditions, and to account for uncertainties in late phase melt progression. This bounding approach, similar to the one proposed in an earlier assessment of steam explosion induced containment failure (NUREG/CR-5030)[4], is considered adequate by the experts.

There is general agreement among the experts that substantial progress has been made in the area of premixing research since the SERG-1 workshop. The MAGICO experiments, performed at the University of California at Santa Barbara (UCSB) using ensembles of hot solid spheres and saturated coolant at low pressures, demonstrated the principles of water depletion phenomena and provided a strong "limits-to-mixing" argument in support of the low likelihood of the α-mode failure. Other similar experiments are now being conducted in France (BILLEAU) and Germany (QUEOS). Premixing research in the past ten years has also involved development of analytical tools (codes) and validation of these tools with experimental data derived mainly from solid particle experiments. Several multiphase, multifield computational analysis codes, as summarized in Table 2, are now available for performing multidimensional calculations of fuel, steam, and water distributions. Of these, CHYMES and PM-ALPHA have undergone validation against data from experiments (CHYMES validated against the MIXA experiments involving pours of molten droplets of UO_2-Mo and PM-ALPHA validated against MAGICO experiments involving pours of hot solid steel spheres into saturated water), and have been used for plant calculations (a generic PWR and Sizewell B, respectively). Other codes (IFCI, TEXAS, COMETA, MC3D, and IVA-KA) have undergone some degree of validation, and have also been used recently for pre-test and post-test calculations of FARO experiments. Moreover, many of these codes are in stages of continued development and assessment.

The substantial progress made in premixing research as mentioned above led to a significantly improved understanding of the phenomena. Based on this improved understanding and based on available experimental data, code calculations, and other basic principles arguments, the experts agree that mixing of fuel and saturated coolant at low pressures would lead to regions of large void fractions, and that water depletion from the interaction zone would have a mitigative effect on the FCI energetics. Most experts also agree that the concept of "limits-to-mixing" provides a strong supporting argument in favor of low likelihood of the α-mode failure.

The experts note that triggering, which plays an important role in linking premixing with propagation, is a complex phenomenon that is difficult to model and to investigate experimentally. There is a lack of understanding of both the triggerability of a prototypic melt and trigger availability in a prototypic situation. From the perspective of risk significance of the α-mode failure issue, most experts agree on a conservative approach to triggering at low pressures ($\sim$0.1 MPa) whereby a premixture would be assumed to trigger at the worst time during a premixing transient leading to trigger amplification or shock wave propagation. The limits-to-mixing argument is not appropriate at high pressures, and the experts argue that at such pressures, it would be difficult to trigger an explosion.

Most experts also agree that a knowledge of propagation phase details is not necessary for resolving the α-mode failure issue because the issue can be treated conservatively from the standpoint of energetics using variants of the thermodynamics approach. The experts believe that the limited melt mass available on basis of melt relocation and premixing arguments, would, in all likelihood, lead to sufficiently low mechanical energy so that there would be a substantial margin to α-mode failure. It is also recognized that a number of mitigative mechanisms are at play, including dissipation by energy transfer to intermediate structures, gas venting if the slug contains significant voids, and bypass of gas around the slug if the slug is not continuous. These mitigative mechanisms can further reduce the yield or offset possible increase (e.g., chemical augmentation of FCI energetics due to chemical energy release from metal-water reactions). Accounting for the mitigative mechanisms, some experts believe that published estimates of mechanical energy release and structural damage are conservative.

A discussion was held the second day of the SERG-2 workshop on the subject of "orderly closure" of the α-mode failure issue using, for example, Theofanous' Risk Oriented Accident Analysis Methodology (ROAAM) as discussed in Appendix C-6. The proposed effort would utilize and integrate the international expertise on the subject to reach a more formal closure on the issue. The need for such a formal closure was favored by only a few experts.

2.2 Residual Uncertainties in the Understanding of FCI Phenomena

Table 3 summarizes the residual uncertainties in the understanding of FCI phenomena as identified by the SERG-2 experts. Individual experts' views are presented in Appendix B and discussion summaries of major FCI topics are presented in Appendix C. Consideration of these uncertainties is relevant for an improved understanding of other important FCI-related issues such as localized FCIs resulting in shock loading of the lower head or reactor cavity structural support, and melt fragmentation and debris quenching. Experts generally agree that further reduction of the residual uncertainties is not likely to change the α-mode failure probability in an appreciable manner. Rather, it will provide additional confirmatory evidence for the consensus that α-mode failure is highly unlikely or physically unreasonable, and will increase the level of confidence associated with such judgement.

Uncertainties in melt progression and FCI initial conditions have been discussed previously in reference to the α-mode failure issue and is not repeated here. It suffices to say that these uncertainties are the same or similar to those considered in the context of other severe accident issues and that, in the issue resolution process, it is an acceptable method to treat these uncertainties in a bounding manner. One expert stressed, however, the need to address more realistic melt progression scenarios in setting up FCI initial conditions.

With the exception of certain residual uncertainties related to melt jet breakup as discussed below, the experts generally agree that the topic of premixing has been researched extensively in the past ten years. However, it is noted that additional confirmatory research, both experimental and analytical, is underway in some countries as a matter of national nuclear safety program policies.

The experts note that the physics of jet breakup is not fully understood, and there is limited assessment of breakup models in the existing codes against experiments involving melt jets (e.g., FARO). A proper assessment would require precise experimental data on jet breakup which, at present, is not available. Consequently, there remains some uncertainties in modelling the jet breakup processes, and in advancing the limits-to-mixing argument for melt jets on a firm basis. The jet breakup can influence the subsequent FCI processes (e.g., melt quenching, steam explosions, shock propagation in a multiphase system) as well. Therefore, the experts agree that an improved understanding of jet breakup is relevant to such issues as debris coolability, and shock loading of lower head and cavity support structures.

Residual uncertainties identified by the SERG-2 experts in the area of triggering are: (1) pressure effect on triggering, (2) triggerability of prototypic melts, and (3) triggering of multiple explosions. Some experts believe that if an explosion is triggered at a high ambient pressure, it would likely be more energetic than the one at low ambient pressure. Another pressure effect relates to the suppression of triggering at or above certain pressure threshold. Past FCI experiments seem to suggest that triggering may be influenced by pressure, but there is no clear evidence that the pressure threshold is universal for all melt compositions of interest. The ongoing and planned KROTOS experiments are expected to provide additional information on these residual uncertainties.

Currently available experimental data with prototypic materials suggest that it is difficult to trigger melts containing UO_2 compared, for example, with simulant melts (both oxidic and metallic). The reasons for this reduced triggerability of the UO_2 melts are not known. Some experts suggest that melt properties may have a significant influence on the FCI processes, and that this influence is neither thoroughly understood nor properly modeled in the codes. The experts agree that an improved understanding of the triggerability would require identification of those material properties that distinguish one material from another with regard to their explosion potential. A related issue is that of trigger availability in a prototypic situation. A previous extensive review of triggering research by Fletcher[5] led to the conclusion that the triggerability is influenced by a number of parameters (e.g., fuel/coolant properties, plant design features, and plant operating conditions), but not in any predictable manner. From the risk perspective, the experts agree that for low pressure scenarios, the conservative assumption of the existence of a trigger source of sufficient strength to initiate an FCI should be made.

The possibility of multiple explosions was raised by one expert, and a scenario was postulated whereby an initially small pressure perturbation would lead to fragmentation and mixing of a larger melt mass, and would provide a source for possible triggering of multiple secondary explosions of higher magnitudes. Other experts contend that multiple secondary explosions from a primary explosion is fundamentally no different from the broader escalation concept in FCI, in which an escalating propagation from a primary explosion may lead to further breakup of melt particles thus creating premixtures for possible secondary explosions.

The experts generally agree that while detailed models of propagation phenomena are not required for analysis of the α-mode failure, other FCI-related issues such as shock loading of structures, lower head loading, etc., would require such details. Practically, all experts also agree that a two-dimensional propagation code would be necessary for these purposes but they differ in their opinions on the need for a three-dimensional code. There are currently several multi-field multi-dimensional FCI codes at various stages of development and validation.

The chemical augmentation of FCI due to the presence of metal(s) in the melt was recognized by most experts as a possibility, but a varying degree of importance was assigned to it by different experts. Generally, if the core melt contains significant quantities of metallic constituents which react chemically in the explosion time scale, all phases of FCI may be affected. Given the uncertainties, however, and noting that the augmentation is material sensitive, the experts find that the significance of chemical augmentation is less clear in a prototypic system.

2.3 Recommendations for Future Research

One of the objectives of the SERG-2 workshop was to formulate recommendations for future research addressing a broad range of FCI issues. The experts were asked to recommend specific research that would be needed to reduce residual uncertainties and to improve our understanding of various FCI phenomena in the context of broader FCI issues. The experts' individual recommendations are provided in Appendix B. In many cases, these recommendations are guided by national nuclear safety program policies and are oriented toward developing independent knowledge bases with regard to investigation of the α-mode failure issue. These recommendations are not elaborated further in this section, but the interested readers are referred to Appendix B for details. Other recommendations for specific research, needed to reduce residual uncertainties identified in the preceding section of this report, are summarized in Table 3 and discussed in the text below. Table 4 summarizes the ongoing or planned FCI experimental programs in several countries addressing many of the recommendations in Table 3.

The current parametric approach to treating melt progression and FCI initial conditions provides conservative bounds for the limiting conditions. Some experts felt that an improved estimate of the FCI initial conditions would be desirable, and recommended development and/or assessment of late phase melt progression modeling capabilities within the severe accident codes.

The experts strongly recommended improved modeling of melt jet breakup and continued assessment of the available premixing codes with the fragmentation modeling capabilities. They further recommended that the analytical codes be used for mixing calculations involving melt jets, for plant-scale calculations (simulating pours of various diameters), and for standard problem exercises. Current and future FCI experiments, particularly those using melt jets, are recommended to be well-instrumented for void fraction and other related measurements so that the premixing codes can be assessed against a wider data base. These experiments should be performed at a reasonably large scale and under prototypic conditions (i.e., melt composition and volume fraction, melt temperature, mass flow rate, and ambient pressure).

The experts recommended several specific studies of triggering acknowledging, however, that due to the complexity of the phenomenon, a conservative approach to triggering would still be a valid option. The recommendations include experiments to determine a pressure threshold, experiments with sufficiently small triggers and with an inert gas void to demonstrate whether a propagation can occur under these conditions, and experiments to determine the minimum trigger strength required for steam explosions. The experts also recommended experiments to provide better understanding of the triggerability of prototypic melts.

Continued development and validation of two-dimensional propagation codes were recommended by the experts to provide a methodology for estimation of localized FCI loading, and to address the geometric scale effects. Some experts even suggested three-dimensional codes for a more accurate description of the propagation phenomena. The experts also recommended continuation of one-dimensional propagation experiments with different melt materials, stressing the importance of well-characterized initial conditions where the void and fuel distributions prior to the FCI event would be measured, and stressing the usefulness of the results for material scaling purposes as well as for providing conservative (because of constraints) bounds for explosive yield. Further recommendations covered such issues as shock wave propagation in two and three dimensions accounting for the effect of reflected waves and shock-structure interactions, development of appropriate analytical models, and validation of the multidimensional propagation codes using appropriate experimental data. Finally, a recommendation was offered to test the propagation codes with respect to their capability for calculating an escalating interaction given a small trigger ($\sim$1-10 kPa).

On the issue of damage consequences, the experts recommended a thorough assessment of the existing structural codes for their intended use in FCI-related response analysis. Finally, with regard to the chemical augmentation issue, the experts recommended a modest research effort to investigate augmentation in metal(zircaloy)-water and metal-oxide-water systems.

REFERENCES

1. Nuclear Regulatory Commission, "Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," NUREG-75/0114 (WASH-1400), October 1975.

2. Nuclear Regulatory Commission, "A Review of the Current Understanding of the Potential for Containment Failure from In-Vessel Steam Explosions," NUREG-1116 (SERG-1 Report), June 1985.

3. OECD Nuclear Energy Agency and Center for Risk Studies and Safety (UCSB), "Proceedings of the CSNI Specialists Meeting on Fuel-Coolant Interactions," NUREG/CP-0127 (NEA/CSNI/R(93)8), January 1993.

4. T. G. Theofanous, et. al., "An Assessment of Steam-Explosion-Induced Containment Failure," Department of Chemical and Nuclear Engineering, University of California at Santa Barbara, NUREG/CR-5030, February 1989.

5. D. F. Fletcher, "A Review of the Available Information on the Triggering Stage of a Steam Explosion," Nuclear Safety, Vol. 35, No. 1, pp. 36-57, January-June, 1994.

Table 1 - Alpha-Mode Failure Probability Estimates Given a Core Melt Accident

Participant	SERG-1 (1985)	SERG-2 (1995)	View on Status of Alpha-Mode Failure Issue
Bankoff (USA)	$< 10^{-4}$	$< 10^{-5}$	Resolved from risk perspective
Berthoud (France)	--	Very unlikely	No statement on resolution
Cho (USA)	< WASH-1400*	$< 10^{-3}$	Resolved from risk perspective
Corradini (USA)	10^{-4} - 10^{-2}	$< 10^{-4}$	Resolved from risk perspective
Fauske (USA)	Vanishingly small	Vanishingly small	Resolved from risk perspective
Fletcher (Australia)	--	$< 10^{-4}$	Resolved from risk perspective
Henry (USA)	--	Vanishingly small	Resolved from risk perspective
Jacobs (Germany)	--	Probably low	Not resolved from risk perspective; needs more quantitative evaluation
Sehgal (Sweden)	--	Physically unreasonable	Resolved from risk perspective
Theofanous (USA)	$< 10^{-4}$	Physically unreasonable	Resolved from risk perspective
Turland (UK)	--	$< 10^{-3}$	Resolved from risk perspective
* **WASH-1400 best estimate $< 10^{-2}$, SERG-1 consensus estimate $< 10^{-3}$**			

Note: The SERG-1 column in this table shows the range of estimates to be 10^{-2} to 10^{-4}. The NUREG-1116 shows the range to be 10^{-1} to 10^{-5}. The latter document contains estimates from additional SERG-1 experts who are not listed here.

Table 2. Status of Development and Validation of Analytical Tools (Codes)

FCI Phase	Computer Code (Source)	Description	Status of Validation
Melt relocation	MELCOR, SCDAP/RELAP5, etc.	Severe accident codes which provide ranges of melt initial conditions for FCI calculations	Early phase melt progression modeled and assessed adequately; late phase melt progression modeling incomplete and assessment inadequate
Premixing	CHYMES (UKAEA) COMETA (JRC) IFCI (SNL) IKEJET (IKE) IVA-KA (FZK) JASMINE (JAERI) MC3D (CEA/IPSN) PM-ALPHA (UCSB) TEXAS III (U. Wisconsin)	2D, 3-fluid Eulerian, R-T breakup model 1D, 2-fluid Eulerian/3-fluid Lagrangian 2D, 3-fluid Eulerian, R-T breakup model 1D, 3-fluid Eulerian, R-T breakup model 3D, 3-fluid Eulerian, R-T breakup model 3D, 3-fluid Eulerian, R-T breakup model 3D, 3-fluid Eulerian, R-T breakup model 2D, 3-fluid Eulerian, breakup capability 1D, 2-fluid Eulerian/3-fluid Lagrangian, R-T and K-H breakup models	Validated against MIXA experiments, plant calculations Pre- and post-test calculations of FARO experiments FARO calculations, additional validation in progress Validation against FARO data Pre- and post-test calculations of FARO experiments Calculations of ALPHA experiments Pre- and post-test calculations of FARO experiments Validation against MAGICO and FARO data, plant calculations Pre- and post-test calculations of FARO experiments
Triggering	No separate code available	Trigger of predetermined strength activated when certain predefined criteria met	No separate validation of triggering models or phenomena
Propagation	CULDESAC (UKAEA) ESPROSE.m (UCSB) IDEMO (IKE) IFCI (SNL) IVA-KA (FZK) MC3D (CEA/IPSN) TEXAS III (U. Wisconsin)	1D, 3-fluid Eulerian, HD breakup 3D, 3-fluid Eulerian, HD breakup 1D, 3-fluid Eulerian, HD breakup 2D, 3-fluid Eulerian, HD breakup 3D, 3-fluid Eulerian, breakup 3D, 3-fluid Eulerian, breakup 1D, 2-fluid Eulerian.3-fluid Lagrangian, thermal breakup	Pre- and post-test calculations of KROTOS Validation against SIGMA and KROTOS experiments Validation against KROTOS experiments Validation in progress Validation in progress Validation in progress Pre- and post-test calculations of KROTOS, WFCI data
Explosion Energetics and Damage Consequences	special analysis tools; structural codes ABAQUS, PLEXUS, etc.	special tools for expansion work and slug acceleration calculations; structural codes for impact loading and structural response calculations	no separate validation exists for special analysis tools; primarily engineering judgement used; structural codes well validated in other fields of engineering and science, but not specifically for FCI analysis

R-T Rayleigh-Taylor instability; K-H Kelvin-Helmholtz instability; HD Hydrodynamic

Table 3. Fuel-Coolant Interactions: Residual Issues

Phenomenological Area	Issue	Research Recommendations
Melt Relocation Phenomena	• late phase melt progression and FCI initial conditions	• improved late phase melt progression modeling and assessment
Premixing Phenomena	• melt jet breakup and premixing of multiple melt jets	• continued assessment of premixing models and codes; plant safety assessment • improved modeling of jet breakup
Triggering Phenomena	• effect of pressure on triggerability • triggerability of UO_2 melts • trigger amplification toward propagation	• experimental evaluation of effect of pressure on triggerability • experimental evaluation of triggerability for UO_2 melts • determination of minimum trigger requirement for propagation
Propagation Phenomena	• melt fragmentation mechanisms during propagation • improvement and assessment of propagation models and codes	• continued assessment of existing propagation models and codes • improved modeling of fragmentation; modeling of fluid-structure interactions and far-field effects • one-dimensional propagation experiments with well-characterized initial conditions
Explosion Energetics and Damage Consequences	• geometric and material scale effects on explosion energetics • chemical augmentation of explosion energetics	• experiments with simulant and prototypic melts • chemical augmentation experiments with melts containing metals

Table 4. Summary of Active FCI Experimental Research Programs

Program/Facility Designation	Organization (Country)	Program Objective
ALPHA(STX)	JAERI (Japan)	Investigate premixing and jet breakup phenomena in the STX series of experiments using molten thermite (FeO and Fe_2O_3 with Al) and molten steel jets (20 kg melt at atmospheric pressure in a square test section of lateral dimension up to 850 mm)
BERDA	FZK (Germany)	Investigate the effects of RPV upper internal structures on slug acceleration using 80 kg of molten Wood's metal and a driver gas at a maximum pressure of 14 MPa in a 1:10 scale facility
BILLEAU	CEA/IPSN (France)	Investigate premixing phenomena with hot solid spheres of different melt simulants at high temperatures (up to 2500 K)
FARO	ISPRA (EU)	Investigate non-explosive melt-coolant interactions (quenching, breakup) of large quantities of prototypic melt (typically up to 250 kg of UO_2-ZrO_2 melt with little or no metal content) at a wide range of system pressures (5 MPa to possibly to 0.1 MPa) and otherwise under prototypic conditions; large test vessel (variable diameter from 470 mm to 1500 mm) used to study two-dimensional effects; a further program objective is to investigate ex-vessel melt spreading
JAVA	CEA/IPSN (France)	Investigate jet breakup phenomena using melt simulants; the program is currently at the planning and design stage
KROTOS	ISPRA (EU)	Investigate explosive melt-coolant interactions involving both prototypic and simulant melts (typically up to 4 kg of UO_2-ZrO_2 and Al_2O_3) in well-characterized, small geometry (up to 200 mm diameter test vessel), usually at atmospheric pressure; some future experiments are planned at higher system pressures to investigate the triggerability issue
MAGICO	UCSB (USA)	Investigate premixing and water depletion phenomena under well characterized conditions with tens of kilograms of hot solid particles (2 to 10 mm size spheres of steel, Al_2O_3, ZrO_2, etc. up to a temperature of 2300 K); make local void fraction measurements using optical and X-ray techniques and also global measurements
MIRA	RIT (Sweden)	Investigate material scaling using different binary oxidic melts (1600 to 1800 K); determine influence of melt physical properties on fragmentation and triggerability
PREMIX	FZK (Germany)	Investigate premixing and jet breakup phenomena at higher than atmospheric pressure using up to 20 kg of molten thermite
QUEOS	FZK (Germany)	Investigate premixing phenomena using hot solid spheres (up to 2600 K) in both saturated and subcooled coolant
SIGMA	UCSB (USA)	Investigate propagation phenomena including the "microinteractions" concept in a well characterized, one-dimensional facility using single melt drops in a simulated explosion environment; obtain data to verify constitutive relations
WFCI	Univ. Wisconsin (USA)	Perform FCI experiments using small mass of simulant melts (up to 5 kg of Sn, FeO, and some oxide-metal mixture) at atmospheric pressure in a well-characterized, small geometry (up to 200 mm diameter test vessel) to determine the effects of various fuel/coolant parameters on FCI energetics, and to develop a scaling rationale to extrapolate the test results to reactor prototypic situation
ZREX	ANL (USA)	Perform experiments using small mass of metallic and mixed melts (up to 1 kg of Zr and Zr-ZrO_2) at atmospheric pressure in a well-characterized, small geometry (100 mm diameter test vessel in a larger diameter containment) to determine whether or not chemical augmentation of FCI energetics occurs, and to determine the extent of such augmentation

APPENDIX A

LETTER FROM DR. THEMIS SPEIS TO THE SERG-2 PANEL MEMBERS

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

May 10, 1995

Professor George S. Bankoff
Chemical Engineering Department
Northwestern University
Evanston, IL 60208

Dear Professor Bankoff:

The U.S. Nuclear Regulatory Commission (NRC) has decided to convene a group of experts to review the current status of the molten fuel-coolant interactions (FCI) issue covering the complete spectrum of interactions, i.e., from mild quenching to very energetic interactions including those that could lead to the α-mode containment failure. For this purpose, the second Steam Explosion Review Group (SERG) workshop will be held in Annapolis, Maryland, on June 15 and 16, 1995. As an internationally recognized expert in this field of research, I would like to invite you to participate in this review workshop. The objectives of the second SERG workshop are to: (1) review the current status of our understanding of the FCI issue, (2) identify any residual uncertainties, (3) revisit the α-mode failure issue in order to make a more definitive statement (i.e., quantitative) vs. the more qualitative ones made at the first SERG workshop, and (4) provide recommendations for future research efforts in the broad area of FCIs.

To help focus on the objectives of the second SERG workshop, I am providing some background on the FCI issue and the progress made to date toward a more complete understanding of the issue. Recall that the steam explosion (highly energetic FCI) and its effect on containment integrity were identified first in WASH-1400 and later quantified in some fashion in NUREG-1150. In 1985, the first SERG workshop was convened by NRC to discuss and evaluate systematically the FCI issue with emphasis on the α-mode containment failure probability. The experts, who participated in that workshop, reviewed the then current understanding of the potential for containment failure arising from in-vessel steam explosions during core melt accidents in light water reactors. At the conclusion of the workshop, there was a consensus among the experts that the occurrence of a steam explosion of sufficient energetics which could lead to an α-mode containment failure had a low probability. However, the experts concluded that more work would be necessary to develop a high confidence level in quantifying the bounds of potential energetics in FCI, in quantifying the associated uncertainties, and in determining the conditions under which energetic interactions could occur.

Much of the FCI work since 1985 has been aimed at enhancing the technical basis of the conclusions reached by the SERG experts, resolving residual uncertainties in our understanding of the FCI issue, in particular, quantification of the α-mode failure issue, and at achieving final resolution of the issue. Recently completed work at the University of California, Santa

Barbara (UCSB) examined experimentally the water depletion phenomenon during premixing, and also the fragmentation kinetics during propagation. The significance of the water depletion phenomenon is that it puts bounding limits on interacting water, steam, and debris masses in a multiphase system, thereby providing a strong technical argument against the α-mode failure. The knowledge of fragmentation kinetics is essential in studying propagation and escalation of pressure waves, and the resulting potential for failure of lower head and adjoining structures.

Other recently completed and/or ongoing work in the area of FCI includes the experimental program at the University of Wisconsin (UW) to address the scaling issue related to thermal-to-mechanical energy conversion to ensure that no major uncertainties due to scaling are ignored, and work at the FARO/KROTOS facilities at JRC/Ispra on high pressure melt quenching tests using prototypic melts (FARO) as well as melt-coolant premixing tests (KROTOS). Additionally, analytical work on FCI was carried out during this period leading to a number of computer codes for modeling separate effects phenomena as well as integral FCI evaluation of complete reactor systems. The recently initiated work at the Argonne National Laboratory (ANL) is intended to examine the possible chemical augmentation of steam explosion energetics due to the presence of metal (Zircalloy) in the melt, and the possible manifestation of such augmentation through dynamic loading of containment structures.

Significant new FCI programs (in addition to those in the U.S. and JRC/Ispra mentioned above) were initiated in other countries during this period as well. Notably among these programs are those in Germany, France, Japan, and the U.K. The work in Germany concentrated on determining premixing conditions which would result in maximum explosive energy release, and on determining the mechanical conversion so that the worst case loading on the vessel head could be calculated. The BILLIEU experimental program on steam explosions and associated analytical development were initiated in France in 1990. The ALPHA program in Japan was also initiated in 1990 to study, in part, melt-coolant interactions and to quantify loads to the containment during FCI. The FCI work in the U.K. during this period was mainly analytical in nature (development and/or assessment of FCI codes), and limited experimental programs were carried out to support the analytical activities.

To share the benefit of this significant progress on the FCI issue, the Committee for the Safety of Nuclear Installations (CSNI) Principal Working Group 2 (PWG2), through its Task Group on In-Vessel Degraded Core Behavior (IVDCB), organized a second Specialists' Meeting on Fuel Coolant Interactions in January 1993 (the first such meeting held more than twelve years ago). International work was presented at this meeting in two broad categories covering the fundamentals of FCI - premixing and quenching, and propagation and energetics. Additionally, papers were presented on integral assessments related to steam explosions (see NUREG/CP-0127, NEA/CSNI/R(93)8). In light of the additional insights gained from the collective research efforts in the years since the first SERG workshop in 1985, the risk assessment presented in the meeting confirmed the conservatism embedded in the first SERG report (NUREG-1116). Furthermore, the assessment concluded that, in light of the new knowledge gained on the water depletion phenomenon and its quantification, there was a substantially reduced potential to intermix large quantities of molten fuel and water thereby limiting the steam explosion energetics and rendering the α-mode containment failure of no significance to risk.

Given the above body of knowledge on the FCI issue, it now appears that there is a renewed consensus that the α-mode failure is of very low likelihood, and there is a general agreement that future efforts (experimental and analytical) are confirmatory in nature and focused on further enhancement of the quantification in areas/parts of the issue where residual questions remain. At the same time, a close examination of the ongoing U.S. programs and the programs outside the U.S. suggests that FCI research has broadened to encompass more than the α-mode failure issue. The recent 4-year FARO program plan, for example, has emphasized the ex-vessel aspects of the overall FCI issue.

To reiterate, then, the objectives of the second SERG workshop are to: (1) review the current status of the FCI issue, (2) identify residual uncertainties, (3) revisit the α-mode failure issue in order to make a more definitive statement on our understanding, and (4) provide recommendations for future research efforts. In order to facilitate the discussions at the workshop which are aimed at achieving the above objectives, I have enclosed a number of questions and issues (Enclosure 1) with this invitation, which you should review and address prior to the meeting. Please provide your responses to these questions and issues in writing to the NRC in advance of the workshop. You will also be expected to verbally summarize your responses in about 40 minutes on the first day of the meeting. Following individual summaries, there will be open discussion on various issues starting the first day of the meeting and continuing on to the second day. Later on the second day, you will be expected to summarize the workshop outcome along the objectives mentioned above.

The administrative arrangements for the workshop are being handled by the Brookhaven National Laboratory. A block of rooms has been set aside at the Historic Inns of Annapolis under "Brookhaven National Laboratory/NRC" at a rate of $76.00 per night (including tax). Please contact the hotel directly at (410) 263-2641 to make your own reservation. For other travel related assistance such as area map, direction to the hotel, seasonal events in the area, etc., you may contact Ms. Kathy Ryan at (516) 282-2630.

In closing this letter, I would like to emphasize that your participation is crucial to the success of this workshop and I hope to see you in Annapolis shortly. In the meantime, if you have any questions concerning this letter or need additional information, please feel free to call Dr. Sudhamay (Sud) Basu of my staff at (301) 415-6774.

Sincerely,

/S/

Themis P. Speis, Deputy Director
Office of Nuclear Regulatory Research

Enclosure: As stated

*Identical letters to be sent to: Berthoud, Catton, Cho, Corradini, Fauske, Fletcher, Henry, Jacobs, Sehgal, Theofanous, and Turland

Questions and Issues for the SERG-2 Workshop Participants

1. In your opinion, what is the status of our understanding of the α-mode containment failure issue for the LWRs? Is it, in your opinion, resolved, i.e., of little or no risk significance?

   (a) If yes, cite the relevant references

   (b) If essentially resolved, what additional confirmatory research is required, in your opinion, to fully resolve the issue?

   (c) If not resolved, i.e., if the residual uncertainties still remain large and/or if there are still unanswered questions about the α-mode failure, discuss specific additional research that will be needed to answer the questions and to address the uncertainties. Discuss the approach to research areas thus identified, potential benefits to be derived from the research, and indicate the time frame for accomplishing the research objectives.

2. Discuss the role and status of premixing in addressing the α-mode failure issue.

3. Discuss the role and status of propagation in addressing the α-mode failure issue.

4. Discuss the role and importance of triggering (trigger availability and triggerability) in addressing the α-mode failure issue. Discuss the role of pressure threshold in suppressing the triggering.

5. Discuss the role and importance of accident progression and melt relocation in addressing the α-mode failure issue.

6. Discuss the role and consequence of mechanical energy release and damage-producing events in the context of the α-mode failure.

7. In your opinion, is our current knowledge of premixing and propagation phenomena adequate for a better quantification of the α-mode failure? Based on your own knowledge, are you now able to assign a better probability (likelihood) measure to this failure mode?

   (a) If yes, provide your estimate(s) and the basis for it. (<u>Note:</u> The plural is for distinguishing among various severe accident classes if you wish.)

   (b) If no, do you think it is reasonable to expect that this will be possible sometime in the future? Provide your reasoning and indicate what key developments will be needed to meet the expectation.

8. Discuss the status and capabilities of the analytical tools/computer codes available to address various components of the FCI methodology (e.g., tools to estimate premixture) or to perform integral FCI assessments. How much verification have these analytical tools had? Are there well defined experiments against which a number of these tools can be assessed? Provide your recommendations regarding the need to perform a "standard" problem, preferably one in conjunction with an integral evaluation.

9. How much of the research performed (both experimental and analytical) in support of the α-mode failure issue is also applicable to "localized" FCIs (e.g., an energetic FCI next to a structural boundary where there is a need to evaluate the dynamic loading on the structure)?

10. Discuss the possibility and importance of chemical augmentation to energetic FCIs. Discuss the impact of chemical augmentation on the dynamic loading of structures.

Second Steam Explosion Review Group (SERG-2) Workshop

Maryland Inn, Annapolis, Maryland

June 15-16, 1995

June 15, 1995

9:00 a.m.	Opening Remarks	W. Hodges
9:10 a.m.	Introduction - Setting the Workshop Focus	T. Speis
9:30 a.m.	Individual Presentation	S. G. Bankoff
10:15 a.m.	Individual Presentation	G. Berthoud
11:00 a.m.	Individual Presentation	I. Catton
11:45 a.m.	Lunch Break	
1:00 p.m.	Individual Presentation	D. Cho
1:45 p.m.	Individual Presentation	M. Corradini
2:30 p.m.	Individual Presentation	H. Fauske
3:15 p.m.	Coffee Break	
3:30 p.m.	Individual Presentation	R. Henry
4:15 p.m.	Individual Presentation	H. Jacobs
5:00 p.m.	Individual Presentation	R. Sehgal
5:45 p.m.	Individual Presentation	T. Theofanous
6:30 p.m.	Individual Presentation	B. Turland

June 16, 1995

8:30 a.m.	Open Discussion Forum	All
10:30 a.m.	Coffee Break	
10:45 a.m.	Open Discussion Forum (continued)	All
12:45 p.m.	Lunch Break	
2:00 - 3:00 p.m.	Open Discussion Forum (concluded)	All
3:00 p.m.	Coffee Break	
3:15 - 6:00 p.m.	Closing Statements	Panelists

List of Expert Panelists at the SERG-2 Workshop (June 15-16, 1995), Annapolis, Maryland

Name	Organization	Telephone No.	Fax No.	e-mail
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* Participation by written submittal only

List of Other Participants at the SERG-2 Workshop (June 15-16, 1995), Annapolis, Maryland

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APPENDIX B

SERG-2 PANEL MEMBER RESPONSES

APPENDIX B-1

SERG-2 PANEL MEMBER RESPONSE

BY

DR. S. GEORGE BANKOFF

NORTHWESTERN UNIVERSITY

RESPONSE TO QUESTIONS AND ISSUES-SERG2

S. G. BANKOFF
Chemical Engineering Dept.
Northwestern University, Evanston IL 60208

Q-1

(a) The probability of an alpha-mode containment failure, in my opinion, is vanishingly small. If required to choose a numerical value for the probability per reactor severe accident I would give it as 10^-5 to show improvement since my last SERG estimate of 10^-4, based on information obtained since that time.

The argument is based on the following physics. In order for a fuel-coolant interaction occur that is sufficiently powerful to rupture the reactor pressure vessel (RPV) and the containment head, the following events must occur sequentially:

1. A massive pour of core melt from the core region into the lower head must occur in a time scale of seconds in coarsely-premixed form.

2. The size range of at least 10-20 tonnes of this melt must be approximately 0.1 to 10 cm in order for the particles not to be quenched before the triggering event, and for the bulk of the energy transfer to occur in a time scale of tens of milliseconds.

3. The particles must be in film boiling, with the void fraction of the coolant being less than 0.5, in order for a detonation to propagate after mixing.

4. A coherent liquid slug must be accelerated upwards after the propagation stage which seals off the expanding mixture , thereby converting thermal energy into mechanical energy

5.This slug must remain intact as it sweeps aside the upper core plate and other steel structure below the containment head.

In my opinion all five of these steps are physically impossible, or at least of very low probability. The arguments for this opinion will be given below.

A listing of some of the relevant references is given here. Others are cited at the end.

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(b) I have some concerns about the possibility of multiple explosions satisfying several of the conditions above, but cannot suggest a suitable experiment properly to examine this possibility, given the cost and the instrumentation difficulties which exist.

(c) Further development of the codes could be useful, particularly for identifying conditions which would not rupture the containment, but which would cause the lower head to fail. An interesting set ofexperiments would be to pour a tonne of so of Woods' metal into a water pool of 1-2 meter depth in a time scale of 1-2 s, with the interfacial contact temperature (ICT) being above and below the freezing point of the metal, and with X-ray pulse instrumentation to determine the local particle concentrations and size distributions. The solidified particles would collected for size analysis. If the ICT is brought close to, but below the spontaneous nucleation temperature (SN), this would even more instructive, but would possibly be dangerous, and would be expensive to carry out safely. This is needed because the ratios of the length and mass scales of current experiments to the corresponding reactor scales are so small that the codes have considerable uncertainties attached to them.

Q-2

The fuel liquid surfaces will always be in film boiling as they enter the pool, unless the vapor is locally the continuous phase. This is because the ICT is above the spontaneous nucleation temperature, except for very fine particles which quench rapidly. If the fuel enters in the form of small-diameter jets leaking from holes in the lower support plate, these will break up into drops which fall through the pool and settle on the bottom, if triggering does not occur first. However, an unreasonable number of small leaks must develop simultaneously, or nearly so, for the pool to have about ten tonnes in transit at the same time. A single large jet seems unlikely, but if it occurs, a calculation by Han and Bankoff (9) shows that it would be protected by a thick vapor layer, which would entrain water into the upwardly-flowing vapor, but would not entrain fuel droplets off the surface of the jet. Unless triggering occurred, this jet would penetrate to the bottom very nearly intact, except for contact with submerged steel. Once a stratified corium layer is formed on the bottom, with water above it, rapid solidification and the coarseness of the premixture would preclude an alpha mode event.

Thus, it is extremely unlikely that about ten tonnes of fuel in transit through the pool with a size range of 0.1 -10 cm can be generated in a well-dispersed array. The lower bound corresponds to particles which would be quenched prior to the triggering event, and the upper bound to particles which are to be fragmented into fine debris in a time scale of milliseconds behind the detonation front, and hence can contribute to maintaining the pressure of the front. The upper size limit has been made rather generous, because the expansion stage is of order of seconds, or less, and further heat transfer can then occur.

Nevertheless, assuming for the sake of argument that upwards of ten tonnes of fuel particles in the correct size range can be generated falling through the pool at the same time, there is another difficulty, first pointed out by Henry and Fauske (10), and since verified by Theofanous and coworkers (6), as well as other investigators. In a region of high fuel particle concentration the heat transfer by radiation and convection to the coolant is so large that the rising vapor becomes essentially continuous, carrying the water droplets out of the region. This "vapor chimney" effect was estimated by applying the Kutateladze fluidization criterion to the vapor-liquid field. Han and Bankoff (11), using the PHOENICS code, showed that the vapor production rate can be very large at the pour rate (which could threaten the containment) of 9000 kg/sec. Even with poor breakup (5 cm particles), and higher than expected pressure (1 MPa), the pool level swell nearly doubles the depth of the pool in one sec. Such a large array of particles would occupy nearly all of the cross-section of the pool, so that a one-dimensional calculation is sufficient. Furthermore, some of the coarse fuel particles are levitated, so that most of the fuel particles remain in the upper half of the pool for the first second. If a smaller pour occupies only the central region of the pool, or a restricted portion of the pool surface area, bypass of the upwardly -flowing liquid can occur. The fuel particles can then penetrate the pool more easily, but the water depletion effect will still be present in the regions of high fuel particle concentration. As discussed later, these water-depleted regions cannot participate efficiently in an explosion.

To these considerations must be added the mechanical energy requirements for producing particles in the above size range in the time period of transit into and though the pool (4). Mechanistic models due to Henry and Fauske (12,13) for the breakup rate in liquid-liquid film boiling and for the limiting size of the fuel particles thus produced indicate that fine-scale premixing can be expected in current "large-scale" experiments, but virtually no premixing on the reactor scale. This variation of particulation scale was demonstrated experimentally by Theofanous and Saito (14) using water and liquid nitrogen. One comes to the conclusion that effectively no premixing would occur in the reactor system which could threaten the containment.

Q-3

To discuss triggering properly, one must first assume that there exists a coarse premixture which can sustain a propagating interaction (detonation) far from the trigger source. As pointed out by Henry (15), this is not always easy to ascertain. A strong trigger will fragment fuel particles, which will then release their energy to the coolant rapidly, so that local escalation can occur. However, far from the source, the propagation may die, since the fragmented particles initially acted as amplifiers for the trigger -induced mixing. If only a limited region is involved, it will not be possible to distinguish between the triggering effect and the true escalation effect. A very powerful trigger could conceivably perform all necessary fragmentation for a large-scale event. However, such a powerful external trigger cannot be identified for a reactor accident.

Self-triggering is always a stochastic event, since the time and place cannot be predicted in advance.However, pouring experiments by Long, involving 50 kg of aluminum into water, showed that it could be quite reproducible, providing the proper combination of pool temperature and depth, pouring rate, and bottom surface condition were present. The hypothesis was that if the tank bottom is wetted by water, a thin water film can be entrapped below the aluminum mass when it reaches the bottom. This film quickly superheats to the spontaneous nucleation temperature and explodes locally. If the bottom was coated with grease or paint, the explosion did not occur. In the reactor situation, the submerged steel in the pool, after long periods in contact with grease-free water, would be well-wetted. Hence, at low pressures, it may be assumed that, with literally millions of contact events between tonnes of corium and submerged steel, the probability of triggering would be essentially unity, if a propagating detonation is possible. Hence no credit can be taken for the difficulty in triggering, except at high pressures. Such pressures have variously estimated at 65 bars, 30 bars and even 10 bars. In almost all actual severe accident cases, however, the pressure would be quite low, because at high pressures it is difficult to get water into the core.

On the other hand, it is impossible to trigger an escalation event in a vapor-continuous region. This is because the trigger implies the arrival of a pressure wave which collapses the vapor film around neighboring droplets. These then produce additional vapor, which transmit a pressure wave to other droplets in film boiling.This is not possible if the medium between the drops is highly compressible, as with void fractions above 0.5, or with a vapor-continuous medium.

Q-4

It has been noted above that propagation may be difficult to ascertain in small-scale events. This would not be the case in large-scale events involving tens of tonnes of coarsely-premixed material. Immediately behind the propagating front is the reaction zone which terminates, according to detonation theory, at the Chapman-Jouguet (C-J) plane. Here the velocity is sonic relative to the front, which is thus protected from weakening by rarefaction waves progressing from the far field. This zone must be thin in comparison to a characteristic length, such as the pool diameter or depth, and hence can be considered to be locally one-dimensional, even if the full-scale propagation front is curved. The theory assumes that at the C-J plane the mixture consists of of a homogeneous mixture of fuel debris and coolant, with equilibrated velocity, temperature and pressure. According to the homogeneous theory, such as for gaseous detonations, the premixture is compressed by the advancing pressure wave adiabatically to a pressure peak, known as the Neumann spike. The mixture then reacts, following a straight line on the pressure- specific volume diagram, which is tangent to the Hugoniot curve. This curve is the locus of states of the reacted mixture as a function of final pressure at the C-J plane. Further expansion can take place in the far field, which may be at rest with respect to the laboratory frame, and hence at supersonic velocity relative to the shock front. When applied to vapor explosions, this is the famous Board-Hall theory (16, 17), which gives an upper bound close to (actually greater than, owing the additional compression by the front) the constant- volume temperature equilibration pressure of Hicks and Menzies (18). Actually, in a multiphase detonation the fuel and coolant temperatures may not be equal at the C-J plane, and even the velocities may not be equal, although some criterion of sonic velocity through the mixture must be satisfied. Thus, only partial thermal energy transfer between the fuel and coolant may be achieved at the end of the reaction zone (C-J plane), leading to reduced explosion efficiency, as shown by Bankoff and Jo (19). Sharon and Bankoff (20) integrated the multiphase mass and momentum conservation equations behind the front to the near-attainment of velocity equilibration. With low initial fuel concentrations, corresponding to high void fractions, the reaction zone was up to a meter in length. Such detonations were deemed impossible, since sideways expansion would weaken the front excessively. Similar calculations were independently performed by Scott and Berthoud (21), with similar results.

This effect of reduced efficiency with high initial void fractions, predicted by the dynamic equations behind the front, is subject to some uncertainty, owing to the empirical character of the fragmentation constitutive equation. However, the amended Board-Hall theory due to Sharon and Bankoff (22) gives the same results without recourse to empiricism. If the energy transfer is incomplete at the C-J plane, the Hugoniot curve has a sharp "knee" so long as vapor is present, but at the critical pressure the curve turns sharply upwards, reflecting the low compressibility of the "liquid" (supercritical) region. With large initial specific volumes, corresponding to high vapor content, the tangency point on the Hugoniot curve is necessarily then slightly below the critical pressure. The highest pressures (and hence efficiency) are obtained in the neighborhood of equal volumes of water, vapor and fuel in the premixture. Such high mass concentrations of fuel would actually lead to much higher void fractions . This is a principal argument against the possibility of an efficient detonation which would cause the containment to fail.

Q-5

In the TMI accident the corium entered the pool though a side pour, and formed a layer on the bottom which quickly solidified. This seems to be a more likely event than pour into the pool through the lower core support plate (LCSP). This is partly because the crust above the plate is more protective, being cooled from the bottom by radiation to the pool and also vapor rising from the pool. In any case, a thick layer of melt, overlain by a water pool with a vapor layer in between, is not an efficient premixture for a propagating detonation. Such detonations have been studied in small-scale experiments, but the region of intermixing is thin, being limited by the propagation time and therefore by the mixing energy requirement. The side pour comes from the top of the melt pool, where the oxidic content is higher, and therefore the chemical energy content and the thermal conductivity are both lower. Both effects would lead a lower stratified-explosion efficiency.

A potentially major issue, to my mind, is the possibility of multiple explosions, with a later explosion being much more powerful than its predecessors. Such events are well-known in volcanic eruptions, such as Krakatoa, which resulted from very large scale mixing of seawater with magma, followed by pressure generation which led to several minor releases, but which eventually led to rapid depressurization. This, in turn, allowed an enormous detonation to proceed, which blew away the island and caused ten-foot tidal waves 2000 miles away.The possibility here is that a one-tonne explosion might blow away the LCSP, causing large-scale mixing of the contents of the melt pool and the lower plenum pool. It is not clear what would then happen. A rapid pressurization might occur, but no detonation or slug impact on the upper core support plate. On the other hand, the mixed material might fall back into the lower plenum and then explode. In my opinion this possibility has been insufficiently examined. The Sizewell B study (5) did some work on it, but ended up by simply assigning a slightly revised probability in tthe Monte Carlo calculation. The codes are currently incapable of following the path of the accident anywhere close to this scenario, which is undoubtedly why little attention has been paid. However, rough calculations to establish order of magnitude of the energy releases would be very useful now, and a more detailed analysis should be performed in the near future. For example, it makes a difference if the LCSP is simply folded out of the way, or whether it is blown upwards in an essentially horizontal position, still separating the melt from the water/steam coming up from the pool.

Q-6

A vapor explosion differs from an underwater explosion in the damage mechanism. In an underwater explosion with conventional explosive, such as tetryl, which has a high brisance, or very rapid pressure rise, the damage done to the submarine by the depth charge is due to the shock wave, the pressure rising to hundreds of thousands of bars over milliseconds, or less. In an alpha mode postulated failure, the expansion occurs over a second or so, and develops mechanical energy in the liquid/solid mixture which is accelerated into the containment head. For this to occur the liquid slug must be continuous. Otherwise, the pressure of the expanding mixture is vented through the porous slug, and little slug acceleration takes place, except that generated by the frictional pressure drop of the flow through the slug. Furthermore, the slug must serve as a pressure seal, which implies that it occupies the entire cross section of the RPV. If not, the expanding mixture simply bypasses around the slug. In the WASH -1400 scenario the liquid slug is generated by an explosion in the lower half of the coolant pool in the lower plenum. This accelerates the upper half of the pool upwards to form, together with the structural steel and the core melt, a massive upwards-moving slug. It is clear now that this scenario is mythical, having been postulated to give the most conservative possible estimates of damage potential. First of all, the explosion is probably triggered in the upper half of the pool. The upper half of the pool contains large water-depleted regions, owing to the large void fractions in regions of high fuel concentrations.Hence a vapor/water/ fuel mixture is blown upwards. More vapor is generated when the liquid water mixes with the core melt. Hence the slug always contains a considerable amount of vapor, even if it is not vapor-continuous. Moreover, Taylor instability will quickly cause the slug to degenerate into an array of drops. Harper, et al (22) examined the exponential growth of Taylor instability fingers into an accelerated liquid sphere at Bond numbers greater than 10^5. This can be very rapid. In the reactor case the acceleration of a 2m high slug by the 200 bar pressure difference is about 1400 g. In experiments by Seo and Bankoff (23), a water column 0.2 m high was accelerated upwards by a 50 bar pressure difference, so that the acceleration was about 1500 g. Taylor instability penetrated from the lower face to the top of the slug by the time that the slug was displaced its own length, in agreement with an approximate nonlinear Taylor instability theory. However, the slug might be significantly decelerated upon encountering structural steel obstacles. Detailed calculations are needed to establish the acceleration vs. distance upwards of the moving mass. Codes for this calculation are not yet available. The fluid-solid interaction codes are needed also to establish whether the bottom head fails, even if the containment does not. This is important, because coolability strategy implies flooding the cavity below the RPV in order to cool the lower head, and thereby terminate the accident. For this calculation two-dimensional codes are needed, and the pressure-time history on the bottom head wall must be calculated.

Q-7

(a) As noted above, my current estimate is 10^-5 to 10^-4, with the weighting on the lower figure. This is based on the work done at Santa Barbara and in the UK, which arrived at similar overall probabilities per reactor severe accident.
I think we have enough knowledge to say that the alpha mode failure is an extremely minor risk, even though the consequences would potentially very serious. When combined with the probability per reactor year of a meltdown accident, and 1000 Western-design reactors operating world wide, there would be a mean waiting time of 10,000 years for this mode of failure. I conclude that resources should be largely shifted elsewhere, such as the coolability question. This estimate was known at the last SERG meeting, but had not been subjected to more precise verification . The progress since then has been good, although the scales of the experiments have been necessarily small. No contradictory information has been uncovered as a result of this work which would

increase the probability of alpha-mode failure. This in itself is important, since one could not predict with confidence that this would be so.

Q-8

First of all, there is a great deal of overlap between codes, which is understandable from the viewpoint of national objectives. However, a much more vigorous international effort to coordinate and slim down this effort might be appropriate, in order to reduce costs and minimize confusion. The difficulty is that each code has a number of adjustable parameters, used to fit predictions to experimental data. They are also inserted in order to make smooth transitions from one flow regime to another, or to make smooth transitions from premixing to triggering, propagation, expansion and finally structural damage. The end result is that one has a large integral code, which it takes an expert living with the code for a good part of a year to decipher, and which has many compensating errors. Even if the codes currently give consistent predictions, despite using different constitutive equations, there is no guarantee that they will agree even approximately when scaled up to reactor dimensions and masses, or that they will predict correctly the actual accident course.. Furthermore, sufficiently large experiments to overcome the scaling problem are not foreseeable, since the output of such an experiment is only an integral pressure record at various locations, some temperature measurements during the premixing stage, and some rough efficiency estimates. More improved instrumentation for this scale explosion does not appear at this time to be feasible, aside from the cost and enhancement of public fears which would ensue. Hence it is still necessary to rely on fundamental principles, as outlined above.

The KROTOS, FARO and ALPHA (Japan) experiments are useful for assessing the codes, although it is a source of uneasiness that codes with quite different constitutive equations from different countries and laboratories can be made to fit the same pressure-time data. The experiments to date have not yielded local velocity, phase mass fraction, pressure or temperature data, so that there no cross-checks on the physics behind the codes at the present time. Some progress has been made on premixing, using pulsed X-rays and the FLUTE instrumentation (Theofanous), but no verification concerning escalation or propagation. Apart from these comments concerning the explosion itself, there is a great deal to be done on the core relocation and the fluid-structure interactions applied to the slug scenario. Little has been done concerning the fluid mechanics of the slug acceleration, and the multiple explosion scenario, both of which, in my opinion, are very important.

The KROTOS and FARO experiments have, in a sense, acted as standard problems, since all codes have been tuned to them. They are thus probably useless for comparison purposes. The one computational test at reactor scales that I can think of gives a comparison with Board-Hall theory. This can be done by boosting the fragmentation rate behind the propagating front to the point where velocity and temperature equilibration are achieved when sonic velocity relative to the front is achieved. Since the principles are simply mass and momentum conservation in the multiphase interaction region, together with thermodynamic principles, they should all agree with each other and with Board-Hall theory. A follow-up set of calculations in which only partial fragmentation, and hence only partial energy transfer, is achieved at the sonic-velocity plane would be an even better test, and can be compared with improved predictions along the line of the Sharon-Bankoff and the Scott-Berthoud predictions.

Q-9

The localized pressure prediction has been discussed above. Here a two-dimensional capability is useful, subject to the limitations noted above. I rather doubt that a three-dimensional capability is needed in the near future. This is, however, an important topic, since the coolability problem, and hence the reactor and containment design, is intimately tied in.

Q-10

There is no doubt that chemical reaction of highly-superheated pure aluminum is very significant, but this is not very pertinent to melt containing zirconium, which is partly oxidic, and the rest diluted by solution in the steel . I think this should be (and is being) looked at, but I do not expect that any great modification will result from this effect. This problem should be wound up quickly.

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APPENDIX B-2

SERG-2 PANEL MEMBER RESPONSE

BY

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COMMISSARIAT A L'ENERGIE ATOMIQUE

STEAM EXPLOSION REVIEW GROUP 2

Annapolis, June 15-16, 1995

Contribution from G. BERTHOUD

CEA-DRN-FRANCE

1. In your opinion, what is the status of our understanding of the α -mode containment failure issue for the LWRs? Is it, in your opinion, resolved, i.e., of little or no risk significance?

(a) If yes, cite the relevant references

(b) If essentially resolved, what additional confirmatory research is required, in your opinion, to fully resolve the issue?

(c) If not resolved, i.e., if the residual uncertainties still remain large and/or if there are still unanswered questions about the a-mode failure, discuss specific additional research that will be needed to answer the questions and to address the uncertainties. Discuss the approach to research areas thus identified, potential benefits to be derived from the research, and indicate the time frame for accomplishing the research objectives.

As you may already know, detailed studies relative to Steam Explosion in PWR started only recently in France e.g. around 1990. We then do not have clear answers but we are in the process of obtaining such answers. We are developping the MC3D Code in order to describe the usual different sequences of a Steam Explosion i.e. the PREMIXING and TRIGGERING/PROPAGATION phases. These studies were undertaken because, after analysis, we found we cannot bound with sufficient credibility the effect of a S.E by producing figures for :

- the amount corium mass which can be involved in a SE

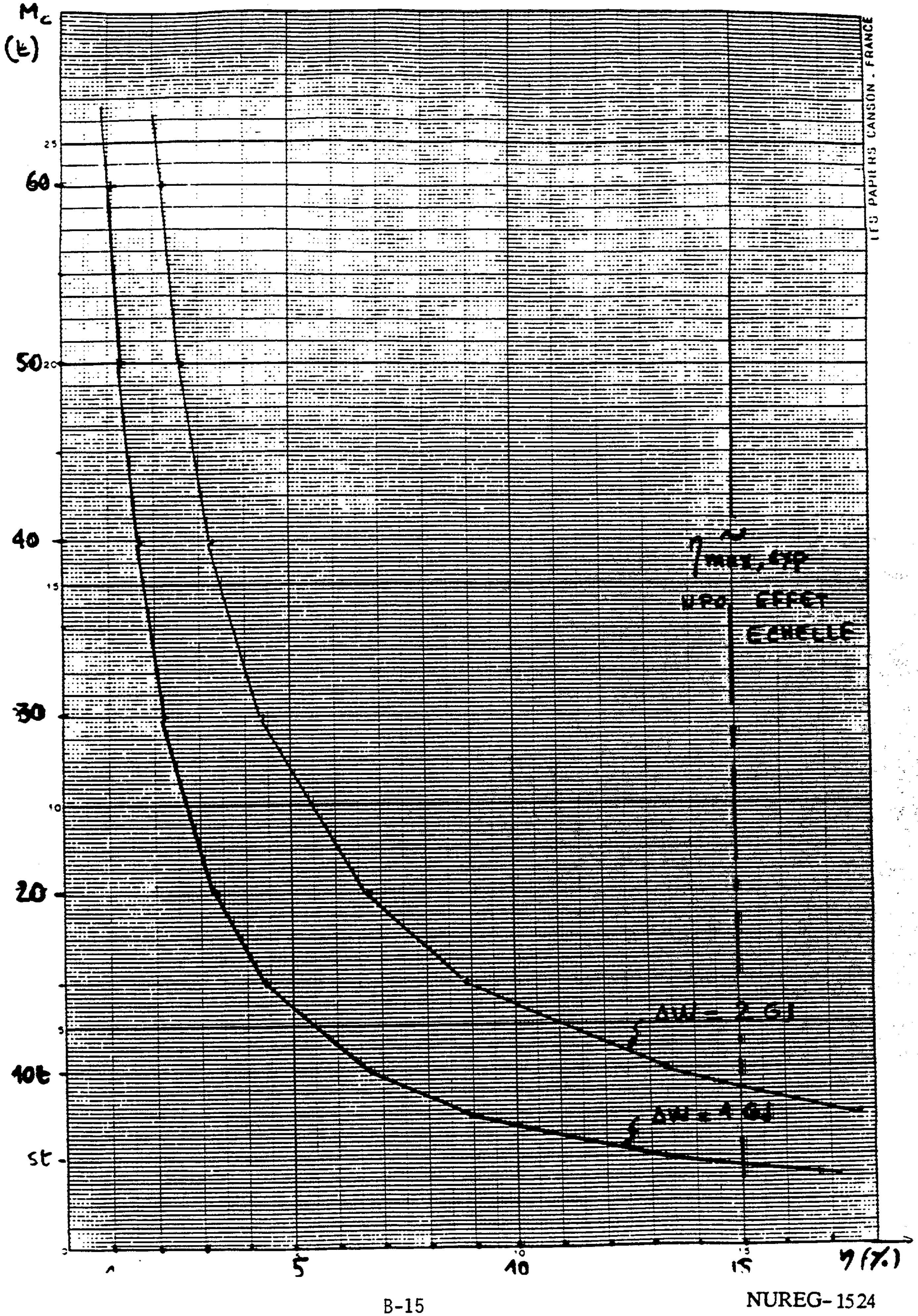
- the efficiency of this S.E.

Indeed we think that this approach suffers from simplicity :

- restricting the amount of melt which can participate to a Steam Explosion may be a trick. In fact, it is likely that the melt which mixes with water will participate, more or less, to the interaction. If we agree with the usual S.E. sequence, once triggered somewhere, the explosion will propagate through the whole mixture, inducing a more or less efficient heat transfer between corium and water according to the conditions in the mixture (geometry, thermodynamic conditions for coolant). Then, if we look at fig. 1, we find that a mechanical energy release of 1 GJ (order of magnitude sufficient to induce risk in vessel behaviour) can be reach with 7 tons of corium and an efficiency of 10 percent or 50 tons of corium and an efficieny of 1.5 percent, or a mixture of these conditions

- using efficiency can also be incorrect for two main reasons. Efficiencies are deduced from small scale experiments (25 kilograms at maximum of melt in the Sandia FITS program, in the Winfrith SUW program and in the Japanese ALPHA program) and their use for reactor situations is difficult because :

  - we have to take into account the effect of SCALE which is not firmly established. In fact, there are physical reasons which favoured an increase of efficiency with scale. First, as during a Steam Explosion, heat is first transfered from fuel to some amount of coolant and then to the surrounding cold coolant, there is a volume to surface ratio which characterizes the ratio of heat received by



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60
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ΔW = 2 GJ
ΔW = 4 GJ
LES PAPIERS CANSON . FRANCE

coolant (roughly proportional to the volume of the interaction zone) to the heat lost by the coolant (roughly proportional to the surface of the interaction zone). So, when the characteristic size L of the interaction zone increases, this ratio, linked with the interaction efficiency, increases proportionally to this size L. Secondly, in a large scale system, the increased contraint will lead to a longer time for heat transfer between corium and water which only disappear when the pressure in the interaction zone is released. We can also expect higher pressure peaks in more constrained systems. In a reactor hypothetical accident, we can also think that the surroundings will not be as cold as in the experiments (where, very often a zone of subcooled water surrounds the interaction zone), so the heat sink effect will be less pronounced.

Some effect of scale were indeed observed in the above mentionned FITS program where it was found for example that the propagation velocity increases with the size of the mixture (its diameter in the experiment) i.e. the interaction is more coherent. Higher pressure peaks are then expected which would produce finer fragmentation (higher relative velocities) leading to a more violent explosion.

However, there is a counter argument: it may be more difficult to get a "good mixture" with very large amounts of melt due to the "water depletion" effect or due to the fact that some amounts of the melt jets may not fragment or the fragments may be too large (10 cm instead of 1 cm which is the dimension often used in premixing calculations). This will be largely governed by the way the corium is poured into the water.

- the experimentally measured efficiency is the response of the experimental loop to the Steam Explosion and its use for other situations with different surroundings has no meaning. We must keep in mind that a Steam Explosion results from the very rapid and intense heat transfer between fuel and coolant as a result of a fine and efficient fragmentation process. Then, the heated and pressurized coolant expands against the surrounding constraint and it is during this expansion phase that most of the mechanical energy is delivered. The expansion phase is obviously dependant of the loop geometry. This behaviour corresponds well to the well-known HICKS-MENZIES approach.

The way to overcome these difficulties consists in the use of "sufficiently validated" multidimensional and multifield Steam Explosion Codes like PM-ALPHA/ESPROSE, IFCI, and more recently MC3D in France and IVA 3 in Germany. These codes will allow us to take into account properly the scale and constraint effects. Then, we will be able to provide the mechanical loads (pressure peaks, kinetic energy of slugs or missiles) to the structure in order to better evaluate the risks (α mode failure or other types).

Up to now, in France, we have not these "sufficiently validated" codes so we are unable to provide realistic estimations (probabilities) for any types of situations including the α-mode containment failure, even though, we can estimate - by expert judgements - that such an event is highly unlikely.

However, with the tools we have already in hands i.e. MC3D for Premixing and PLEXUS for fluid-structure interactions, we made some screening calculations but not strictly connected to the α mode failure. In fact, from MC3D calculation results, we define by expert judgements, a zone in which a Steam Explosion could occur. Then we estimate a time history heat transfer law to the water which is introduced into the PLEXUS Code which calculates the effect of this energy injection into the water. The first parametric calculations with PLEXUS showed that there was a risk of lower head vessel rupture when the energy injection was located close to the vessel bottom. At this time, I have to recall that these are preliminary results which must be taken with care.

Our scope is that at the end of 1997 we will be able to perform calculations with MC3D of the premixing and propagation phases in order to transfer to PLEXUS pressure time histories for the loading of the different structures and kinetics of slugs or missile. Then, PLEXUS will calculate the structure responses without any coupling with the Steam Explosion calculations.

But to be sure that these calculations are pessimistics (i.e. conservative) we will have to answer the two following questions :

- What are the effects of a reflexive wave on the steam explosion itself i.e. does it act as a trigger?

- Is the maximum load on the structure obtained by fluid-structure interaction calculations or rigid structure calculations?

As for the key phenomena involved an early containment failure due to a Steam Explosion (the α-mode containment failure), we identify and this is not really original :

- the late phases of core degradation which are less well understood than the early phases which will give us the initial (boundary) conditions for a Steam Explosion calculation :
  - nature, superheat and mass of molten corium
  - mode, location and size of the crust failure allowing the corium-flow which give the pour rate (according to the possible paths to the lower plenum)
- the way the corium will mix with the water (premixing) including :
  - jet and drop fragmentation in a two phase medium
  - corium-water heat transfer including the role of radiation in steam production
  - drag laws in multiphase media (mixing, water depletion)
- the triggerability of a mixture which is far from being deterministic
- the fine fragmentation processes i.e. how we move from thermal fragmentation (coolant jet penetration?) to hydrodynamic fragmentation
- the heat transfer between the corium debris and water : is the "micro interaction concept" valid and if yes, how is it possible to validate it, or does turbulence, radiation into coolant permit to deal with only one coolant temperature?
- the slug composition and behaviour up to the vessel head
- the missile formation

At the present time, I think that our physical understanding of all these phenomena is not sufficient to allow me to establish probabilities of any type of events (including the α-mode failure issue). Nethertheless, when I look to the different conditions I think necessary to get this α mode failure : large, coherent and rapid enough mixing of sufficiently superheat melt with water, existence of a strong enough trigger, existence of a sufficiently coherent slug, ... I can extend this list of conditions without being able to give figures for each item [sufficiently?], I find that this α mode failure is very unlikely.

2. Discuss the role and status of premixing in addressing the α -mode failure issue

As I already mentionned, premixing studies should not be aimed at defining the amount of melt which can participate to a Steam Explosion (all the melt will be more or less involved) but at defining the initial conditions for the explosion itself i.e. mainly :

- melt dispersion and characteristic size

- water and steam volumetric concentrations and temperatures

We think that in most of the scenarios, corium will enter the water under the form of jets with diameters from some centimeters to some tens of centimeters. We then have to provide models for jet fragmentation because we can expect that the non fragmented mass of a jet will not participate to a Steam Explosion. At the present time, all the premixing codes use corium droplets as initial conditions. In that case, all the melt will more or less participate but the "water depletion effect" will be overestimated so we cannot really prove that the calculation is conservative. At this point, we must not forget that the non fragmented part of the jets will participate to the thermal loading of the RPV which allow an easier rupture (but this is not linked with the α-mode failure) except that this rupture of the lower head will decrease the risk of α-mode failure). This non fragmented part may eventually be involved in a Steam Explosion if one is triggered in the other part which is premixed with the coolant. Up to now, we cannot say that jet fragmentation is well understood. Interpretations of the FARO tests will certainly help.

Then, to study the melt dispersion and water depletion effect, we have to describe :

- the steam production in a multiphase medium

- the different drag laws between the different components, and particularly the drag between steam and liquid which will carry the water out of the mixing region (bubble and droplet sizes?)

We then have to say that none of these constitutives laws are well established. As for the steam production law, it exists some film boiling models validated up to 1000°C but when we leave this type of configuration (film boiling) there are no firm validation. As an example of this, we can look at a calculation made by B. Turland for the SOA Report of the EEC Group working on MFCI of the mass transfer rate from liquid to steam as a function of the steam void fraction for a given set of fixed conditions, and this using the constitutive laws of the different premixing codes (without including the radiation component)

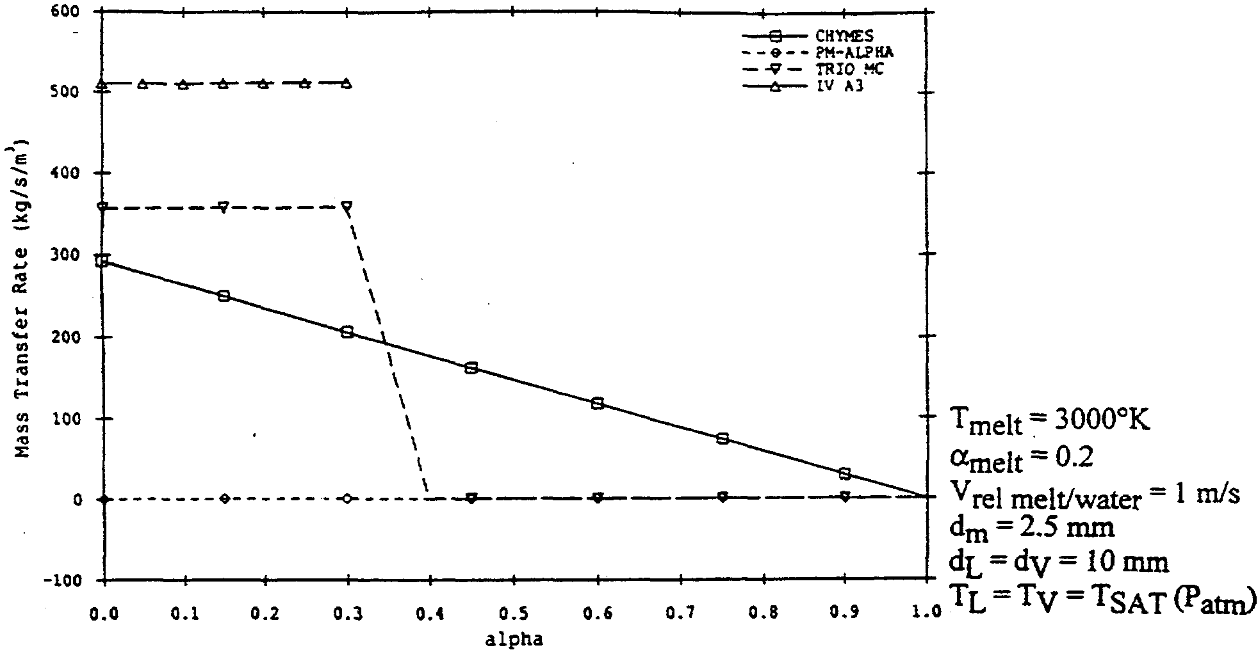


Figure 2 Mass transfer as a function of steam void fraction
Radiation component suppressed

Additionaly, we have to include the radiation terms and particularly its contribution to steam production when water is subcooled. We must note that, even if the water is initially at saturation conditions, the induced subcooling due to the local pressurization will be of importance. This was clearly identified in CHYMES calculations of the FARO tests.

As for the drag laws, in most of the premixing codes, they come from the work of ISHII and ZUBER (1979) who derived them for a two fluid system for given sizes of droplets or bubbles. These laws are extended to a three fluid system in which droplet or bubble diameters are generally specified from the local conditions.

At least, we also have to describe the melt fragmentation by the steam-water flow. All the codes use a formulation which is more or less derived from the PILCH work for the fragmentation in liquid-liquid or liquid-gas systems. Once again, this law has to be extended to a three phase system.

3. Discuss the role and status of propagation in addressing the α -mode failure issue

It is during this propagation phase that the heat stored in the melt is transferred intensely into the coolant, that work will be performed against the surroundings and that kinetic energy will be imparted to a slug which may result in the α-mode failure.

During this propagation phase, the obvious key phenomena are :

- the fragmentation kinetics of the melt droplets into small debris whose size and amount must be specified

- the heat transfer law from debris to coolant

As for the fragmentation, there are two types of processes which may be involved :

- some kind of "thermal fragmentation" (coolant jet may splash or penetrate into the melt?) which may be dominant in the early phase of the escalation process

- followed by some type of hydrodynamic fragmentation in the later phase of the escalation (i.e. when the pressure peak is high leading to high relative velocities)

To describe the propagation phase, we will have to combine these two processes as it was done by Burger et al (NED, 131, 1991) in their attempt to reproduce the KROTOS 21 test with tin.

If the hydrodynamic fragmentation of liquid-gas (and liquid-liquid) systems has received some attention leading to established constitutive laws, we cannot say the same for the so called "thermal figuration". For the hydrodynamic fragmentation, it exists very few experiments in a two phase medium (SIGMA from Theofanous and some starting experiments at IKE Stuttgart).

The heat transfer from debris to coolant is also crucial in describing the effect of a S. E (including the α-mode failure issue). Recently, Theofanous presented his "micro interaction concept" which consists in transfering heat only to some amount of coolant. This add new parameters which may help to better fit the experimental results but which need to be quantified in order to be used for reactor calculation. We also have to prove the validity of this concept i.e. if the turbulence will not distribute the debris throughout the coolant such that water temperature will be more or less uniform. This homogeneity of temperature is also renforced by the radiation effect which transfers heat to the water which is not in direct contact with the debris.

Quantification of the heat transfer rate is not evident. The experiments of Derewnicki et al showed that for some tens of microseconds, liquid-liquid contact is maintained leading to very high heat transfer before nucleation occurs. In a propagation code, these processes have to be averaged in time on a timescale relevant to the phenomena. To better show the difficulty of achieving this quantification, we can mention that it exists very few models validated on single drop experiment i.e. able to recalculate the bubble expansion and collapse law from the steam production by the fragmented debris.

Finally, the number of fields to be described in a propagation code is not well assessed. Does the debris travel in mechanical equilibrium with water as it is supposed in most of the codes? This obviously depends of the size of the debris and of their initial velocity.

4. Discuss the role and importance of triggering (trigger availability and triggerability) in addressing the α -mode failure issue. Discuss the role of pressure threshold in suppressing the triggering

I think that this problem is the one which is the less well understood. We have also to keep in min the stochastic nature of such an event. While performing similar experiments, you may or may not have a spontaneous interaction, or the triggering location may be variable (at melt//water contact, at melt/bottom contact, or at any place in the mixture due to random processes). For reactor applications, we are only looking for natural triggers which may consist in entrapment of water between melt and structures or within the melt itself. Other natural triggers may result from small pressure waves produced when the melt contact a structure or when a large mass will fall from the still degrading core into a suitable premixture.

Always for reactor applications, it is generally admitted that there will be a stable vapour film around the melt droplets and that there is a need of an initiating pressure pulse to destabilize this film in order to induce some fine fragmentation. As for the fragmentation process itself, there is no definite explanation (see question 3 the point about single drop experiment interpretation) neither for the amount and size of fragments nor for the subsequent heat transfer to coolant.

To summarize our knowledge, I would say that:

- it will be very difficult (even impossible) to determine where a S.E. explosion will be triggered : stochastic nature (trigger availability)

- for the triggerability of a mixture :

  - there is a mass effect: we cannot get an explosion with a steel droplet while we get one with kilogram masses of steel. Another example was obtained in the EXO FITS program where there seems to be a threshold of 4 kg below which no spontaneous explosion was obtained for a corium melt

  - there is an effect of water subcooling: it is easier to trigger a mixture with subcooled water (EXO FITS, KROTOS with alumina at 2300°C where spontaneous explosions are observed in the 2 tests with water at 20°C while there is a need of external trigger with water at 80°C, ...) but SE can be triggered (if any natural trigger can be obtained) even with water at saturation.

  - there is an effect of melt superheat which is probably due to partial freezing during the mixing phase. This may be the reason why in the KROTOS facility using a UO_2-ZrO_2 mixture, no explosions are observed even with external trigger similar to the ones used with Al_2O_3.

    The observations of spontaneous S.E. in the SUW facility using a UO_2-MO mixture may be explained by a higher melt superheat (3300°C) or by the presence of a metallic phase.

    We must then note that when a shock wave is produced, it is then possible to fragment a droplet which is partially solidified. So in a reactor case, if the melt which is just entering the water pool is able to trigger a S.E., the resulting pressure wave may be able to fragment the melt which penetrated before and which may have a solidified crust.

  - there is an effect of ambient pressure which may be associated with the resistance of the vapour film to its destabilization by a pressure wave. This has been observed in many experiments (FITS, SUW, ALPHA, ...) where it is more difficult to trigger an explosion at high pressure. For a reactor application, the question is then to estimate if we may have a natural trigger of sufficient energy to collapse the vapour film. This will give the answer to the pressure threshold issue. (we must recall that one of the UK HTPR test a S.E. was observed at 58 bar but the cause of this S.E. was the injection of a cold water slug into the premixture: system effect?)

In the small-scale FITS program, with iron oxide it also appears that it was easier to trigger an explosion when the pressure was between 2 and 8 bars instead of 1 bar. Up to now, we have not found an explanation for this observation and it would be interesting to know this easier triggering pressure range for actual corium (existence and pressure range).

We must also recall that, once triggered, a S.E. at high ambient pressure is more energetic that at low ambient pressure: the volume occupied by steam is reduced allowing more heat exchange between melt and liquid water. It also appears that the mass of melt participating to a S.E. increases with ambient pressure. This was clearly observed in the UK SUW tests as seen in the following table:

n° test	M_{tot} (kg)	V_G (l)	Structure	P_∞ (bar)	ΔT sus (oC)	Nb of SE	fraction of melt involved	Mechanical energy (MJ)
05	24	252	YES	1	61	2	0,13	0,162
08	-	259	-	5	60	1	0,482	0,521
09	-	260	-	10	60	1	0,75	0,884

In this program, it was also observed that the explosion was more coherent at high ambient pressure: only one explosion occurred instead of 2 or 3 at 1 bar.

This is probably due to the fact that the melt is less dispersed at high ambient pressure (constraint effect).

Another effect which has been observed in the single drop experiments of Nelson is that the maximum pressure peak increases with ambient pressure whatever is the trigger pressure, as does the mechanical work done during the resulting bubble.

- There are evidences that if the melt is predispersed, it is more difficult to trigger an explosion. This predispersion is generally produced by the use of a grid to prefragment the pour and such a device has been used in MIXA and ALPHA tests. In all the MIXA tests and in all, but one, the ALPHA tests no spontaneous explosions were observed. But in the ALPHA test STX 019, the predispersion device was probably the cause of the most energetic explosion observed in the series (in that case the promotion of the prefragmentation takes over the water depletion effect) while in STX 020, in similar conditions, no spontaneous explosion was observed.

5. Discuss the role and importance of accident progression and melt relocation in addressing the α -mode failure issue.

As the premixture configuration - which is important for the development of a SE - depends on the way the melt is poured into water - the late phase of core degradation (accident progression and melt relocation) is of importance for determining the consequences of a SE, including the α mode failure issue.

The sensitivity of these pouring conditions of these pouring conditions can be illustrated by 2 recalculations of the premixing FARO QT2 test with MC3D. In these calculations, we started with an initial jet of 1 cm droplets and according to the whole jet diameter (10 or 20 cm) we were able or not to reproduce the experimental pressure evolution. Our explanation is that, with the larger diameter, we involve more water in the film boiling configuration where the steaming rates are higher so we get a higher pressure in the vessel.

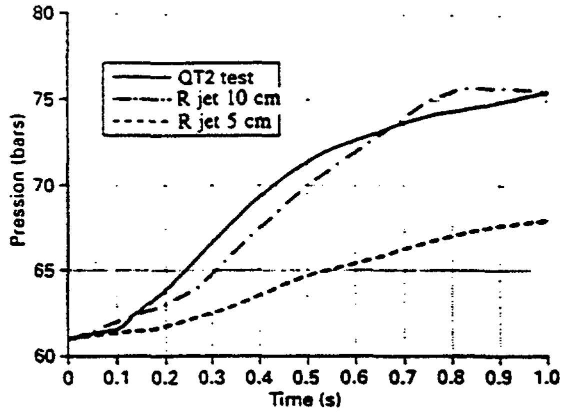
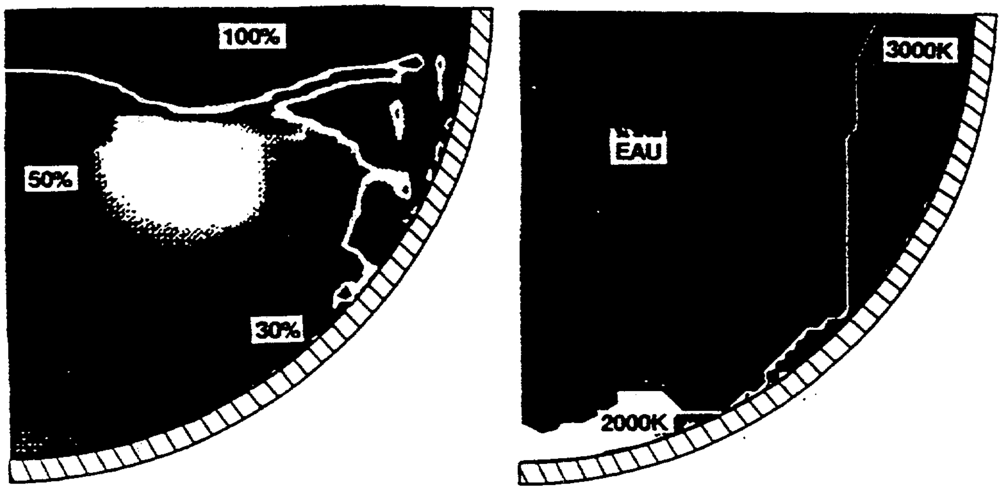


Fig. 5. FARO QT2 calculation: influence of jet diameter at melt water contact.

In France, the codes VULCAIN and ICARE are dealing with this late phase of core degradation: how the molten pool surrounded by a crust will be delivered to the water of the lower head. As their development has not reach a sufficient level, we cannot have calculated behaviours of such pools: ie where and how the crust will fail? Will it be sideways by the by-pass like in TMI2 or by failure of the crust at the bottom of the pool? This will influence the pour rate (pour area, velocity of melt) and the melt superheat which may be high if the crust fails by natural convection close to the top of the pool.

It seems obvious (expert judgement) that, in order to get a large scale efficient Steam-Explosion, it is preferable to deliver the melt all over the pool under the form of about 10 cm jets than to have a sideways flow. This corresponds to the scenario where the crust will fail at the bottom of a melt pool with a not too large superheat (unfavourable for efficient S.E.).

An 2D example of a MC3D calculation of sideways flow is presented on the following figure showing that the size of the premixing is limited to the region close to the R.P.V. With such a mixture it is rather impossible to get a SE which can produce a slug of sufficient energy to fail the upper head. It may be easier to rupture the lower head according to some PLEXUS calculations already mentioned at point 1.



Présence de vapeur d'eau

Température du corium

Simulation avec le logiciel MC3D d'une coulée latérale de corium dans le fond de cuve d'un réacteur à eau pressurisée

For actual reactor cases, the effect of internal structures will have to be assessed. These structures may have 2 effects: they may trigger a SE as the melt contacts them and they certainly help in fragmenting the melt pours. Nethertheless, they will certainly reduce the likelihood of the α mode failure.

6. Discuss the role and consequence of mechanical energy release and damage-producing events in the context of the α -mode failure

These points have not yet been addressed in France in the context of the α mode failure. As already mentioned in 1, only screening calculations with PLEXUS have been performed to study the behaviour of the lower head.

At the present time, as the models for late phase of core degradation and for SE are not yet sufficiently validated, we have not performed calculations for slug expulsion but it is possible to perform such calculations in a parametric manner with a given slug composition and a given energy delivery law.

7. In your opinion, is our current knowledge of premixing and propagation phenomena adequate for a better quantification of the α -mode failure? Based on your own knowledge, are you now able to assign a better probability (likelihood) measure to this failure mode?

(a) If yes, provide your estimate(s) and the basis for it. (Note: the plural is for distinguishing among various severe accident classes if you wish).

(b) If no, do you think it is reasonable to expect that this will be possible sometime in the future? Provide your reasoning and indicate what key developments will be needed to meet the expectation.

As it has already been mentioned in points 2 and 3, I think that the ensemble of constitutive laws used in premixing and propagation codes is not sufficiently validated to allow us to quantify the probability of α mode containment failure. However, we think that we really need these "sufficiently" validated integral models of SE (premixing and propagation) if we really want to give probabilities for the α-mode failure. In fact, we think that the "step by step" method adopted by Theofanous et al and Turland et al should be considered as a first "simple" approach. To explain the word "simple" I can give an example: to characterize the pour by <u>one</u> variable: the pour area (with a probability density function) to evaluate the mass of melt in the premixture (<u>one</u> characteristic variable) is difficult in that sense that a lot of other characteristics variables are not taken properly into account. The way to include these other variables in the estimation is to use validated codes to describe all the sequences involved: melt relocation, premixing, triggering, propagation. In fact, as I already mentioned, there is no validated way of determining the mass of the melt in the premixture that will participate to the SE: all the melt will more or less participate. It is also very difficult for me to quantify the conversion ratio for a reactor situation. I already said that the efficiency is the response of a system to a SE and that the extrapolation from an experiment to a reactor situation can only be done by the use of a code.

To get these "sufficiently" validated codes requires their assessment against well instrumented experiments. For example, we cannot say that MC3D is validated for premixing because we have been able to reproduce the pressure traces of three different FARO experiments (all the other premixing codes have done so even with their differences as mentioned in point 2: see fig. 2). To be able to say so, it would be necessary to know the state of the melt when it enters the water (this is not the case for this experiment). Is it in the form of droplets as all the premixing codes assumes up to now? If yes, what is the characteristic size of these droplets and their volumetric concentrations? If no, is it conservative to assume that the melt is in the form of droplets instead of fragmenting jets i.e. does the overestimated water depletion effect takes over the overestimation of the fragmented mass? Obviously the answer to this question may only be obtained by calculations with validated codes.

Finally, I think that the foreseen experiment BERDA at FZK in which a well characterized slug will be expulsed through structures towards the upper head of a vessel will allow us to validate fluid-structures interaction codes like PLEXUS in their estimation of the slug energy at impact. For a reactor situations, even with validated SE models we have to know the state of the upper structures which will be obtained from Core Degradation Codes.

8. Discuss the status and capabilities of the analytical tools/computer codes available to address various components of the FCI methodology (e.g.;, tools to estimate premixture) or to perform integral FCI assessments. How much verification have these analytical tools had? Are there well defined experiments against which a number of these tools can be assessed? Provide your recommendations regarding the need to perform a "standard" problem, preferably one in conjunction with an integral evaluation.

These last years a lot of effort has been undertaken in developing and validating premixing codes and more recently, multidimensional propagation codes. In the past, one dimensional propagation codes were developped (CULDESAC at AEA and IDEMO at IKE Stuttgart) but, to deal with reactor calculations, at least 2D codes are necessary like ESPROSE and IFCI in order to properly take into account the effect of the surroundings (the constraint). In a multidimensional FCI code, this constraint will not be uniform, there will be a "weak" point through which the pressure will be **preferentially** released.

The numerous constitutive laws for fragmentation, drag, heat transfer, ... are extracted from experiments which were far to be in the necessary range to allow us to use them with great confidence for reactor calculations. For example:

- fragmentation laws are derived from experiments which were mainly using liquid-gas systems in isothermal conditions (some were using liquid-liquid systems). Just recently experiments using single tin drop at about 1000 K (SIGMA at U. of Santa Barbara and an experiment at IKE Stuttgart) were or are to be performed. But what about a cloud of UO_2-ZrO_2 droplets?

- drag laws are derived from experiments using mainly drop or bubble at their terminal velocity and in isothermal conditions.

- the film boiling heat transfer laws used in the premixing codes are validated up to 1000 K.

- heat transfer between debris and coolant is for from being established.

So in CULDESAC for example, a given heat transfer coefficient is provided by the user.

At present, mostly in EEC, an ensemble of more or less analytical experiments is underway to allow a better qualification of these constitutive laws for premixing. Experiments using hot solid spheres are and will be performed up to 2500°K (BILLEAU in CEA, QUEOS at FZK and MAGICO at U. of Santa Barbara). The use of 2D plane geometry will allow local measurements of steam and spheres volumetric concentrations and we then expect to validate heat transfer and drag laws in three phase systems. The cooling of a hot sphere (2500°K) will be studied in the QUEOS facility and this will allow us to establish the film boiling heat transfer at high temperature. The study of the behaviour of an initially well characterized two phase flow through an array of hot spheres at the Oxford University will also allow us to study constitutive laws in three phase systems. Hot jet fragmentation experiments are performed at IKE Stuttgart and are planned at CEA in order to validate the jet fragmentation models.

For propagation, analytical fragmentation experiments of single hot droplet are or are to be performed (SIGMA, IKE). At IKE it is planned to study the transition from thermal to hydrodynamic fragmentation.

When more credible constitutive laws will be derived from this program and applied to integral experiments using prototypical materials, we will have the "sufficiently" validated codes I mentionned earlier.

As for these integral experiments using prototypical materials, there are not numerous. Up to now, only the FARO and KROTOS experiments performed at JRC Ispra may be used but, in my view, they are not sufficient due to a lack of measurements. For example, in FARO, we need to have an estimation of the way the melt enters the water to better assess our premixing codes. For the validation of the propagation codes, the KROTOS facility does not allow us to know the state of the premixture when the SE is triggered. We have to rely on premixing calculations so, as for as the premixing codes are not qualified, we cannot trust the propagation calculation results so it is difficult to validate the propagation codes. To overcome this difficulty it would be necessary to have measurements in KROTOS or to build an experiment in which the premixture will be well characterized.

To qualify the premixing codes, we also have the MIXA experiments using UO_2-Mo mixture at P AEA and the PREMIX experiment using Al_2O_3 at FZK. These experiments can also be called integral due to the absence of local measurements.

To perform a "standart problem" is always useful for benchmarcking codes, and this task in underway within the MFCI group of EEC where all the different experiments mentioned above are used by the different codes and discussed during meetings. To perform a blind calculation of a foreseen experiment (it was done for the PREMIX test) is also not very useful because, most of the time, the experiment is performed in conditions which are different from the foreseen ones.

Nethertheless, I think that a well defined standart problem will be useful because it will allow us to identify where our codes are different. Then we will have to test these differences against experimental results where these differences are supposed to be of importance in order to make some choice between the models.

9. How much of the research performed (both experimental and analytical) in support of the α - mode failure issue is also applicable to "localized" FCIs (e.g., an energetic FCI next to a structural boundary where there is a need to evaluate the dynamic loading on the structure)?

As the performed research is done in order the validate the different models necessary for describing the whole sequence of a SE, all the work done can be used to study the probability of occurrence of any consequences of a SE.

But, it exists some configurations which are not expected to be involved in a SE leading to α-mode failure of the containment. As example, lets mention the SE explosion which can occur while flooding a degraded core (there is no strong enough slug in that case) or the SE which can occur in stratified geometry if any melt reach the reactor cavity.

10. Discuss the possibility and importance of chemical augmentation to energetic FCIs. Discuss the impact of chemical augmentation on the dynamic loading of structures.

To answer this question, we have to estimate if the chemical reaction will significantly modify one or some of the phenomena involved in the whole sequence of an FCI. There is obviously the problem of chemical energy release which has not jet received an answer, especially in the fragmentation propagation expansion phases of a SE.

For premixing, it seems that the presence of some around of Zr (5 kg) in the FARO L11 test (~ 150 kg melt) is responsible for the different behaviour than the one observed in FARO L14 performed in quasi-similar conditions but without Zr.

In L14 (without Zr) from the TC located just below the free surface, it was observed that the jet was less dispersed during its fall in the vapour. Confirmation of this observation is also obtained with the lower pressure increase in the vapour space during the fall in the vapour.

As for the melt penetration velocity, it appears from the curves penetration velocity vs time that the jet was probably completely fragmented at 600 mm from the bottom in L11 (with Zr) as opposite to L14 results which showed a constant penetration velocity (no change in the slope).

This is also consistent with the observation of a cake (1/6 of the total melt) in L14.

If then seems that the presence of Zr (i.e. chemical reaction) was responsible of an increased (complete) fragmentation of the jet (but we have to be cautious, there is only one experimental result). This observation is consistent with our physics of jet fragmentation in which the effect of gas temperature at jet-gas interface is important (viscosity increases with temperature). In the case of chemical reaction, this temperature will be higher, so the fragmentation will be larger but we are not yet able to reproduce these tests.

If this observation is confirmed, we can conclude that the presence of a chemical reaction will increase the amount of melt jet that will be transformed into droplets so that can participate to a SE.

If this is confirmed - for the same reasons - the fine fragmentation will be increased so that the consequences of the SE will be higher. But we will also have a counter effect: the presence of a non condensable gas will augment the difficulty to trigger a SE (the vapour film will be more stable) and may reduce the HT between debris and coolant in the case of a SE occurrence.

Once again, to answer this question, we need to take into these phenomena in our codes.

APPENDIX B-3

SERG-2 PANEL MEMBER RESPONSE
BY
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RESPONSES TO QUESTIONS AND ISSUES
FOR THE SERG-2 WORKSHOP

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1. Status of the α-mode Containment Failure Issue

I believe the issue has largely been resolved from a risk standpoint. The following two papers presented at a recent CSNI Specialists meeting are relevant in this regard.

- B. D. Turland et al., "Quantification of the Probability of Containment Failure Caused by an In-Vessel Steam Explosion for the Sizewell B PWR," Proceedings of the CSNI Specialists Meeting on Fuel-Coolant Interactions, Santa Barbara, CA, January 5-8, 1993, NUREG/CP-0127, pp. 309-321.

- T. G. Theofanous and W. W. Yuen, "The Probability of Alpha-mode Containment Failure Updated," ibid., pp. 330-342.

To fully resolve the issue, however, additional confirmatory research would be needed, in particular, in the following two areas:

- Limits to mixing at ambient pressures of 0.2-0.4 MPa

A number of experiments as well as modeling analyses have been conducted to support arguments for limited premixing of corium melt and water due to water depletion in the mixing zone. It appears that all these experiments and analyses were performed for the ambient pressure of 0.1 MPa (atmospheric pressure). In typical low-pressure scenarios such as large-break LOCAs, the containment back pressure would most likely be in the range of 0.2-0.4 MPa. No experimental data or analytical work seems to be available to support "limits-to-mixing" arguments for this range of ambient pressures. The water depletion phenomenon might be influenced by the much higher steam densities at these ambient pressures compared to the case of 0.1 MPa. It is important to establish that the experimental and analytical results obtained for 0.1 MPa are still valid for somewhat higher ambient pressures such as 0.2-0.4 MPa. I think this objective can be achieved by conducting limited experiments as well as modeling analyses over a time frame of two years.

- Suppression of Triggering at Elevated Ambient Pressure

The Sizewell B assessment by Turland et al. was the first to consider the effects of elevated pressures (6 MPa and 15 MPa) in a systematic manner. The results of this assessment suggest only a modest sensitivity to system pressure. This appears to be the net outcome of the increased energetics and other factors (which would tend to increase the α-mode failure probability) being canceled by the low probabilities of triggering at elevated pressures. Clearly, it would be important to establish the low probability of triggering at high pressure. As recently discussed by Fletcher ("A Review of the Available Information on the Triggering Stage of a Steam Explosion," Nuclear Safety, Vol. 35, No. 1, 1994, pp. 36-57), available data seem inadequate. A systematic study of the effect of pressure on triggering is needed. This objective may be achieved by conducting experiments of a generic nature over a time frame of 2-3 years.

2. Role and Status of Premixing

Premixing is important, since it would determine the mass of corium melt that could be efficiently mixed with water in the lower plenum. Because the probability of triggering is high at low pressure, the role of premixing would probably be more important for low-pressure scenarios than for high-pressure scenarios in addressing the α-mode containment failure issue.

As discussed in Item 1, it appears that available data and analytical work are limited to the system pressure of 0.1 MPa. In addition, many of the experiments and modeling analyses to date were performed for prefragmented melt drops pouring into a pool of water. Thus, the sizes of melt drops are well defined prior to premixing. In fact, a number of experiments employed heated solid spheres being poured into water. In reality, however, melt streams of various sizes would be draining into the lower plenum. These melt streams would undergo breakup as they move through the water. Available data on the melt stream breakup and premixing are largely global in nature (e.g., the overall steam production rate) and the relevant modeling work is relatively limited.

3. Role and Status of Propagation

Assessment of the α-mode failure issue depends primarily on the slug energy, which is an integral quantity (pressure integrated over expansion volume), rather than details of pressure distributions in the interaction zone. Thus, the role of propagation in addressing the α-mode failure issue would be relatively minor except for assessing the lower head failure.

However, a better understanding of aspects of propagation in voided mixtures will aid in refining "limits-to-mixing" arguments.

The current status of propagation is probably adequate for the purpose of addressing the overall issue of α-mode failure. However, an adequate assessment of the lower head failure issue would require a 2-D or even 3-D treatment of pressure propagations in the interaction zone.

4. Role and Importance of Triggering (Trigger Availability and Triggerability)

There are a number of mechanisms that could potentially serve as triggers for in-vessel melt/water interactions. These mechanisms generally involve pressure or flow disturbances in the mixing zone. Examples are as follows:

- Mechanical impact caused by control/scram rod dropping, falling objects, collapsing structure, etc.;

- Bubble/void collapse due to condensation following cold water injection;

- Water hammer induced by sudden valve closure;

- Pressure and/or flow disturbances due to pump pulsations and cavitation;

- Pressure disturbances and flow turbulence associated with boiling during mixing of melt and coolant; and

- The not-so-well-understood effects of surfaces (e.g., base triggering).

The question is whether any one of these potential triggers could be effective in bringing about a large-scale explosion. This is the issue of triggerability.

Assuming that the potential triggers are available in accident situations, the triggerability is expected to be relatively high for low-pressure scenarios (say, less than 1 MPa). For high-pressure scenarios (say, 10 MPa or greater), the triggerability is considered to be extremely low (perhaps almost zero?), although few supporting data currently exist.

As already discussed in Item 1, it is important to demonstrate that the triggerability is very low when addressing the α-mode failure issue for high-pressure scenarios. The triggerability may be considered practically zero, if no explosions should occur when corium melt-water mixtures are subjected to those triggers that are potentially available in accident situations (some examples were given above). Such zero triggerability may become a reality above a certain pressure level ("pressure threshold"). If this pressure threshold could be established experimentally, it would be possible to simply rule out the α-mode failure for all accident scenarios at pressures above the threshold level.

5. Role and Importance of Accident Progression and Melt Relocation

Undoubtedly, accident progression and melt relocation scenarios are very important, since they define the initial conditions for melt-water interactions. However, it seems difficult to quantify the effects of accident progression and melt relocation in assessing the α-mode failure probability. Moreover, the accident progression and melt relocation scenarios would likely depend on the specific design of a reactor.

6. Role and Consequence of Mechanical Energy Release and Damage-Producing Events

Obviously, mechanical energy release and damage-producing events play an important role in the context of the α-mode failure. After all, it is the missile from the reactor upper head that threatens the integrity of the containment. The process of missile generation needs to be carefully evaluated. I believe that recent assessments (e.g., two references cited in Item 1) have done a credible job on this particular subissue. Also, a significant effort to evaluate the slug/structure interaction is currently being made at KfK, Germany (R. Kreig et al., "Experiments on Slug Impact Loading of the Reactor Vessel Head During a Postulated Steam Explosion," Kerntechnik, Vol. 59, No. 4-5, 1994, pp. 178-184). This effort is expected to lead to a better understanding of the slug impact loading process.

7. Better Quantification of the α-mode Failure

- Some improvements are needed in our knowledge of premixing for ambient pressures of 0.2-0.4 MPa, as discussed in Items 1 and 2.

- Our current knowledge of propagation is probably adequate for the purpose of a assigning an overall probability measure to the α-mode failure.

- For low-pressure scenarios, particularly for the ambient pressure of 0.1 MPa, existing assessments such as provided in the two references cited in Item 1, appear to be reasonable and adequate.

- For high-pressure scenarios, our knowledge of triggering needs to be improved to fully support existing assessments.

8. Status and Capabilities of Analytical Tools/Computer Codes

- Premixing

Those premixing models which consider prefragmented melt drops pouring into water have been assessed against well-defined experiments (e.g., heated steel balls into water) at 0.1 MPa. No experimental data appear to be available for higher pressures.

Those premixing models which consider melt breakups in water have been assessed against experiments in terms of a global property such as the overall steam production rate. No data on local properties (e.g., the melt and void fractions) seem available.

- Propagation

Comparisons of the available analytical tools/computer codes against experiments are very limited. These analytical tools have had little verification, if any. There is a strong need for assessing the analytical tools and codes against well-defined experimental data.

- Triggering

No analytical tools exist to address this particular subissue.

- Slug Energy Transmission and Coupling to Structure

The analytical tools available to address this subissue are considered adequate. Significant components of the tools are believed to have been verified. The ongoing effort at KfK, Germany, as mentioned in Item 6, is expected to provide significant database for assessment of the analytical tools and codes.

- <u>Integral Assessment</u>

  I am not sure whether there are any complete analytical tools/codes available to perform integral FCI assessments.

- <u>Need for a "Standard" Problem</u>

  There is no need to perform a "standard" problem in conjunction with an integral evaluation of the α-mode failure issue.

  I might, however, recommend performing a well-defined "standard" problem in conjunction with an evaluation of pressure loading on the vessel lower head or on the reactor cavity walls.

9. <u>Applicability of Research to Localized FCI's</u>

I believe most of the research performed in support of the α-mode failure issue is also applicable to "localized" FCI's such as those which might cause dynamic pressure loads on structure. The possible exception would be the work done on the slug impact process.

I wish to note that 2-D propagation modeling is essential for an adequate assessment of FCI pressure loading on a structural boundary (e.g., the reactor lower head and ex-vessel cavity walls).

10. <u>Chemical Augmentation to FCI Energetics</u>

The possibility of chemical augmentation to the FCI energetics would exist whenever a significant amount of unreacted Zircaloy is contained in core melt. Obviously, its importance would depend on the extent of Zircaloy oxidation prior to core melt and, perhaps, on the amounts of oxygen dissolved in Zircaloy as well (e.g., α-Zr). According to our current knowledge of melt progression scenarios, the presence of a significant amount of unreacted Zircaloy in core melt appears to be a distinct possibility, particularly for BWR's.

The importance of chemical augmentation to the FCI energetics may be illustrated by comparing the stored thermal energy with the heat of Zr/water chemical reaction. At 2000°C, the stored thermal energy per gram of Zircaloy melt is 0.94 kJ, while the heat of reaction per gram of zirconium is 6.4 kJ. Clearly, the potential chemical energy is much greater than the stored thermal energy. If this chemical energy could be released during FCIs, the energetics might be strongly augmented by the chemical reaction.

Increased energetics due to chemical augmentation would definitely have an impact on the dynamic loading of structures. More important, however, is the possibility of chemical augmentation influencing the characteristics of pressure loads such as the peak pressure and impulse. At present, no data are available to discuss this possibility.

APPENDIX B-4
SERG-2 PANEL MEMBER RESPONSE
BY
DR. MICHAEL CORRADINI
UNIVERSITY OF WISCONSIN

<u>Questions and Issues for the SERG-2 Workshop</u>

1. **In your opinion, what is the status of our understanding of the α-mode containment failure issue for the LWRs? Is it, in your opinion, resolved, i.e., of little or no risk significance?**

   (a) If yes, cite the relevant references

   (b) If essentially resolved, what additional confirmatory research is required, in your opinion, to fully resolve the issue?

   (c) If not resolved, i.e., if the residual uncertainties still remain large and/or if there are still unanswered questions about the α-mode failure, discuss specific additional research that will be needed to answer the questions and to address the uncertainties. Discuss the approach to research areas thus identified, potential benefits to be derived from the research, and indicate the time frame for accomplishing the research objectives.

My current opinion on the likelihood of α–mode failure has not changed substantially since the first SERG meeting; i.e., the probability of α-mode failure given a core melt is much less than first estimated by WASH-1400 (upper bound $<10^{-2}$/yr) and the actual probability estimate is more an expression of our lack of confidence in the actual outcome than an expression of any actual stochastic processes. This estimate is probably lower for the BWR than a PWR since the physical geometry is not as conducive to allow such an energetic event. The attached paper discusses this in some detail in the Introduction with References given.

Given this opinion, the next question (which was asked) can be: "Is the α-mode failure of low enough probability to consider it a resolved safety issue?" My answer to this question is that it is essentially resolved from an engineering judgment standpoint, but not necessarily from a basic physics standpoint. My judgment that α–mode failure is of low probability is based on the belief that certain physical processes will behave in certain ways:

(a) Fuel-coolant mixing with corium and water will naturally result in a mixture which has a large void fraction with limited amounts of corium fuel mixed with liquid coolant; i.e., $V_f/V_c << 1$ with V_v/V_c ~1.

(b) That under these mixture conditions an explosion is possible but will be relatively weak in energetics and not capable of generating a solid missile to threaten containment.

However, there is still not conclusive physical evidence that these (or any) opinions are valid over many such accident conditions. Thus, it is prudent to continue confirmatory research on fuel-coolant interactions in 'mixing' and 'energetics' and the scaling of these phenomena to gain further insight into these processes and thus increase our confidence in our opinions.

It is also crucial to point out that for the ALWR the safety importance goes beyond α–mode failure toward how the FCI may challenge in-vessel or ex-vessel debris coolability, by either dynamic pressures threatening the vessel or cavity boundary integrity or by creating fine debris that will not be coolable. Both of these important issues are discussed in the attached paper, and are directly related to the need for selected continued work.

2. Discuss the role and status of premixing in addressing the α–mode failure issue.

Mixing is the most crucial phase of the FCI because it establishes the pre-conditions to the explosion propagation and thus has one of the strongest influences on the explosion energetics. Because of this the void fraction profile within the fuel-coolant mixture is probably the important quantity to know at any given time with the fuel mixing diameter as the other important variable.

The status of our understanding of the mixing phase is not good, although initial 'separate-effects' experiments (MIXA, MAGICO and now BILLEAU) give us a reasonable picture of processes for hot solid particles dropped into a liquid. If one compares fuel-coolant mixing to the mixing process studied in diesel engine spray breakup, our current experimental knowledge is integral in quantitative terms with some qualitative understanding of the details of the process. Thus, better experimental understanding of mixing process with molten fuel injected into a coolant is needed. I have discussed this in detail in a CSNI paper with Dr. H. Hohmann and this is referenced in the attached paper.

3. Discuss the role and status of propagation in addressing the α–mode failure issue.

The explosion propagation phase is the heart of the vapor explosion process, because it allows the fuel to rapidly give up its energy to the coolant in such a manner to 'explosively' generate high pressure vapor. However, because it is preceded by the mixing phase it is strongly affected by it. Thus, it is my view that one can experimentally explore the energetics of the FCI with associated analysis to actually gain insight into the fuel-coolant mixing phase and to understand how both mixing and the energetics may scale. For example, one can examine the energetics from the explosion and associated propagation characteristics [peak pressure, quasi-steady plateau pressures, and propagation velocities] and possibly deduce the initial conditions which pre-exist prior to the explosion propagation. This is the major focus of the attached paper.

4. Discuss the role and importance of triggering (trigger availability and triggerability) in addressing the α–mode failure issue. Discuss the role of pressure threshold in suppressing the triggering.

The triggering of the FCI from a safety perspective has been one of the most researched topics in industrial processes. Thus, I do not feel it alone warrants more effort at this time. The effect of high ambient pressure is empirically known to suppress the trigger quite reliable. However, past Sandia and Ispra tests both clearly indicate a stronger trigger can again induce an energetic FCI, where one did not trigger spontaneously or with a lower trigger threshold. Thus, it is really a question of what are realistic trigger sources during the accident.

5. Discuss the role and importance of accident progression and melt relocation in addressing the α–mode failure issue.

The accident progression and melt relocation sequence is a strong determinant of the melt and coolant composition and temperature. It may also affect the melt jet relocation geometry, although this may be the only stochastic part of the process. Thus, one may have to parameterize this jet release process over a reasonable range of conditions to examine the effect of the jet entry on the subsequent FCI.

6. Discuss the role and consequence of mechanical energy release and damage-producing events in the context of the α–mode failure.

This has been adequately address in our work in 1980 and 81 as well as the later work by Theofanous in 1987 (see attached paper references). There is no need to repeat that here and references are given in the attached paper.

7. In your opinion, is our current knowledge of premixing and propagation phenomena adequate for a better quantification off the α–mode failure? Based on your own knowledge, are you now able to assign a better probability (likelihood) measure to this failure mode?

(a) If yes, provide your estimate(s) and the basis for it. (<u>Note</u>: The plural is for distinguishing among various severe accident classes if you wish.)

(b) If no, do you think it is reasonable to expect that this will be possible sometime in the future? Provide your reasoning and indicate what key developments will be needed to meet the expectation.

I have already answered some of these point previously, so I will focus on the needed confirmatory research on mixing and propagation/energetics to establish a better understanding of the physics and thus increase our confidence in the opinions concerning α–mode containment failure (as well as in-vessel and ex-vessel structural integrity and coolability).

Mixing

The previous 'separate-effects' mixing experiments (MIXA, MAGICO and now BILLEAU) clearly demonstrated the 'water-depletion' concept within an array of hot discrete spheres quenching in water, but I do not feel that gives one a complete or adequate picture of fuel-coolant mixing for actual molten fuel jet transient breakup. However, to get a better picture under appropriate conditions one must be able to determine the quantitative local void fraction profile (and fuel mixing size) over some sizable area of the fuel-coolant mixture; i.e., not just local regions which require multiple experiments and ensemble averaging of possibly not repeatable data. This implies that advanced instrumentation that needs to be developed to determine the void fraction and/or fuel mixture size. We have begun this approach at UW, but this requires a long term effort.

Another possibility is to approach the concept of mixing by observing it effects through the explosion propagation and energetics. This is specifically the approach we have used in analyzing our own WFCI experiments and the KROTOS experiments. In both cases we have used a quasi-steady thermodynamic approach to analyze the energetics and deduce the mixing conditions that lead to the observed explosion propagation; e.g., see the papers at NURETH-6 and PISA conferences. In fact the analysis of these tests by TEXAS is just an extension of this process using a transient FCI model. In both cases one uses such a tool to investigate how the explosion process is affected by the mixing condition just prior to triggering and how mixing may be altered by the experimental initial and boundary conditions. This approach is explained in more detail in the attached paper.

Propagation-Energetics

Given our previous statements on mixing and experiments related to the explosion propagation and energetics, the necessary research in this area should address scaling of the FCI experiments to verify that the interpretation of the data has the proper relationship to the prototypic reactor accident conditions. The attached paper is a first step to directly address this point. Past α–mode failure analyses assumed thermodynamic bounding energetics. If we are to do better we must address the question explosion scaling; i.e., not only in geometric sense but also the fuel composition effects.

An additional area of research into the physics of the FCI is the detailed mechanisms of fuel fragmentation. The experiments by many investigators has given insight into this topic (most recently separate papers by Frost and Theofanous at NURETH-5). However, this may be the most difficult and elusive piece of FCI physics and may not be directly needed for safety issues in the near future. I would only favor such research purely out of academic interest.

The final area of energetics related research involves the 'localized' effects of the FCI; i.e., dynamic pressures. This is probably the most important area for the ALWR and I would support quite strongly the KROTOS and FARO efforts with some simulant experimental support to directly address these points. In this area the unique behavior of the corium fuel must be also be addressed. This is again discussed in the paper.

8. Discuss the status and capabilities of the analytical tools/computer codes available to address various components of the FCI methodology (e.g., tools to estimate premixture) or to perfo:m integral FCI assessments. How much verification have these analytical ιools had? Are there well defines experiments against which a number of these tools can be assessed? Provide your recommendations regarding the need to perform a "standard" problem, preferably one in conjunction with an integral evaluation.

The attached table of mixing and explosion models is given to summarize the status and capabilities of each one. One general comment to make is that all of the models are sophisticated enough in their physics relative to the experiments they have been applied to, simply because the physical picture is not complete at this time.

Thus, this indicates better experimental data is needed to help us understand the FCI process, not more FCI code development. The best indication of this point is that FCI models can 'predict' the data by matching specific integral FCI data of a past test, but all have great difficulty in predicting the next experiment quantitatively. Part of this difficulty is that experimental initial and boundary conditions are quite difficult to control and part of the difficulty is that important aspects of the FCI models are semi-empirical with some 'tuning' being continually needed.

I would recommend that future FCI model assessment focus on well-controlled experiments. For investigation of heat transfer during mixing in the absence fuel fragmentation, the BILLEAU tests are recommended since they are on-going, and have two separate and distinct methods of measuring the spatial void profile at a particular time. For fuel quenching and mixing tests under prototypic conditions I would focus on the FARO-LWR tests. Finally, for fuel-coolant mixing and energetics tests I would favor 1-D experiments such as KROTOS, WFCI and ZREX. These set of experiments are specifically chosen since they have evolved from past scoping and threshold experiments in which not all the pertinent parameters have been measured. The approach for analysis of such tests are discussed in the attached paper.

9. How much of the research performed (both experimental and analytical) in support of the α-mode failure issue is also applicable to 'localized' FCIs (e.g., an energetic FCI next to a structural boundary where there is a need to evaluate the dynamic loading on the structure)?

It is my view that very little previous FCI research is applicable to the 'localized' effects of the FCI, since the proper instrumentation was not available for these tests or the data was not successfully gathered. Thus, it is most crucial to the in-vessel or ex-vessel structural integrity issues (or associated debris coolability). To address this issue the experimental apparatus must be of large enough scale to measure 'far-field' explosion effects. The modifications planned for the FARO-LWR experiment will probably best address this issue. One reason is that the apparatus may be of large enough radial size to distinguish between near and far field effects. Another reason is that the corium fuel and its FCI behavior is unique. Thus, we must have at least a limited data base with this fuel type and FARO-LWR is the only facility equipped for this under prototypic conditions.

10. Discuss the possibility and importance of chemical augmentation to energetic FCIs. Discuss the impact of chemical augmentation on the dynamic loading of structures.

For actual severe accident conditions I do not feel that chemical augmentation of the FCI will be significant, primarily because the metallic melt fraction will be small. In addition, our experiments with a metal clad fuel (cermet and uranium-silicide fuels mixed with aluminum clad material) show little chemical augmentation. Granted these are not LWR fuels, but zirconium is enough in thermodynamic behavior that if this avenue is studied, it will confirm such a judgement and yield no big surprises for prototypic fuel compositions.

I think this topic is potentially quite interesting from a physics perspective, but we must be very careful to not directly judge its reactor safety importance from pure metal-water FCI tests. The reason for this point is that again with the aluminum-cermet or aluminum-silicide tests a less than majority fraction of non-reactive fuel was needed to completely remove the autocatalytic effects of the aluminum reaction.

TABLE I

FUEL-COOLANT MIXING COMPUTER MODELS

- Simulate the transient process of melt penetration into a water pool
- Provide estimates of fuel spatial and temporal distribution as well as steam production and pressurization during mixing phase

MODELS	REMARKS
CHYMES (Fletcher et al, C ulham)	2-D with discrete particles
IVA3 (Kolev et al, KFK)	3-D with discrete particles
MC-3D (Berthoud et al, CEN)	3-D with discrete particles
PM-ALPHA (Theofanous et al, UCSB)	2-D with discrete particles
TEXAS-V (Corradini et al, UW)	1-D Lagrangian and Eulerian, dynamic fragmentation (Chu/Yang)
IFCI* (Young et al, SNL)	2-Eulerian with dynamic fragmentation (Pilch model)
THIRMAL (Sienicki, Chu et al, ANL)	1-D Lagrangian in a pool of water, dynamic fragmentation (Chu)

[IFCI, TEXAS and THIRMAL dynamic fragmentation models simplified from analytic derivations]

*NRC supported

TABLE II

EXPLOSION/DETONATION COMPUTER MODELS

- Provides estimates of the dynamics of explosion, pressure and velocities
- Simulates the explosion expansion process and work output

KROTOS/WFCI provide benchmark data for comparison of models

MODELS	REMARKS
IFCI* (Young et al, SNL)	2-D parametric fragmentation model
CULDESAC (Fletcher et al, Culham)	1-D parametric fragmentation heat transfer rate
ESPROSE (Theofanous et al, UCSB)	2-D hydrodynamic fragmentation
IDEMO (Carachalios et al, IKE)	1-D Eulerian assorted mechanistic fragmentation models
TEXAS-V (Corradini et al, UW)	1-D Lagrangian/Eulerian combined jet mixing and thermal fragmentation model

[ESPROSE, IDEMO and TEXAS have semi-empirical fuel fragmentation models)

*NRC supported

APPENDIX B-5
SERG-2 PANEL MEMBER RESPONSE
BY
DR. HANS K. FAUSKE
FAUSKE & ASSOCIATES, INC.

Questions and Issues for the SERG-2 Workshop
Perspective: Robert E. Henry and Hans K. Fauske

1. In your opinion, what is the status of our understanding of the α-mode containment failure issue for the LWRs? Is it, in your opinion, resolved, i.e., of little or no risk significance?

   (a) If yes, cite the relevant references.

   (b) If essentially resolved, what additional confirmatory research is required, in your opinion, to fully resolve the issue?

   (c) If not resolved, i.e., if the residual uncertainties still remain large and/or if there are still unanswered questions about the α-mode failure, discuss specific additional research that will be needed to answer the questions and to address the uncertainties. Discuss the approach to research areas thus identified, potential benefits to be derived from the research, and indicate the time frame for accomplishing the research objectives.

Response: In our opinion the understanding of the likelihood of α-mode containment failure is sufficient to be considered a resolved issue, i.e. it is of no risk significance. The relevant references are the SERG-1 report, which one can view as an initial assessment and directions that should be pursued if one differed with the stated opinions in the report. Secondly, the CSNI-FCI meeting in Santa Barbara (January 1993) provided another forum for reviewing and evaluating the results of new research relating to α-mode failure. If anything, the results discussed with respect to void formation during the premixing stage (Fletcher and Denham, "Validation of the CHYMES Mixing Model" and Angelini, Yuen and Theofanous, "Premixing-Related Behavior of Steam Explosions") demonstrated limited potential for premixing substantial masses of core debris and water due to the steam formed as the high temperature melt attempts to premix. The conclusion from these studies was that the energy transfer during premixing would substantially deplete the water in the interaction zone, thereby reducing the efficiency of the interaction to levels less than that which were considered in the first SERG meeting. Moreover, additional experiments in the ALPHA program further demonstrated the importance of system pressure in preventing interactions from being initiated. This further substantiated work on high pressure termination performed prior to the previous SERG meeting.

With the above additional information that has been published, it is our opinion that the conclusions of the first SERG workshop have been substantiated such that this issue can be concluded as being resolved.

2. Discuss the role and status of premixing in addressing the α-mode failure issue.

Response: Premixing is, and always has been, a key element of assessing the potential for steam explosion energetics, and thus the α-mode failure issue. More detailed computer modeling has been performed in recent years and this has provided the necessary analytical verification of the concept that the premixing phase is self-limited. Specifically, the extent of materials that can be involved is limited as a result of the ongoing energy transfer during premixing, i.e. the steam formation forces water from the interaction zone (water depletion). As the water is depleted, the efficiency of the interaction that could be initiated is decreased. Furthermore, the premixing stage also establishes how much of the melt could be sufficiently subdivided and intermixed. Hence, if anything, the importance of the premixing details have taken on increasing importance and have continued to show that it is extremely difficult to efficiently pre-mix large quantities of high temperature molten core debris with water.

3. Discuss the role and status of propagation in addressing the α-mode failure issue.

Response: Propagation is another major element in the understanding of steam explosions and the α-mode failure issue. However, propagation is sometimes difficult to understand if substantial external triggering events have been imposed. Specifically, if the mechanical work imposed by the trigger is capable of rapidly mixing sufficient high temperature melt to explain the dynamic interaction, the issue of propagation becomes difficult to sort out of the global response. There is no argument that propagation occurs! On the other hand, propagation is more than observing a pressure wave that moves at the mixture sonic velocity. Propagation is usually interpreted as the premixed materials are further disintegrated, mixed and transfer energy on a timescale sufficient to support the traveling wave. In the interpretation of many experiments propagation has only been represented as a wave that is traveling through the two-phase mixture at the local velocity of sound. In fact, for many experiments and analyses which have been performed, the pressure wave is sufficient to completely collapse the steam void. In such configurations the recorded event could be substantially determined by relatively standard heat transfer between coarsely particulated debris and water if the experiment or analysis utilizes a long inertial length. To clearly demonstrate whether a system can propagation, we propose that such experiments be performed with an inert gas void, for example 10%, in the long column before the two liquids are mixed. In this regard, the substantial pressurization would be in a mixture with significant compressibility (compliance) and the issues of propagation would be more easily understood.

4. Discuss the role and importance of triggering (trigger availability and triggerability) in addressing the α-mode failure issue. Discuss the role of pressure threshold in suppressing the triggering.

Response: External triggering always has the potential of clouding the results. Since the system is dynamically unstable, imposing a significant external stimulus, could also merely result in an amplification of the external trigger. Certainly if one utilizes conservative estimations of the mixing energies, an external stimulus could mix substantial quantities of materials to result in a pressurization that is much greater than the trigger pulse, independent of any propagation. Thus, experiments with external triggers should be interpreted very carefully to assess whether the situation is perhaps only an amplification of the external stimulus or actually is demonstrating propagation in a system (for example see Henry, R. E., 1994, "Externally Triggered Steam Explosions Experiments: Amplification or Propagation?", CSNI-FCI Meeting, Santa Barbara, California).

Pressure threshold in suppressing the initiation of vapor explosions is one of the most intriguing facets discovered for steam explosions and this observation has been recorded by many different laboratories. For those experiments in which there are no external triggers, a system pressure which is 5% of the thermodynamic critical pressure of the exploding liquid provides a comfortable upper bound of the pressure sufficient to prevent such interactions. It is possible that this pressure could even be substantially less than 10 bars for water, even perhaps as low as a few atmospheres. This is particularly important for reactor accident calculations since various pressures could exist within the RPV depending on the accident sequence. Also, because the low pressure under which such accident could be initiated means that the water depletion in the premixing zone is of increasing importance and perhaps the major reason for inefficient explosive interactions.

5. Discuss the role and importance of accident progression and melt relocation in addressing the α-mode failure issue.

Response: One element of significance discussed above is the pressure in the RCS at the time of melt relocation. If the pressure is above 10 bars, data would suggest that explosions do not occur. Furthermore, data and analyses suggest that if explosions do occur, they would not be expected to have a significant efficiency, i.e. they would not be expected to have sufficient strength to rupture the RCS pressure boundary.

Another element of the accident progression that has gained some recognition over the past few years is that the core melt progression would tend to cause metallic zircalloy to relocate to the lowest regions of the core. This is certainly consistent with the experience in the TMI-2 accident as well as with the respective melting temperatures of metallic and oxidic materials in the core. Such a downward relocation results in two components of the accident progression that are important. First, the metallic constituents tend to form a lower crust and are the last regions to become molten because of the reduced power and the initial axial temperature profiles in the core at the time relocation initiates. Secondly, the material that does relocate into the lower plenum is principally oxidic material from the region comprised of molten UO_2 and molten ZrO_2. Failure is calculated to be sidewards through a crust around the core debris and drainage occurs through the bypass region into the lower plenum. Hence, the material that enters the lower plenum is generally oxidic material as dictated by the accident progression. This again is consistent with the TMI-2 observations as well as the SCDAP/RELAP5/MOD3 analyses used to assess the potential for high pressure melt ejection and also consistent with the MAAP4 analyses for core melt progression. Therefore, while we believe that this issue can be resolved independent of the accident progression and melt relocation assessments, there are issues embedded in each of these which further reduces the likelihood of (1) initiating an explosive interaction and (2) having any significant contribution from chemical augmentation.

6. Discuss the role and consequence of mechanical energy release and damage-producing events in the context of the α-mode failure.

Response: If an explosive interaction is postulated, the energy release is clearly dependent upon the efficiency of the interaction and the means whereby the energy can be transmitted to the RPV pressure boundary. Since explosive interactions have not been demonstrated at elevated pressures, accident sequences which evolve at an elevated pressure should not be assessed as if explosive interactions occur. Furthermore, those sequences with low RPV pressures (less than 10 bars) should be assessed as having a significant water depletion condition when the two liquids are premixed. In this case, the premixing situation influences two additional elements, the first is the mass of material that can be premixed and second is the possibility that there is any significant continuous overlying liquid slug that could act as a missile to be accelerated upward against the RCS pressure boundary. With the conditions of:

1. explosions only at low pressures,

2. water depletion in the interaction zone augmented by the low pressures, and

3. no substantive slug to transmit the energy,

it is extremely remote to have a mechanical energy release that would challenge RPV integrity.

7. In your opinion, is our current knowledge of premixing and propagation phenomena adequate for a better quantification of the α-mode failure? Based on your own knowledge, are you now able to assign a better probability (likelihood) measure to this failure mode?

(a) If yes, provide your estimate(s) and the basis for it. (Note: The plural is for distinguishing among various severe accident classes if you wish.)

(b) If no, do you think it is reasonable to expect that this will be possible sometime in the future? Provide your reasoning and indicate what key developments will be needed to meet the expectation.

<u>Response</u>: We have always believed that the probability of α-mode failure was essentially zero. With all the confirmatory information that has been provided in recent years, both experimental and analytical, we are both even more convinced that the probability is essentially zero.

8. Discuss the status and capabilities of the analytical tools/computer codes available to address various components of the FCI methodology (e.g., tools to estimate premixture) or to perform integral FCI assessments. How much verification have these analytical tools had? Are there well defined experiments against which a number of these tools can be assessed? Provide your recommendations regarding the need to perform a "standard" problem, preferably one in conjunction with an integral evaluation.

<u>Response</u>: While the fundamental physical process limiting the likelihood of an explosive interaction, as well as the strength of the interaction when explosions can occur can be viewed in simple terms, it is always helpful for issue resolution to have verification of more complete analytical methods to examine issues particularly related to the time dependent evolution of a premixing situation. In this case, the calculations for water depletion in the interaction zone have been extremely helpful and an important contribution to resolution of the α-mode failure issue. It is certainly helpful if these evaluations are compared to a "standard problem" such that the detailed behavior of various models can be compared. To some extent this was done in the OECD FCI meeting at the University of California Santa Barbara in 1993.

9. How much of the research performed (both experimental and analytical) in support of the α-mode failure issue is also applicable to "localized" FCIs (e.g., an energetic FCI next to a structural boundary where there is a need to evaluate the dynamic loading on the structure)?

<u>Response</u>: Dynamic loadings would be determined by two-dimensional propagation and mitigation of pressure increases resulting from the interaction. Most experiments have been performed in an environment where the interactions are essentially one-dimensional. Hence, the dynamic behavior of situations where an explosions has occurred would not be particularly meaningful for localized events. On the other hand, the issues related to premixing (water depletion) and the ability to initiate an event an a function of system pressure are directly applicable.

10. Discuss the possibility and importance of chemical augmentation to energetic FCIs. Discuss the impact of chemical augmentation on the dynamic loading of structures.

Response: Chemical augmentation is a possible way that the explosive energy release could be increased. However, as discussed in the response to item 5, the accident progression has a substantial influence on the chemical character of material that would enter the RPV lower plenum. Hence, we do not view this augmentation as a substantial influence with respect to α-mode failure conclusions.

APPENDIX B-6

SERG-2 PANEL MEMBER RESPONSE

BY

DR. DAVID F. FLETCHER

UNIVERSITY OF SYDNEY

Submission to SERG–2 Workshop
D.F. Fletcher, University of Sydney,
NSW 2006, Australia.
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Background

This submission is based on my experience gained from participation in the steam explosion research field over a period of 13 years. For ten years I worked for the United Kingdom Atomic Energy Authority where I participated in the experimental studies performed at Winfrith (SUW, WUMT, MIXA tests) and took a leading role in the development of the CHYMES (premixing) and CULDESAC (propagation) models. This work culminated in the production of a quantification of the probability of α-mode failure for the Sizewell B PWR in the UK [1].

Since leaving the UK, whilst working at the University of Sydney, I have been involved with industrial steam explosion investigations and have maintained an active interest in the nuclear area. I am currently co-authoring (with Prof. Theofanous) a review article on steam explosions for Advances in Heat Transfer.

Qu. 1 — Is the α-mode failure issue resolved?

My belief is that the issue is essentially resolved and that all that is required is confirmatory research. This view is based on the outcome of studies performed by Theofanous and co-workers [2, 3, 4, 5, 6], the study in which I participated in the UK [1] and my full agreement with the conclusions reached at the CSNI Specialist Meeting at Santa Barbara in 1993 [7].

I believe that most areas of importance are currently undergoing active research. What is needed is greater collaboration and more application of the models to real situations. *It is only when one has performed a quantification that it is possible to understand fully the complex and improbable sequence of events required to lead to α-mode failure.*

Qu. 2 — Status and Role of Premixing

As soon as an assumption is made that very large masses of melt can relocate it is necessary to appeal to premixing arguments. The fact that at low pressure there is so much steam produced that the water is expelled from the mixture, leading to a mixture which cannot sustain a propagation wave, can be exploited in two ways. The premixing calculation can be used to generate an initial condition for a propagation calculation which then gives the pressure field development within the vessel following a specified trigger. Clearly this is the preferred route, as no assumptions about what melt can participate needs to be made. However, it requires a validated propagation model. Alternatively, as in the UK study, the premixing calculation can be used to generate input data for a multi-volume Hicks-Menzies calculation. This approach is conservative and does not yield the type of information required to predict dynamic pressure loads. Thus in the UK assessment we could make no assessment of lower head failure.

The premixing area is undoubtedly the area that has undergone most research and development since the last SERG meeting. There are now a very large number of models (PM-ALPHA, CHYMES, TRIO-MC, IVA3, IFCI) which have been used to study premixing. These are all based on multiphase flow models and there is convergence on the essential modelling features. These are the capability to perform transient, 2D, three phase calculations which allow for steam superheating and water subcooling. Some models have a capability to allow for droplet and jet breakup but there has been little validation of this feature to date. There are some differences between the constitutive laws. These could be resolved by making more use of the available experimental data. For example, the MAGICO tests allow the mixing behaviour to be calculated in the absence of fragmentation. Furthermore, in saturated conditions much of the constitutive physics becomes redundant, so that a stage by stage validation process is possible. *At present only* PM-ALPHA *and* CHYMES *have been employed in α-mode failure assessments.*

On the experimental side, the water depletion phenomenon first proposed by Henry and Fauske [8] has been clearly demonstrated in experiments using solid particulate MAGICO [9] and in the MIXA [10] tests which used a droplet stream of prototypic melt.

The validation of models against experimental data is less well developed. Both PM-ALPHA [9] and CHYMES [11] have been subjected to careful validation studies and to inter-model comparisons [6, 12]. In addition, most models have been used to interpret the FARO experiments but there seems to be a wide range of initial conditions (which are not known from the experiment) which have been used by the various groups.

My residual concerns in the premixing field are whether there is a need to be able to model jet breakup within a premixing code. At first thought this would seem desirable but when one takes the real geometry into account it seems to me to be a very difficult task, as jets would contact plates, columns etc. causing melt to spray or flow and then subsequently breakup. There is a danger that spurious accuracy would be claimed even if a code could be shown to model fragmentation of a single jet in an empty vessel.

Finally, it should be remembered that steam voiding of water from the premixture is essentially a low pressure phenomenon. The utility of limits to mixing at even modest pressures has not been widely considered. (Question: Are FARO tests planned at a wide range of pressures?)

Qu. 3 — Status and Role of Propagation

As noted above, the preferred method of estimating the outcome of an event is via a combined premixing/propagation simulation. Again it is important to realize that whilst this is now feasible, there are issues concerning the complex geometry and interaction of shock waves with structures that mean this area can never be addressed in a fully predictive manner.

Propagation models are less well developed than mixing models. Until recently no model could reproduce experimental data in a consistent manner [13]. I believe that the development of ESPROSE.m [14] to include the physics of microinteractions [15] is a very significant step forward. Whilst at present the database for the necessary constitutive physics is relatively sparse, the model has been demonstrated to work in principle and to be able to reproduce the extremes of very weak and very strong propagation events observed in the KROTOS tests [16]. *It is important to realize that* *the microinteraction concept allows propagation to occur in situations where it would not be predicted by a model which does not allow for this phenomenology.*

I am not aware that any α-mode assessment has been based on the use of premixing/propagation arguments. I believe the time is right to have a go and see what residual difficulties remain in this approach. Clearly Theofanous and co-workers at UCSB are well placed to take the lead in this task. They have already made interesting simulations for ex-vessel steam explosions and demonstrated the codes' capabilities in this area [16].

Qu. 4 — Status and Role of Triggering

I performed a major review of information on the triggering stage of a steam explosion for the Sizewell B quantification. This has subsequently been updated and published [17]. In particular, an attempt was made to answer the following questions: (i) "Is early triggering as likely at low pressure as some workers claim?", (ii) "Is there any reliable evidence on the effect of pressure on triggering?" and, (iii) "Is it possible to draw any general conclusions on the factors which affect triggering in any given situation?"

The following conclusions and comments were made following examination of the available data:

- There are no developed and validated models of triggering which can be used with any degree of confidence;
- The evidence from model predictions is that triggering becomes more difficult at higher pressure and for higher melt temperature. As the pressure increases the vapour mass and energy densities increase and the latent heat of vaporization decreases so that it becomes more difficult to compress the film, more difficult to condense the vapour and easier to evaporate the leading edge of the water slug;
- The presence of a permanent gas can affect the triggering process. Small quantities inhibit triggering, whereas rapid gas evolution can lead to spontaneous explosions;
- Experimental data shows very clearly the random nature of the triggering process;
- Explosions can be triggered as the melt enters the water pool, as it is falling, upon base contact or after melt has collected on the base of the mixing vessel. Explosions frequently occur without an applied external trigger;
- The spontaneous explosions which occur when melt contacts the water can be suppressed by a small increase in the ambient pressure (as little as 0.5–1.0 MPa is often sufficient);
- There is no clear evidence for a triggered explosion occurring at pressures above about 3 MPa. An explosion was triggered at 5.8 MPa in the HPTR experiments but this involved the injection of a slug of cold water into the mixture;
- Explosions are much more likely to occur in subcooled conditions compared with saturated conditions;
- There is considerable evidence that if the melt is pre-dispersed it is much less likely that an explosion will trigger;

- There is evidence that if the melt has a low superheat, partial solidification during the melt/water interaction can inhibit triggering.

In the UK assessment we felt justified in specifying a range of possible trigger times and making modest claims for the lack of a suitable trigger at mid and high pressure [1]. At high pressure the probability that there was no suitable trigger was set to 0.9, which I believe to be very conservative on the basis of the available data.

Qu. 5 — Role and Importance of Accident Progression

As with any modelling problem, it is important to know the initial and boundary conditions. The accident progression path determines the likely relocation route of melt, the quantity of melt available to relocate, its temperature, the system pressure (of crucial importance in mixing and triggering) and the possibility of subcooled water being present (important for triggering).

Our experience in the UK was that system models used a noding which was too coarse to determine best-estimate melt relocation paths and we had to result to our own simplified models to provide the data needed in this area [1].

In the UK study [1] we found that it was very important to look at the details of the plant and to identify possible relocation paths for the melt (in this case these were through the core and via the bypass) and to quantify likely flowrates. We were able to rule-out massive flowrates of the 100 tonnes/s scale which have been considered in early studies and mixing calculations. This immediately sets a limit on the mass of melt that can be in transit between the core support plate and the vessel base. Our study showed that virtually no α-mode failures were predicted to occur for events in which relocation was via the bypass region. *The message here is that the starting point for an α-mode failure study must be realistic and based on sound analysis of melt progression.*

Qu. 6 — Role and Consequence of Energy Release

The consequences of an explosion in the lower head range from minor damage, to causing lower head failure to acceleration of a slug into the upper head. My belief is that at low pressure triggering is likely to occur and that some region of the mixture will explode. The efficiency of conversion of thermal to mechanical energy is still somewhat uncertain. In the UK study we were confident that the efficiency of an explosion is most likely to lie in the range 2–5% at low pressure, with the possibility of slightly higher values at high pressure and with outlier events having efficiencies as high as 20%. (We had no propagation model in a suitable state to use in our study.)

Multiple and stratified explosions are often raised as possible means of causing α-mode failure. In the first explosion, the pressure generated would push surrounding water and melt away from the explosion zone and then the system would settle as melt and water fall under gravity. This would lead to a stratified situation, as the water would be pushed further away than the melt by the same pressure force. In the UK assessment we were unable to identify any credible mechanism by which successive explosions could increase in magnitude. I developed a simple multi-layer model to estimate how much melt could be "stirred up" from the pool and we included this melt in the mass of melt participating (assumed to be *all* of that falling through the water).

The question of lower head failure is difficult. Detailed simulations are needed to determine the likely pressure loads and durations. Whilst very high pressures have been recorded in the KROTOS tests (~100 MPa) I do not see how such high pressures could develop in the highly 3D configuration which would develop as steam escapes from the mixture due to buoyancy. Theofanous *et al.* [16] have shown that such 'steam chimneys' play an important role in relieving pressure loads.

In early α-mode failure assessments the assumption of the existence of a coherent slug to integrate the explosion energy into kinetic energy was crucial in providing the energy to fail the upper head. The assumption of a coherent slug is unduly pessimistic and allowance for a 'leaky' slug, due to the presence of downcomers, residual core structure etc. has a significant effect on the predicted load on the upper head [1]. In addition, following the work of Lucas *et al.* [5] and the work performed for the UK study by Attwood [18] it is evident that the details of the core and above core structure must be taken into account in any study, as they have a significant dissipational effect.

Qu. 7 — Adequacy of Information for a Better Quantification

My view is that the results obtained in the UK study, which gave failure probabilities of a few in 10,000 at all pressures considered, provide an effective upper bound. In that study we used thermodynamic models to calculate efficiencies and did not allow for the possibility of lower head failure. Since then there has been considerable model development and validation. In addition, none of the ongoing experiments suggest that anything was missed in the above study. I have not seen the results of a study which uses a propagation model in place of a thermodynamic model to predict energy conversion/pressure loads. However, I would expect the results of such a study to give lower failure probabilities than the UK study. Therefore I feel comfortable giving an upper bound probability of 10^{-4} given core melt for α-mode failure at all pressures.

Qu. 8 — Status and Capabilities of Analytic Tools

In the UK study we were asked to produce validation statements for the major codes used. When doing this for the CHYMES code we first asked "What features are we using that need validation?" and then we tried to answer this question after performing verification tests and comparison of calculations with experimental data from the MIXA series. This concept of "fitness for purpose" is discussed further in reference [11].

I classify the available models into premixing codes, propagation codes and structural response codes. *I deliberately differentiate between premixing and propagation models as I believe they need to contain different physics and numerics because of the difference in timescales between the phenomenology: 1 s in premixing and 10 ms in propagation.* My view of the current status of the models is:

- For premixing, I am only aware that the CHYMES and PM-ALPHA codes have undergone extensive comparison with experimental data.
- For propagation, only ESPROSE.m has been compared with experimental data in what I consider to be a 'consistent' manner.
- The structural analysis codes seem to be well validated and, subject to the limitation of dealing with uncertain inputs, seem to be in a good state.

There are a significant number of experimental data-sets available world-wide which could be used for validation, if they were made available by the proprietors. For mixing, from the MIXA series. This concept of "fitness for purpose" is discussed further in reference [11].

I classify the available models into premixing codes, propagation codes and structural response codes. The latter seam to be well validated and, subject to the limitation of dealing with uncertain inputs, seem to be in a good state. I class integral codes, such as IFCI, as premixing/propagation models which have been joined transparently. Other code combinations, most notably PM-ALPHA/ESPROSE.m perform the same role but are being validated separately.

For premixing, I am only aware that the CHYMES and PM-ALPHA codes have undergone extensive comparison with experimental data. For propagation, only ESPROSE.m has been compared with experimental data in what I consider to be a 'consistent' manner.

There are a significant number of experimental data-sets available world-wide which could be used for validation, if they were made available by the proprietors. For mixing, successful simulation of MAGICO or BILLEAU, MIXA and FARO (especially a test at low pressure) tests would provide significant confidence in a model. For propagation, the best-characterized data seam to be from the KROTOS experiments (there may be good data from the WFCI facility that I am not aware of). However, this is all one-dimensional. Data from the ALPHA facility in Japan may be sufficient to allow an integral comparison. Alternatively, performing a low pressure FARO test (with more extensive instrumentation) should lead to a steam explosion and provide data for model validation.

I would be in favor of seeing a sets of data made available for validation purposes and calculations being made for a number of standard problems. As stated earlier, a blind FARO comparison would be worthwhile.

Qu. 9 — Applicability to Localized Events

The development of mechanistic models of premixing and propagation means that it is possible to address the consequences of localized events. If these events are to be predicted accurately there is a need for even greater validation of the models than for the α-mode failure application. (The α-mode calculations are robust to model uncertainties, in the sense that there is a significant separation between predicted energy yields and those required for α-mode failure.)

At present no propagation model is sufficiently well validated to calculate local pressure loads with a high degree of confidence. Also I have concerns about the ability to allow for the complex shock patterns that would develop in a complex geometry. Ongoing validation programmes should address these aspects.

Qu. 10 — Possibility and Importance of Chemical Augmentation

The fact that steam explosions can be augmented significantly in the aluminum/water system has been clearly established. However, the situation for the core melt/water system is less clear. I co-authored a review of hydrogen production during melt/water interaction several years ago [19]. The conclusion of that review was that the current models were not sufficiently well developed to explain experimental data and therefore to make quantitative predictions. I am not aware of any work that has changed the situation. However, there is currently renewed interest in understanding the underlying mechanism occurring in such interactions which should assist with model development.

Summary

In my view very significant progress has been made towards closure of the α-mode failure issue since the last SERG meeting. All studies show the probability to be very low and I feel confident in assigning a value of $< 10^{-4}$ given core melt.

There has been a considerable amount of model development in the areas of premixing and propagation. It should be noted that model validation is less well developed, and only PM-ALPHA, CHYMES and ESPROSE.m have undergone significant verification and validation programmes (as can be determined from the open literature). What is required now is a period of consolidation in which the available experimental data are fully analysed. This would result in improved confidence in the α-mode failure assessment and tools useful for exploring the effect of localized explosions, ex-vessel explosions and accident management issues. I would strongly endorse running a standard problem exercise, and whilst not able to participate directly would be very happy to be involved, perhaps by using my previous experience to help with the problem formulation and to analyze the outcomes.

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APPENDIX B-7

SERG-2 PANEL MEMBER RESPONSE

BY

DR. ROBERT E. HENRY

FAUSKE & ASSOCIATES, INC.

Questions and Issues for the SERG-2 Workshop
Perspective: Robert E. Henry and Hans K. Fauske

1. In your opinion, what is the status of our understanding of the α-mode containment failure issue for the LWRs? Is it, in your opinion, resolved, i.e., of little or no risk significance?

   (a) If yes, cite the relevant references.

   (b) If essentially resolved, what additional confirmatory research is required, in your opinion, to fully resolve the issue?

   (c) If not resolved, i.e., if the residual uncertainties still remain large and/or if there are still unanswered questions about the α-mode failure, discuss specific additional research that will be needed to answer the questions and to address the uncertainties. Discuss the approach to research areas thus identified, potential benefits to be derived from the research, and indicate the time frame for accomplishing the research objectives.

<u>Response</u>: In our opinion the understanding of the likelihood of α-mode containment failure is sufficient to be considered a resolved issue, i.e. it is of no risk significance. The relevant references are the SERG-1 report, which one can view as an initial assessment and directions that should be pursued if one differed with the stated opinions in the report. Secondly, the CSNI-FCI meeting in Santa Barbara (January 1993) provided another forum for reviewing and evaluating the results of new research relating to α-mode failure. If anything, the results discussed with respect to void formation during the premixing stage (Fletcher and Denham, "Validation of the CHYMES Mixing Model" and Angelini, Yuen and Theofanous, "Premixing-Related Behavior of Steam Explosions") demonstrated limited potential for premixing substantial masses of core debris and water due to the steam formed as the high temperature melt attempts to premix. The conclusion from these studies was that the energy transfer during premixing would substantially deplete the water in the interaction zone, thereby reducing the efficiency of the interaction to levels less than that which were considered in the first SERG meeting. Moreover, additional experiments in the ALPHA program further demonstrated the importance of system pressure in preventing interactions from being initiated. This further substantiated work on high pressure termination performed prior to the previous SERG meeting.

With the above additional information that has been published, it is our opinion that the conclusions of the first SERG workshop have been substantiated such that this issue can be concluded as being resolved.

2. Discuss the role and status of premixing in addressing the α-mode failure issue.

Response: Premixing is, and always has been, a key element of assessing the potential for steam explosion energetics, and thus the α-mode failure issue. More detailed computer modeling has been performed in recent years and this has provided the necessary analytical verification of the concept that the premixing phase is self-limited. Specifically, the extent of materials that can be involved is limited as a result of the ongoing energy transfer during premixing, i.e. the steam formation forces water from the interaction zone (water depletion). As the water is depleted, the efficiency of the interaction that could be initiated is decreased. Furthermore, the premixing stage also establishes how much of the melt could be sufficiently subdivided and intermixed. Hence, if anything, the importance of the premixing details have taken on increasing importance and have continued to show that it is extremely difficult to efficiently pre-mix large quantities of high temperature molten core debris with water.

3. Discuss the role and status of propagation in addressing the α-mode failure issue.

Response: Propagation is another major element in the understanding of steam explosions and the α-mode failure issue. However, propagation is sometimes difficult to understand if substantial external triggering events have been imposed. Specifically, if the mechanical work imposed by the trigger is capable of rapidly mixing sufficient high temperature melt to explain the dynamic interaction, the issue of propagation becomes difficult to sort out of the global response. There is no argument that propagation occurs! On the other hand, propagation is more than observing a pressure wave that moves at the mixture sonic velocity. Propagation is usually interpreted as the premixed materials are further disintegrated, mixed and transfer energy on a timescale sufficient to support the traveling wave. In the interpretation of many experiments propagation has only been represented as a wave that is traveling through the two-phase mixture at the local velocity of sound. In fact, for many experiments and analyses which have been performed, the pressure wave is sufficient to completely collapse the steam void. In such configurations the recorded event could be substantially determined by relatively standard heat transfer between coarsely particulated debris and water if the experiment or analysis utilizes a long inertial length. To clearly demonstrate whether a system can propagation, we propose that such experiments be performed with an inert gas void, for example 10%, in the long column before the two liquids are mixed. In this regard, the substantial pressurization would be in a mixture with significant compressibility (compliance) and the issues of propagation would be more easily understood.

4. Discuss the role and importance of triggering (trigger availability and triggerability) in addressing the α-mode failure issue. Discuss the role of pressure threshold in suppressing the triggering.

Response: External triggering always has the potential of clouding the results. Since the system is dynamically unstable, imposing a significant external stimulus, could also merely result in an amplification of the external trigger. Certainly if one utilizes conservative estimations of the mixing energies, an external stimulus could mix substantial quantities of materials to result in a pressurization that is much greater than the trigger pulse, independent of any propagation. Thus, experiments with external triggers should be interpreted very carefully to assess whether the situation is perhaps only an amplification of the external stimulus or actually is demonstrating propagation in a system (for example see Henry, R. E., 1994, "Externally Triggered Steam Explosions Experiments: Amplification or Propagation?", CSNI-FCI Meeting, Santa Barbara, California).

Pressure threshold in suppressing the initiation of vapor explosions is one of the most intriguing facets discovered for steam explosions and this observation has been recorded by many different laboratories. For those experiments in which there are no external triggers, a system pressure which is 5% of the thermodynamic critical pressure of the exploding liquid provides a comfortable upper bound of the pressure sufficient to prevent such interactions. It is possible that this pressure could even be substantially less than 10 bars for water, even perhaps as low as a few atmospheres. This is particularly important for reactor accident calculations since various pressures could exist within the RPV depending on the accident sequence. Also, because the low pressure under which such accident could be initiated means that the water depletion in the premixing zone is of increasing importance and perhaps the major reason for inefficient explosive interactions.

5. Discuss the role and importance of accident progression and melt relocation in addressing the α-mode failure issue.

Response: One element of significance discussed above is the pressure in the RCS at the time of melt relocation. If the pressure is above 10 bars, data would suggest that explosions do not occur. Furthermore, data and analyses suggest that if explosions do occur, they would not be expected to have a significant efficiency, i.e. they would not be expected to have sufficient strength to rupture the RCS pressure boundary.

Another element of the accident progression that has gained some recognition over the past few years is that the core melt progression would tend to cause metallic zircalloy to relocate to the lowest regions of the core. This is certainly consistent with the experience in the TMI-2 accident as well as with the respective melting temperatures of metallic and oxidic materials in the core. Such a downward relocation results in two components of the accident progression that are important. First, the metallic constituents tend to form a lower crust and are the last regions to become molten because of the reduced power and the initial axial temperature profiles in the core at the time relocation initiates. Secondly, the material that does relocate into the lower plenum is principally oxidic material from the region comprised of molten UO_2 and molten ZrO_2. Failure is calculated to be sidewards through a crust around the core debris and drainage occurs through the bypass region into the lower plenum. Hence, the material that enters the lower plenum is generally oxidic material as dictated by the accident progression. This again is consistent with the TMI-2 observations as well as the SCDAP/RELAP5/MOD3 analyses used to assess the potential for high pressure melt ejection and also consistent with the MAAP4 analyses for core melt progression. Therefore, while we believe that this issue can be resolved independent of the accident progression and melt relocation assessments, there are issues embedded in each of these which further reduces the likelihood of (1) initiating an explosive interaction and (2) having any significant contribution from chemical augmentation.

6. Discuss the role and consequence of mechanical energy release and damage-producing events in the context of the α-mode failure.

Response: If an explosive interaction is postulated, the energy release is clearly dependent upon the efficiency of the interaction and the means whereby the energy can be transmitted to the RPV pressure boundary. Since explosive interactions have not been demonstrated at elevated pressures, accident sequences which evolve at an elevated pressure should not be assessed as if explosive interactions occur. Furthermore, those sequences with low RPV pressures (less than 10 bars) should be assessed as having a significant water depletion condition when the two liquids are premixed. In this case, the premixing situation influences two additional elements, the first is the mass of material that can be premixed and second is the possibility that there is any significant continuous overlying liquid slug that could act as a missile to be accelerated upward against the RCS pressure boundary. With the conditions of:

1. explosions only at low pressures,
2. water depletion in the interaction zone augmented by the low pressures, and
3. no substantive slug to transmit the energy,

it is extremely remote to have a mechanical energy release that would challenge RPV integrity.

7. In your opinion, is our current knowledge of premixing and propagation phenomena adequate for a better quantification of the α-mode failure? Based on your own knowledge, are you now able to assign a better probability (likelihood) measure to this failure mode?

(a) If yes, provide your estimate(s) and the basis for it. (Note: The plural is for distinguishing among various severe accident classes if you wish.)

(b) If no, do you think it is reasonable to expect that this will be possible sometime in the future? Provide your reasoning and indicate what key developments will be needed to meet the expectation.

Response: We have always believed that the probability of α-mode failure was essentially zero. With all the confirmatory information that has been provided in recent years, both experimental and analytical, we are both even more convinced that the probability is essentially zero.

8. Discuss the status and capabilities of the analytical tools/computer codes available to address various components of the FCI methodology (e.g., tools to estimate premixture) or to perform integral FCI assessments. How much verification have these analytical tools had? Are there well defined experiments against which a number of these tools can be assessed? Provide your recommendations regarding the need to perform a "standard" problem, preferably one in conjunction with an integral evaluation.

Response: While the fundamental physical process limiting the likelihood of an explosive interaction, as well as the strength of the interaction when explosions can occur can be viewed in simple terms, it is always helpful for issue resolution to have verification of more complete analytical methods to examine issues particularly related to the time dependent evolution of a premixing situation. In this case, the calculations for water depletion in the interaction zone have been extremely helpful and an important contribution to resolution of the α-mode failure issue. It is certainly helpful if these evaluations are compared to a "standard problem" such that the detailed behavior of various models can be compared. To some extent this was done in the OECD FCI meeting at the University of California Santa Barbara in 1993.

9. How much of the research performed (both experimental and analytical) in support of the α-mode failure issue is also applicable to "localized" FCIs (e.g., an energetic FCI next to a structural boundary where there is a need to evaluate the dynamic loading on the structure)?

Response: Dynamic loadings would be determined by two-dimensional propagation and mitigation of pressure increases resulting from the interaction. Most experiments have been performed in an environment where the interactions are essentially one-dimensional. Hence, the dynamic behavior of situations where an explosions has occurred would not be particularly meaningful for localized events. On the other hand, the issues related to premixing (water depletion) and the ability to initiate an event an a function of system pressure are directly applicable.

10. Discuss the possibility and importance of chemical augmentation to energetic FCIs. Discuss the impact of chemical augmentation on the dynamic loading of structures.

Response: Chemical augmentation is a possible way that the explosive energy release could be increased. However, as discussed in the response to item 5, the accident progression has a substantial influence on the chemical character of material that would enter the RPV lower plenum. Hence, we do not view this augmentation as a substantial influence with respect to α-mode failure conclusions.

APPENDIX B-8

SERG-2 PANEL MEMBER RESPONSE

BY

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Second Steam Explosion Review Group (SERG-2)

NRC questions and personal answers

Question No. 1:

In your opinion, what is the status of our understanding of the α –mode containment failure issue for the LWR's? Is it, in your opinion, resolved, i.e., of little or no risk significance?

a) If yes, cite the relevant references
b) If essentially resolved, what additional confirmatory research is required, in your opinion, to fully resolve the issue?
c) If not resolved, i.e., if the residual uncertainties still remain large and/or if there are still unanswered questions about the α –mode failure, discuss specific additional research that will be needed to answer the questions and to address the uncertainties. Discuss the approach to research areas thus identified, potential benefits to be derived from the research, and indicate the time frame for accomplishing the research objectives.

Personal answer:

In my opinion the issue is not resolved, mainly because we don't have the knowledge that is required to exclude α –mode failure with sufficient confidence. (Assigning a low probability to α –mode failure doesn't say much if the confidence level of this assignment is low itself.)

In my view, research into steam explosions does not represent itself as a thoroughly studied and settled field of research in the sense that we have fully understood and can explain any observation and that we are sure not to have overlooked or missed important facts. Specifically:

a) Our knowledge and understanding of the basic phenomena occurring in steam explosions is limited and has gaps.
b) The codes available are partly too simplistic; the more complete ones are not (yet) developed sufficiently. None of the codes has (yet) been verified extensively by comparison with relevant experimental data.
c) In many aspects of the steam explosion, there are no relevant experimental data available. The main points determining relevance are scale, temperature of the melt, its volume fraction on entry into the water, and its composition.
d) There is no demonstrated method for the required extrapolation from the by necessity small scale of experiments (cm...dm) to the large scale of an accident situation (m).

Remark concerning the background:

At Forschungszentrum Karlsruhe (FZK) we do not consider it to be sufficient to show that the probability of α −mode failure is small. This is because such a failure (an early containment failure) would - in the densely populated Western Europe - cause a national or even multinational catastrophy against which no counter measures would be possible. Therefore we rather aim at excluding α −mode failure in a 'mechanistic' way, i.e. beyond any reasonable doubt. With respect to the research needs, this difference in safety philosophy doesn't make a lot of difference because in any case the loads and there counterpart, the load carrying capabilities must be evaluated reliably.

Suggested approach (as persued at Forschungszentrum Karlsruhe):

a) Develop a calculational tool for mechanistic description of premixing.

b) Develop the same tool to describe in a conservative way pressure generation and energy relase during the steam explosion proper. (The models describing the explosion may partly be parametric.)

c) Verify this tool with respect to premixing including its capability of extrapolation from small to large scale.

d) Verify that this tool gives conservative results with respect to pressure and energy.

e) Use this tool to find a few melt-water configurations that bound (with respect to their load potential) all contact modes that reasonably must be accounted for.

f) Calculate for these bounding cases the load potentials:
- pressure-time history on lower head and
- mass and kinetic energy of upward moving slug (assuming pessimistically the existence/formation of such a slug).

g) Calculate with standard tools and appropriate material laws whether the lower head fails under the above determined pressure-time histories. If failure can be proven, account for the additional expansion paths when determining the slug energy.

h) Determine the forces on the upper head that result from the impact of the upward moving slug on the upper internal structures and both together on the head.

i) Determine if the bolts or the head itself will fail and, if so, determine mass and kinetic energy of the missile.

j) If a missile is created, design reinforced internal containment structures that keep the missile within the reactor cavity.

In strategic parts of this chain of proofs conservatism must be ensured in order to avoid the cliff edge effect.

Question No. 2:

Discuss the role and status of premixing in addressing the α —mode failure issue.

Personal answer:

Premixing is expected to limit inherently the masses that can participate in a steam explosion by the removal of water from the volumes accessed by the corium melt (water depletion phenomenon). Therefore I consider it as a key to establishing realistic (i.e. not unduely pessimistic) upper bounds to steam explosion loads.

As the phenomenon cannot be simulated full scale in an experiment, assessment of the amounts of melt and water that might be involved in a steam explosion in an accident situation can only be performed with a code. This requires a multifield fluid dynamics code with at least three fields to describe the three phases gas, water, and corium. This code must describe at least two spatial dimensions. And the code must describe mechanistically all processes that govern premixing because it must be able to perform reliably the extrapolation from the scale of experiments to the reactor scale. For the sake of its results being dependable, the code must be verified with relevant experimental data on at least two scales to demonstrate its scaling capability. (For further details see answer to question 8.)

The above code development and verification require an improved understanding of the phenomena and the availability of relevant experimental data. Therefore, premixing experiments must be performed under conditions representative of the envisaged accident conditions, i.e.

- on a relevant scale (not too small),
- with a relevant temperature of the corium melt (or its simulant),
- at representative ambient pressure,
- with the corium (simulant) entering the water with a volume fraction that is typical of the most serious melt relocation scenarios,
- using corium mixtures (simulants) that span the possible corium compositions.

While the first four points pose essentially technical problems, the last point requires knowledge of the possible melt compositions at the time of melt relocation into the lower plenum. But these compositions remain to be determined in accident progression analysis (see question 5). If, however, the melt should contain relevant amounts of unoxidized metals, special emphasis will have to be placed on the modelling of metal oxidation by steam and its consequences. (Which is not well developed presently.)

In the past it has been tried to determine the potentially interacting corium mass with the help of (pioneering) calculations of the above required type and use of a local criterion for deciding which melt is premixed and which is not. This is a questionable procedure. First, there is no strictly derived or generally accepted criterion for premixing. Secondly, it is doubtful whether at all a local criterion can be used for that purpose. This is because in an inhomogeneous mixing zone, melt and water may be separated locally but still occupy neighbouring volumes and these masses might be forced together again after the start of the interaction. In this context it is important to note that the steam explosion in the lower coolant plenum of a reactor vessel is not the matter of a few milliseconds. The acceleration of the (pessimistically assumed) overlying material slug may take several tens of milliseconds and will involve gross material motion so that further mixing of corium and water is not excluded. This may not influence the initial pressure spike but may certainly increase the sustained pressure level at later times and the energy release. It is, therefore, indispensable to evaluate the load potential of premixing configurations by performing explosion calculations - preferrably with the same code as used to analyze premixing.

The decicive water depletion phenomenon depends on the volume created by evaporation of water. This in turn depends strongly on the ambient pressure. So the whole phenomenon strongly depends on pressure. But up to now no experimental data are available with pressure as a parameter. (Data of this type will be obtained with the PREMIX experiment at Forschungszentrum Karlsruhe.)

Question No. 3:

Discuss the role and status of propagation in addressing the α –mode failure issue.

Personal answer:

Propagation is the mechanism that advances the onset of interaction throughout a premixture, i.e. triggers the remaining part of the mixture after an initial trigger has occurred locally. It is an important issue of large scale steam explosions because it determines the amount of mass that is involved in a coherent interaction initially.

Propagation is usually thought to be produced by a pressure wave advancing through the premixture, which is strong enough to break the vapor shrouds around the coarsely prefragmented melt drops at least locally and thus triggers fine scale fragmentation. In most circumstances there will be no external source of such a pressure wave. So, the pressure wave must be supported by the premixture itself. The most popular propagation mechanism is the shock wave at the front of the reaction zone in the thermal detonation model of Board and Hall. But there are other possibilities of supporting a pressure wave as e.g. the explosive boiling phenomenon as suggested by me.[1] These questions are not finally settled but the current understanding may be sufficient for a conservative estimate of steam explosion loads as it is certainly conservative to assume that propagation occurs. It should be possible to include corresponding models of fast propagation into the codes used for analyzing steam explosions.

Missing or at least inadequate propagation might be the (or one) reason of the socalled pressure suppression of steam explosions (see question 4).

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1 H. Jacobs, 'Propagation of vapor explosions due to explosive boiling,' Proc. Int. Sem. The Physics of Vapor Explosions, Tomakomai, Japan, October 25-29, 1993, pp. 118-127

Question No. 4:

Discuss the role and importance of triggering (trigger availabilility and triggerability) in addressing the α –mode failure issue. Discuss the role of pressure threshold in suppressing the triggering.

Personal answer:

The trigger is an event that starts the interaction locally by causing the onset of fine scale fragmentation and thus increased heat transfer. Several basic sources of triggering have been discussed, all leading to the (at least) local bridging of the vapor shroud around one coarse melt fragment so that direct contact of hot melt and liquid water occurs. Among these possibilities are a local pressure increase, cooling of the melt surface below the minimum film boiling regime, and cooling of the surrounding water below saturation. In most of them but especially with pressure increase hydrodynamic instabilities of the vapor/coolant interface will play an important role.

By definition (so to say) no steam explosion will occur without trigger but there are so many possible sources of triggers (e.g. local pressure rises) that it seems to be difficult to exclude the occurrence of a trigger altogether in an accident condition. (Small scale experiments sometimes need an external trigger to produce 'steam explosions' but as the mass of hot melt involved increases the possibilities to obtain spontaneous triggers should increase even more.)

These questions are not finally settled but the current understanding may be sufficient for a conservative estimate of steam explosion loads as it is certainly conservative to assume that triggering occurs. In a mechanistic analysis of steam explosion loads, the time of triggering must be varied parametrically in order to find the most conservative assumption.

The socalled pressure suppression of steam explosions is sometimes thought to be caused by an increased difficulty (e.g. a higher energy requirement) for triggering. Although the effect has been observed in model experiments (with very unprototypical materials) and especially the absence of a steam explosion during the TMI-2 accident is in accordance with this hypothesis, the extrapolation to reactor accident situations must still be subject to doubts. There is at least one experiment (HPTR, Winfrith) in which one interaction was triggered at about 50 bar pressure. If there should be a cut-off pressure, it will at least be higher than 10 bar because that was the initial pressure of the only really energetic explosion (test 09) among the SUW test series in the MFTF at Winfrith.

Question No. 5:

Discuss the role and importance of accident progression and melt relocation in addressing the α —mode failure issue.

Personal answer:

Accident progression is a potentially highly important topic. It could, e.g. provide an upper limit (possibly even a useful one) to the amount of melt available during one relocation (and thus mixing) event. In addition, it determines the initial and boundary conditions of premixing, as e.g. the melt relocation path, the system pressure, and the chemical nature of the relocating melt.

It is obvious that the melt relocation path sets very important initial conditions for premixing. It can be hoped that the uncertainties connected with these initial conditions presently can be covered conservatively by analyzing a large variety of premixing scenarios and relying on the water depletion phenomenon alone in finding upper limits to the interacting masses. However, any additional reliable information could help in finding more realistic and therefore more useful limits. The relocation process itself is a possible source of metallic components in the corium mixture.

A very important information that must be provided by accident progression analysis is the pressure level at the time of melt relocation because the ambient pressure has a very important effect on the water depletion phenomenon.

As a consequence, high priority should be assigned to further develop the capabilities of late phase description in accident progression codes.

Question No. 6:

Discuss the role and consequence of mechanical energy release and damage producing events in the context of the α −mode failure.

Personal answer:

Formation and acceleration of a material slug that moves towards the vessel head are critical elements of α −mode failure. So, energy conversion during acceleration of such a slug is one of the things that must be analyzed conservatively.

In view of the need to establish reasonably conservative estimates of the loads from steam explosions, it is highly important to arrive at models of energy conversion that give efficiencies much below the theoretical upper limits (e.g. Hicks-Menzies). This requires a better understanding of effects that tend to limit energy conversion in reality and experiments that demonstrate the effectiveness of these effects under conditions that are typical of reactor accident conditions. (Again representative experimental data are required.) Following our present state of knowledge these must involve a confinement of the interaction zone at least as effective as in a pressure vessel that does not fail. (This confinement will force corium and water to continue to interact to some degree during the extended period of slug acceleration mentioned above in the answer to question 2 und thus increase energy conversion.) It is also imparative that the mechanical energy is measured reliably to avoid the uncertainties in the interpretation of some previous experiments, notably the SANDIA RC-2 experiment. Still this experiment forces us to throw overboard all former hypothesis of conversion efficiency decreasing with increasing melt mass. Theoretical considerations of heat losses as well lead to just the opposite expectation - at least under confined conditions.

The above mentioned slug finally loads the vessel head. In our opinion, the analysis of its failure must be based on forces instead of energies. A realistic estimate of these forces by theoretical tools is, however, very difficult in presence of the deforming structures between core and vessel head. We are, therefore, performing scaled (1:10) model tests for this purpose at Forschungszentrum Karlsruhe, the BERDA tests.

The vessel bottom is loaded directly by the pressure developing in the interaction zone. In case of very energetic steam explosions this was thought to lead to early failure of the vessel bottom. According to our own skoping analysis at Forschungszentrum Karlsruhe this doesn't seem to be ascertainable in the range of explosions that lead to loads on the vessel head that we tentatively expect to be tolerable. Of course, lower head rupture is thought to increase that range. But it may come (be provable) too late (i.e. at too high explosion energies).

If, on the other hand, lower head rupture cannot be excluded, its consequences in terms of damage caused by the moving parts of the vessel, DCH, etc. must be considered.

Question No. 7:

In your opinion, is our current knowledge of premixing and propagation phenomena adequate for a better quantification of the α –mode failure? Based on your knowledge, are you now able to assign a better probability (likelyhood) measure to this failure mode?

a) If yes, provide your estimate(s) and the basis for it. (Note: The plural is for distinguishinh among various severe accident classes if you wish.)
b) If no, do you think it is reasonable to expect that this will be possible soemtime in the future? Provide your reasoning and indicate what key developments will be needed to meet the expectations.

Personal answer:

In my opinion it is still premature to assign a probability to α –mode failure. I expect that the probability can be determined with sufficient confidence once the tools required for mechanistic analysis of the important processes involved have been developed sufficiently.

The reasoning for this and the tasks to be fulfilled to reach a reasonable and defendable result have been described in the answer to question 1. Here only a few general remarks are made in addition.

a) We need both:
   - a general understanding of the processes and
   - a sufficient knowledge of how the processes develop and interact under relevant conditions, i.e. under the conditions of a reactor accident.

b) Therefore it is mandatory to perform experiments under relevant conditions, e.g. concerning scale, temperature of the melt, volume fractions, melt composition.

c) Yet, small-scale studies of a more basic nature can be helpful.

d) For transferring the knowledge to the reactor accident case mechanistic codes must be developed and validated.

e) Therefore the above experiments must as well provide definite and critical data that can be used to verify and validate the mechanistic codes.

Question No. 8:

Discuss the status and capabilities of the analytical tools/computer codes available to address various components of the FCI methodology (e.g., tools to estimate premixture) or to perform integral FCI assessments. How much verification have these analytical tools had? Are there well defined experiments against which a number of these tools can be assessed? Provide your recommendations regarding the need to perform a "standard" problem, preferably one in conjunction with an integral evaluation.

Personal answer:

A detailed answer to this question would take the volume of a whole report and is, therefore, out of scope. Here only a few general remarks can be made.

a) There is little hope to resolve the problem with analytical tools. So we need either representative experiments (which are possible and affordable in very few cases) or highly sophisticated computer codes.

b) **Premixing**
This is the field in which the codes are most advanced. It is agreed almost unanimously that in the end multidimensional multifluid codes with at least three fluids (or fields) are required and several such codes are under development, e.g. CHYMES (AEA-T), PM-ALPHA (UCSB), IFCI (SNL), MC3D (CEA), IVA-KA (FZK), IVA4 (Siemens). Not all of these codes, however, treat all the required physics and none of them can be considered as sufficiently verified at present - partly because no sufficiently relevant data have been available until now. In some cases, comparison with available data has shown very promising agreement. Several experimental programmes that should be able to provide relevant data are now under way.

One at present still open problem is common to all of these codes, i.e. the treatment of melt jet breakup. In this area as well the basic knowledge (or at least sufficient correlations) as a satisfactory general technique for incorporating such correlations are lacking. This is especially serious because it is in no way clear how this phenomenon can be covered conservatively.

Besides the above mentioned formation and breakup of melt jets (and the obvious points like fluid motion and gas dynamics), the premixing codes must describe the following phenomena reasonably:

- melt drop fragmentation
- heat transfer by radiation
- evaporation due to heat addition to saturated water
- evaporation due to water becoming superheated
- condensation due to steam becoming subcooled
- hydrogen generation and its consequences (?, see answers to questions 2 and 10).

c) **Propagation**
This is a second field in which codes are relatively well developed. Most of these codes are onedimensional because (at least in the past) they *aim(ed)* at analyzing thermal detonations as hypothesized by Board and Hall. In this model the propagation wave (the shock front) is driven by the same heat exchange processes that lead to the final pressure development and energy conversion. So, as long as the basic fragmentation is modelled mechanistically in these codes there is the danger that other possibilities of propagation are overseen. This problem, fortunately, is relaxed by the lack of fully reliable (fine scale) fragmentation models so that the codes must in any case use some parametric description which needs verification by comparison with experiments.

The final solution to this problem must be the application of the above mentioned premixing codes to the propagation (and expansion) phase as well. But in most cases this new field of application is just under first testing. The only twodimensional special propagation code, ESPROSE from UCSB, may be considered as intermediate step in this (necessary) development.

None of these codes has been verified in detail.

Valuable experimental data have been and are being provided by the KROTOS programme performed at JRC Ispra. As onedimensional propagation is most probably the most pessimistic case (which will almost never occur under realistic or accident conditions) these experiments are suited to demonstrate that the codes are capable of predicting the worst case consequences when applied to worst case conditions. One should, however, keep in mind that energy conversion in these tests and corresponding calculations is essentially limited to the propagation phase while the main part of the mechanical energy may be released during the expansion phase.

d) **Expansion**
In this field only insufficient tools have been used until now, i.e. analytical correlations or simplistic parametrical models. (The most advanced approach was the use of a special version of SIMMER-II by W. Bohl from LANL in the ZIP study. But as this code combined melt and liquid water in one field, the results are most probably far too pessimistic.) Here again it must be the aim to apply the same codes used for premixing and propagation analysis and perform closed (consecutive) analysis of all three phases. The development in this area is still in a very early stage. Most probably we will have to resign ourselves to parametric correlations that ensure a conservative treatment. How liberal we can be in that will partly depend on the success in limiting the interacting masses by the premixing analysis.

In order to prove conservatism of the tools to be developed, experimental data deserving that designation will be required.

A standard problem is most useful when

- the results can be checked against an experiment,
- this experiment is clearly different from previous experiments and is performed only after the calculational results have been delivered (this creates the danger that 'real case' calculations may become necessary),

- a sizable number of codes is represented, and
- these codes have reached a degree of maturity that ensures that the results are not soon invalidated by decicive code improvements.

Therefore, at the moment, only the premixing codes can be envisaged to be checked in this way within the near future, next year at the earliest. The test problem should be complicated enough to involve several features that are hypothesized to be important under reactor accident conditions. In this way, not all codes will be able to describe all features but that is better than defining a problem that is so much simplified that all codes can describe all features. A way out could be to provide the full problem for comparison with an experiment and a simplified problem for inter-code comparison.

Question No. 9:

How much of the research performed (both experimental and analytical) in support of the α –mode failure issue is also applicable to "localized" FCI's (e.g., an energetic FCI next to a structural boundary where there is a need to evaluate the dynamic loading on the structure)?

Personal answer:

The primary uncertainty in determining steam explosion loads are the amounts of mass participating in the interaction. So, transfer of the results should be possible as long as the conditions for premixing are the ones considered for the in-vessel steam explosion, i.e. melt jet(s) penetrating into (deep) water. This is especially true if threedimensional code calculations can be ápplied.

Things become much more unclear when the opposite situation (water jet into melt) or stratified situations with water on top are to be considered. Such situations can most probably not be analyzed with the tools presently under development. The most (although not very much so) promising approach to these problems are special experiments. Maybe in these cases the requirement of conservatism can be somewhat relaxed because they cannot lead directly to α –mode failure (or another mode of early containment failure).

Question No. 10

Discuss the possibility and importance of chemical augmentation to energetic FCIs. Discuss the impact of chemical augmentation on the dynamic loading of structures.

Personal answer:

This problem seems to be of high potential importance. But its importance hinges on two points:

a) How much unoxidized metal is contained in the melt that relaocates?

b) How much of this metal is still unoxidized at the end of the premixing phase, i.e. when the trigger occurs?

There are indications that the presence of unoxidized zirconium may be very important for the premixing process and that it may lead to a very fine prefragmentation of the melt and thus effective quenching. This may lead to conditions not very supportive for steam explosions. So, do not only ask for explosion augmentation.

On the other side, when there should still be unoxidized metals available during the steam explosion proper they might lead to increased energy release. To what extent will largely depend on its physico-chemical state (e.g. pure metal or substoichiometric oxidic solution).

At any rate, it appears that this problem must be persued by

- experimental studies of the effects of metals,
- theoretical studies of the composition of core melts under the (many) different sequences of events that finally lead to the discharge of corium into water, and
- developing (in a first step) the premixing codes to make them capable of treating the problem of metal(s) oxidation and the influence of that on the premixing process.

From the point of view of energetics, the metals to be considered are in the first place zirconium and in the second place cromium. The other metals, notably iron and nickle, are less important because of their much smaller heat releases. However, the premixing process might be influenced by the hydrogen resulting from iron oxidation as well.

APPENDIX B-9

SERG-2 PANEL MEMBER RESPONSE

BY

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COMMENTS ON STEAM EXPLOSION INDUCED α-MODE FAILURE ISSUE*

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* To be discussed at the Second Steam Explosion Review Group Workshop (SERG-2) in Annapolis, Maryland, USA, June 15-16, 1995.

QUESTION 1

Status of Our Understanding of the α-Mode Containment Failure Issue For LWRS

ANSWER

- We believe that the answer to this question is (b). The work performed by Theofanous and colleagues and recently confirmed by other researchers has essentially resolved this issue [Cf references (6) to (8)].

- The additional confirmatory research required in our opinion relates to:

  - Melt jet fragmentation kinetics and its connection to the work on pre-mixing performed with constant diameter particles.

  - Understanding the cause(s) for the very low steam explosion potential of a (UO_2+ZrO_2) melt.

  - Work on relationship of melt properties (crust formation, variation of viscosity and thermal conductivity versus temperature) to steam explosion potential.

QUESTION 1 (CONTD.)

ADDITIONAL REMARKS

- We believe that a definitive statement, that the α-mode failure issue is not relevant for BWRs, should be issued after due consideration.

- We believe that further work on the subjects indicated above will make α-mode containment failure a non-issue. We believe that a (UO_2+ZrO_2) melt will only suffer a weak explosion, if at all, and there are large structural margins available. We believe that the fixation with α-mode containment failure is similar to that which prevailed over many years with the large LOCA. We should consider the effects of in-vessel steam explosions, which may damage the vessel internals, and possibly damage the lower head. For example,

  - Leakage from lower head and its consequence on decay heat removal.

  - Consequences of steam explosion induced water slug impact, or, shock wave, on steam generator tubes and tube sheat.

  - Consequences of substantial core material transport to steam generators, and possible release to atmosphere, depending on the scenario.

QUESTION 1 (CONTD.)

- We believe that after an accident with in-vessel steam explosion, the accident has to be terminated, and the public assured that there is no danger of a radioactivity release. The cleanup would also have to be performed.

QUESTION 2
Role & Status of Pre-Mixing

ANSWER

- We believe that melt-water pre-mixing defines the initial-conditions for steam explosion energetics, and thus plays an extremely important role.

- The pre-mixing experiments have demonstrated that the large initial heat transfer from melt to water will produce a large steam volume around the melt particles. This will limit the further exchange of energy and the initiation of the propagation phase.

- Another mechanism is that of water escape from the lower plenum through the downcomers which also limits the heat exchange possible between the melt particles and the water.

- The experimental demonstration of coolant voiding is with discrete particles of known diameter and temperature. Demonstration with melt jet is lacking.

- The analysis development on steam explosion is comprehensive for the pre-mixing phase. The codes PM-ALPHA and CHYMES predict the behavior observed in the MAGICO and other experiments, and quantatively support the limitation on energy transfer imposed by the development of a high void region.

QUESTION 2 (CONTD.)

- The choice of a large melt mass (6 to 10 tonnes) for pre-mixing by Theofanous in the prototypic case should envelop the possible participation of some melt from a stratified pool, some melt from the continuous melt delivery process, as in a jet subjected to an explosion.

- The other choices made by Theofanous, e.g., large particle diameters is conservative.

- The pressure chosen is atmospheric, which may produce greater size of the voided region than at high pressure. However, this may not be significant.

- All in all, the case of limited energy transfer during the pre-mixing phase is quite sound.

QUESTION 2 (CONTD.)

ADDITIONAL REMARKS

- The pre-mixing experiments and analysis development (2- or 3-D) have not included jet fragmentation kinetics and their effect on the pre-mixing phenomenology. We believe this is an important omission. It may have a deleterious effect, although not enough to change any conclusions.

- The melt property variations between the liquidus and solidus lines in the phase diagram have not been considered in the experiments and the analysis development. There may be additional effects and possibly large margins; e.g.,

  - UO_2-ZrO_2-Zr phase diagram shows a large change in solidus-liquidus temperature difference as a function of Zr content. This may explain the greater fragmentation observed in FARO test with Zr addition.

  - Formation of an insulating crust on particles, may reduce the heat transfer to water or steam.

  - Increase of melt viscosity may reduce heat transfer and the particle fragmentation.

  - Small ΔT between the liquidus and the solidus temperatures will reduce the penetration distance of the melt particles, before they solidify, and do not participate in the explosion process.

QUESTION 2 (CONTD.)

- Zirconium in the melt particles may oxidize. This will be a function of particle size, and will increase the particle temperature and heat transfer. The large steam volume formed may promote Zr oxidation in particles.

- The influence of the above-listed parameters, i.e. of jet fragmentation kinetics, and of the melt properties, on the pre-mixing energy-transfer-limitation case should be evaluated, experimentally and analytically. We believe, however, that the case made will hold.

QUESTION 3 (CONTD.)

ADDITIONAL REMARKS

- Perhaps, more work should be performed on this phase. The reasons are to delineate the effects of
  - Chemical energy release on oxidation of Zr in the micro particles.
  - Material properties and their variation with temperature (e.g. comparing Al_2O_3 vs. Tin or Al_2O_3 vs. UO_2-ZrO_2).
  - Ambient pressure.
  - Subcooling, which substantially reduces steam volume.

QUESTION 4
Role & Status of Triggering

ANSWER

- A trigger is generally needed to generate a steam explosion.
- Its availability for in-vessel steam explosions is not evident.
- However, as concluded by Fletcher, it is difficult to dismiss the availability of a trigger for prototypical situations.
- Thus, a trigger should be considered. However, as advised by Henry, using strong triggers in steam explosion experiments is not a good idea.
- Greater ambient pressure seems to inhibit triggering. However, reasons for this are not known.
- The ideal solution would be to determine the strength of the trigger required to generate a steam explosion in a certain mixture at the prescribed ambient conditions.

QUESTION 4 (CONTD.)

- There appears to be no model to predict the trigger strength needed. It is not clear why some mixtures explode spontaneously, while others do not, and will not, even with strong triggers.

- Thus, the status of understanding on triggering is relatively primitive.

QUESTION 5
Role & Importance of Accident Progression and Melt Relocation

ANSWER

- Mid-phase, in-core accident progression for a PWR is relatively well known for the high pressure station black-out scenario, because of the TMI-2 accident.

- For the high-pressure scenario, however, steam explosion probabilities are very low.

- Large and small LOCA with loss of ECCS, and the depressurization scenarios, are more prone to steam explosion events.

- In these scenarios, if the core becomes dry, it is possible that the melt may relocate from the core bottom, instead of from the side.

- This may result in larger masses of melt pouring, with larger mass flow rates, into the lower head water pool.

- This should not affect the alpha-mode failure estimates, since the Theofanous analyses consider melt addition over a large area and at very high rates.

QUESTION 6

Role & Consequences of Mechanical Energy Release and Damage Producing Events

ANSWER

- The role of mechanical energy release is crucial in terms of producing an alpha-mode containment failure.

- The mechanical energy release occurs in the expansion phase of the steam explosion, which commences after the propagation phase.

- The thermal energy generated can be very large (a few GJs). The mechanical/thermal energy conversion ratio is conservatively taken as ≤ 20 %. Thus, the energy partitioning and dissipation has to be very large to preclude vessel and containment failure. It has been estimated that ≤ 2 % of the thermal energy released will end up as the missile energy. Thus, if the missile energy to fail the containment is 200 MJ, and the specific melt energy is 1.2 MJ/kg, the fuel melt involved in the pre-mixing and propagation phases has to be at least 8000 kg. This is more than 1 m^3 of fuel in the lower plenum volume of about 3.6 m^3, which is highly unlikely.

- We believe that the estimates for energy conversion, partitioning and dissipation are all biased towards large conservatisms. However, there is no validation of the estimates made.

QUESTION 6 (CONTD.)

ADDITIONAL REMARKS

- We are more worried about local failure of the lower head, which leads to a break at the worst location. The lower head weld joints may become weak with prolonged heat-up. Consequences of lower head failure should be examined, e.g., for core coolability.

- It is conceivable that the upper head does not fail and the slug implodes the core and the upper internal structures into a dense ball containing 100 tonnes of UO_2. The implications of such a scenario should be examined.

- Steam generator tubes may be subjected to a slug impact due to the venting from downcomer and from the hot legs. The fuel particulates may join the slug. Tube failure and containment bypass scenarios should be examined; and discounted if found to be highly unlikely.

QUESTION 7

Adequacy of the Current Knowledge For Quantification of the α-Mode Failure Probability

ANSWER

- We believe that the current knowledge is adequate for assigning an upper limit for the probability of alpha-mode containment failure. Our estimate is 10^{-2}. We believe, however, that the additional research work recommended, particularly on the effect of melt properties on the pre-mixing and propagation phases, will reduce this estimate further. If the estimate of 10^{-2} is acceptable for issue resolution purposes, then, this issue may be considered as resolved. Confirmatory research, recommended earlier, would provide a somewhat firmer basis.

- Our basis for the 10^{-2} value is the fundamental data obtained on pre-mixing and propagation phases, and the relatively sophisticated modeling developed recently for these phases. The integral validation is very meager, and at very small scale, however, the basic limitations discovered make good sense and they should be effective at proto-typic scale.

QUESTION 7 (CONTD.)

- We believe that the research in steam explosions will continue in Europe and USA. The key areas, where we recommend further research are:

  - Jet fragmentation and its effect on the pre-mixing phase.

  - Why UO_2-ZrO_2 melt does not want to explode?

  - Effect of melt properties, and their temperature variations, on explosion potential (pre-mixing and propagation).

  - Chemical energy released during propagation and expansion phases.

  - Strength of trigger required for generating an explosion.

  - Interactions during propagation phase to define limits on conversion ratio.

- We believe that the progress achieved will be much faster than at the previous pace, since much better fundamental understanding has been achieved recently.

QUESTION 8
Status & Capabilities of the Analytical Tools/Computer Codes

ANSWER

- The status and capabilities of the analytical tools/computers codes, available to address components of the FCI methodology, or, to perform integral FCI assessments, is evaluated as follows:

  - Melt relocation and delivery to lower head: There are significant uncertainties, however conservative bounds can be established. Analyses should consider side, bottom and more than one melt pours, with different mass flow rates.

  - Melt jet fragmentation: There are models/codes (e.g., THIRMAL, TEXAS, IKEJET); however they do not specifically involve melt jet properties and phase change. The models need enhancement. There are only very limited data for model/code validation.

  - Pre-mixing: There are advanced models (e.g., PM-ALPHA, CHYMES, IVA) for this phase of the FCI. Again, their development does not explicitly involve the variation of melt properties with temperature. These models should also employ jet fragmentation as the source of the droplets they employed. The validation of these codes should be pursued further.

QUESTION 8 (CONTD.)

- Triggering: There is no understanding of this process. We believe experimental work (e.g. in SIGMA facility or at U of W) should determine the strength of trigger required to make a pre-mixture go into propogation phase, as a function of melt droplet properties. Models to predict that are needed.

- Propogation: The codes/models, ESPROSE-M and CULDESAC are quite advanced and new ideas, e.g. micro-interactions have been incorporated. However, there are not sufficient observations/data to be certain. Focused effort in obtaining the applicable data to validate these models is required.

- Mechanical energy release and damage: This is an art. Certainly, there are hydrodynamic and structural codes available, however, their application for the in-vessel geometry is not validated. Perhaps some data available from defense department, on under-water explosions should be used for validation of the codes. Ex-vessel applications are important for BWRs.

QUESTION 8 (CONTD.)

- The FCI analysis tools/computer codes have made tremendous progress in last 5 years. The multi dimensional, multi-field approach appears to be essential for description of the melt jet fragmentation, pre-mixing, propagation and expansion. The main issue is the description of the exchange terms, and, perhaps, the mechanisms of energy and mass exchange. More fundamental experiments are needed.

- A standard problem can be posed from the KROTOS test series. The standard problem procedures of 'double blind' and 'single blind' should be strictly enforced. The code developers are analysing the KROTOS experiments and there is a danger that they may be able to tune their codes to KROTOS before the standard problem exercise. An integral evaluation can be performed concurrently.

- The KROTOS test in new vessel may have greater definition. The visual record should also be available to check the calculated time variation of the various fields (droplets, steam, water, etc.) at various space locations. Thus, differential comparisons could be made.

QUESTION 9

Applicability of Research Performed to 'Localized' FCI's

ANSWER

- 'Localized' FCI's can be analysed with the analytical tools/codes recently available, e.g., PM-ALPHA, ESPROSE-M, TEXAS-III. Since there is not much validation, 'localized' FCI analyses could be performed on relative basis, i.e., compare the damage potential of an FCI near the side of pool vs. in the middle of the pool, or, an FCI at large depth vs. shallow depth. Again, under-water explosion data should be examined for clues on modeling; and later for validation of the models.

- Jet fragmentation, which is not in the leading codes, should be the source for determining the potential of a local FCI.

- We do not believe there is any data for definition of the effects of local FCI's.

- The damage potential of the 'localized' FCI´s should be evaluated.

QUESTION 10

Possibility & Importance of Chemical Augmentation of Energetic FCI's

ANSWER

- Chemical energy release during the 4 phases of a FCI is a distinct possibility. The generation of a steam volume around the melt droplets, which limits energy transfer during pre-mixing, is also conducive to the generation of chemical energy. The pre-mixing time may not be sufficient for diffusion of steam to the Zirconium in the droplets, however, the same droplets will be fragmenting during the propagation phase, and making new Zirconium layers available. Oxidation of Zr is also possible during the expansion phase, which is of relatively longer duration.

- The importance of chemical augmentation may be substantial, since the maximum energy release could equal the maximum thermal energy transfer for the pre-mixed fuel.

- The experiments currently scheduled in ANL may provide good indications. The process, however, must be scale-dependent, and one may not be able to apply the measured data to prototypic situations. Also, one should experiment with mixtures of Zr with other metallic materials; and with UO_2+ZrO_2.

QUESTION 10 (CONTD.)

- The chemical augmentation issue may be of greater importance for the ex-vessel steam explosions, e.g., for a BWR in which large amounts of Zr and other metals may be released from the vessel.

APPENDIX B-10

SERG-2 PANEL MEMBER RESPONSE

BY

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UNIVERSITY OF CALIFORNIA,

SANTA BARBARA

QUESTIONS AND ISSUES FOR THE SERG-2 WORKSHOP PARTICIPANTS

Response by T.G. Theofanous

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June 7, 1995

CONTENTS

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* These appendices were provided at the meeting but are not included here because they have now appeared in publication (see citations).

1. INTRODUCTION

Together with my co-workers (see acknowledgements) I have been deeply involved in the study of steam explosions for the past 10 years or so. We began with an application-focused approach, followed it up with fundamentally-oriented research in several topical areas, and now we are taking up again applications. By applications I don't mean merely some reactor-scale calculations, but comprehensive assessments aimed for definitive answers. We make use of the Risk Oriented Accident Analysis Methodology (ROAAM), that in fact found its genesis in the course of our treatment of the α-failure problem, and evolved in the interim while addressing the Mark I Liner Attach, and Direct Containment Heating, problems, as well as the In-Vessel Retention severe accident management scheme. We are preparing now assessments of Lower Head Integrity (under steam explosions, a companion to the in-vessel retention mentioned above) for the AP600, and of the Lower Drywell Boundary for the SBWR. These assessments require pressure-time histories on the structures evaluated, and hence an unprecedented level of understanding of the basic physics, of sophistication in analytical tools to capture them, and of depth in the verification that this is indeed so. Thus, while for α-failure some rough assessment of premixing and basic energetic-bounding considerations were quite sufficient for α-failure, now the burden of duty shifts to propagation, and by implication to also more detailed understanding of premixing. As a consequence, our fundamentally-oriented work mentioned above evolved from confirmation to the rough premixing arguments needed for α-failure, to encompass all key aspects of the coupling phenomenology in both premixing and propagation. Clearly, with all these we can do even better the α-failure.

This work creates the basis for my responses to the questions posed to the review group, and I will refer extensively to it. To help put these references in a context that they can be understood without disrupting the flow of the response, they are all summarized and explained, hopefully coherently, in this introduction.

Our overall approach to assessing steam explosions in severe reactor accidents has been recently summarized in DOE/ID-10489 (Theofanous et al., 1995A). It involves a methodology, as outlined in Appendix A of Theofanous et al., (1994a), and a set of codes as illustrated in Table 1.

The lead document in this table (DOE/ID-10489) serves as an introduction to the problem and the analytical approach. Accordingly it provides a discussion of the key phrases, including previous literature and terminology, as well as sample results from PM-ALPHA (premixing) and ESPROSE.m (propagation). The manuals (DOE/ID-10502, and DOE/ID-10501) of these two codes contain also the modelling approach, and since the reports are restricted (DOE applied

Table 1 Steam Explosion Energetics and Structural Damage Potential

Introductory and Overall Approach		The Study–DOE/ID-10489[1]
Topical Element	**Codes**	**Documents**
Initial Conditions	Special Purpose Models	In-Vessel SE: DOE/ID-10505[2] Ex-Vessel SE: DOE/ID-10506[3]
Premixing	PM-ALPHA	Manual: DOE/ID-10502[4] Verification: DOE/ID-10504[5]
	THIRMAL	Manual: EPRI TR-103417[6]
Propagation	ESPROSE.m	Manual: DOE/ID-10501[7] Verification: DOE/ID-10503[8]
Structural Response	ANACAP-3D/ABAQUS	Manual:[9] Verification: ANA-89-0094[10]
Integration/Application		In-Vessel SE: DOE/ID-10505[2] Ex-Vessel SE: DOE/ID-10506[3]

(1) T.G. Theofanous, W.W. Yuen, S. Angelini and X. Chen, "The Study of Steam Explosions in Nuclear Systems," DOE/ID-10489, January 1995.

(2) T.G. Theofanous, W.W. Yuen, J.J. Sienicki and C.C. Chu, "The probability of a reactor pressure vessel failure by steam explosions in an AP600-like design," DOE/ID-10505.

(3) T.G. Theofanous, W.W. Yuen, J.J. Sienicki and C.C. Chu, "The probability of containment failure by steam explosions in an SBWR-like lower drywell," DOE/ID-10506.

(4) W.W. Yuen and T.G. Theofanous, "PM-ALPHA: A computer code for assessing the premixing of steam explosions," DOE/ID-10502, May 1995.

(5) T.G. Theofanous and W.W. Yuen, "Premixing of steam explosions: PM-ALPHA verification studies," DOE/ID-10504.

(6) THIRMAL-1 Computer code for analysis of interactions between a stream of molten corium and a water pool. Vol. 1: Code Manual, EPRI TR-103417-V1, Project 3130-01, Final Report (December 1993). Vol. 2: User's Manual, EPRI TR-103417-V2, Project 3130-01, Final Report (December 1993).

(7) W.W. Yuen and T.G. Theofanous, "ESPROSE.m: A computer code to simulate the transient behavior of a steam explosion based on the microinteractions concept," DOE/ID-10501, April 1995.

(8) T.G. Theofanous and W.W. Yuen, "Escalation and propagation of steam explosions: ESPROSE.m verification studies," DOE/ID-10503.

(9) H.D. Hibbit, et al., "ABAQUS Version 5.3," 1994.

(10) R.J. James, "ANACAP-3D — Three-dimensional analysis of concrete structures: theory, user's and verification manuals," ANATECH No. ANA-89-0094, 1989.

technology), the respective chapters are provided here as Appendices A and B. The respective verification reports (DOE/ID-10504 and DOE/ID-10503) are expected to come out by the end of July 1995. They contain comparisons with analytical and experimental results that test key features of both the mathematical formulations and numerical implementation. Besides perspectives on strengths and limitations of the simulations, these special applications of the codes provide guidance (to the potential user) on how the codes are to be applied to various situations. An overview of the verification approach is illustrated in Tables 2 and 3. More details are provided in Appendix C, and sample results will be shown at the meeting. The type of analysis needed to assess melt pour conditions, the methodological framework employed in the utilization of these results, the tie-in to the premixing calculations, and the full demonstration of the assessment methodology can be found in the two first applications listed under both initial conditions, and Integration/Application (DOE/ID-10505 and DOE/ID-10506) (scheduled to appear shortly). Moreover, a first ad hoc demonstration of cavity (concrete) structural response under ESPROSE.m loads can be found in Rashid et al (1995).

Initial (illustrative) reactor-scale results have been provided for both in-vessel (Theofanous and Yuen, 1993) and ex-vessel (Yuen and Theofanous, 1993, Theofanous and Yuen, 1994, Theofanous et al, 1994b, and Theofanous and Corradini, 1995b) situations, in addition to those presented in DOE/ID-10489). Moreover we followed up, and confirmed, our original assessment of α-failure (Theofanous et al, 1987) in terms of the capability available a couple of years ago (Theofanous and Yuen, 1993).

We wish to close this introduction by highlighting the basic features of our approach (in order of importance):

(a) The microinteraction model, and constitutive laws to describe it, obtained under simulation of *large scale* explosions in the SIGMA-2000 facility. So far we have data for tin (up to 1800°C) and constitutive laws to describe them (Chen et al, 1995, provided as Appendix D). We are now generating data under two-phase conditions in the premixture, so as to obtain wide range of pressure-velocity combinations behind the shock wave. In the near future we have plans to do the same with iron as well as oxidic melts (ZrO_2 $A\ell_2O_2$).

(b) A comprehensive set of comparisons with analytical solutions to establish the wave mechanics aspects of ESPROSE.m in two dimensions, and in the presence of reflections off all sorts of interphases (from free water-air, to rigid water-solid, to intermediate water-two-phase). This included special solutions with large heat sources near interfaces, and nodalization studies, to realistic reactor dimensions.

Table 1. Melt Initial Condition—Summary View

Key Consideration and Related Physics	Models	Basis and Verification Status
• Thermal loading at melt pool boundaries		
—Natural convection	Correlations Nu = $f(Ra)$	COPO, UCLA experiments, and mini-ACOPO/ACOPO [Theofanous et al., 1994]
• Melt release path		
—Melt attack, Crust formation		PNC experiments [Saito et al., 1990]
—Penetration failure, Deformation, and External forces	Plugging vs Ablation	TMI experience
—Creep failure	Finite element	TMI analyses [Witt 1994]
—Heat losses to water (if present)	Film boiling, Radiation	ULPU experiments [Theofanous et al., 1994] MUPHIN experiments [Liu, 1994]
• Melt flow around structures		
—Flow distribution through perforated plates under melt inertia, gravity forces, and vapor venting	If vapor venting important, need feedback to melt pour rate	

Note: Scripted items are in progress.

Results: Melt Pour Rate ($\dot{m}_f$), Effective Pour Area (A_f), Effective Melt Length Scale (L_{f_e}) and Velocity (V_{f_e}) entering the premixing zone

Table 2. Premixing—Summary View

Key Consideration and Related Physics	Models	Basis and Verification Status
• Multifield thermal and momentum interactions	3-fluid, 2D, PM-ALPHA [App 2] 4-fluid *3D PM-ALPHA*	Integral verification with MAGICO [App. 1 and 2] and *MAGICO-2000 (Possibly also with MIXA)* PM-ALPHA — CHYMES comparisons [App 5]
• Boiling and Condensation	Film boiling, direct contact condensation, radiation transport	MUPHIN experiments, including high subcooling and high velocities [Liu, 1994]
• Multiphase drag	Friction factor correlations and collective-particle behavior	*"Cold" MAGICO-2000 runs*
• Breakup —Taylor instabilities —Helmholtz instabilities —Turbulence —Condensation shocks	*Interfacial area transport with parametric source terms*	*Guided by sample test cases under ideal conditions* Some global, indirect testing with FARO experiments [App 2], *and ALPHA experiments*

Note: Scripted items are in progress.

Results: Space time distribution of volume fractions and length scales

Melt: $\theta_f(\vec{r},t)$ $L_f(\vec{r},t)$ Water: $\theta_\ell(\vec{r},t)$ $L_\ell(\vec{r},t)$ Steam: $\theta_g(\vec{r},t)$ $L_g(\vec{r},t)$

(c) A comprehensive set of data for film boiling from spheres under single and two-phase flow (the MUPHIN facility), a unified ease-to-implement correlation, and a predictive theoretical model (Liu and Theofanous, 1995, provided at Appendix E). The correlation, is a key ingredient in PM-ALPHA.

(d) Detailed data on the multifield aspects of premixing in the MAGICO-2000 facility (Angelini et al, 1995, provided as Appendix F). These cover collective momentum interactions with cold particles of various densities, phase change dynamics with hot particles up to 1500° (moderate radiation effects) in saturated water, and condensation effects in the presence of slight (3°C) and moderate (18°C) subcoolings. Now we are prepared for experiments at 2000°C in which thermal radiation plays a dominant role. The data include premixture internal structure, such as local void fractions and particle packing.

(e) Integral simulation of the KROTOS experiments (using ESPROSE.m with the constitutive laws mentioned above) and consistent interpretation of tests that "fizzled" as well as those that produced supercritical detonations (Theofanous and Yuen, 1994)

(f) Integral "simulations" of the FARO experiments, to obtain a perspective on the breakup aspect and to exercise the PM-ALPHA capability in this area. Due to compensating effects (see DOE/ID-10489) and inherent difficulties in modelling/verification, our goal here is *not to be predictive* but rather provide reasonable envelopes of what premixtures are possible (note that data on the premixtures themselves are *not* available).

2. RESPONSES TO THE QUESTIONS

1. Is α-failure resolved?

(a) Yes. The references are: Theofanous et al (1987), Theofanous and Yuen (1993), Turland et al (1993), and the "Summary" of the CSNI Meeting in Santa Barbara (1993).

Our 1987 study was reviewed rather extensively. The main question raised in this review was on the causal relation that described premixing. The figure that shows the relation we used, and some alternatives proposed by one of the reviewers (M. Berman) is reproduced here as Figure 1. In a recent revisit to this question (Theofanous and Yuen 1994) using PM-ALPHA, which was at the time tested against the MAGICO experiments, and also compared with the CHYMES code, we find the result shown in Figure 2. The premixing limitations used in 1987 are now well established.

(b) None. Work carried out in context of assessing lower head integrity for certain PWRs, and addressing structural concerns from en-vessel explosion in certain BWRs, will provide higher in-depth insights of the large margins available.

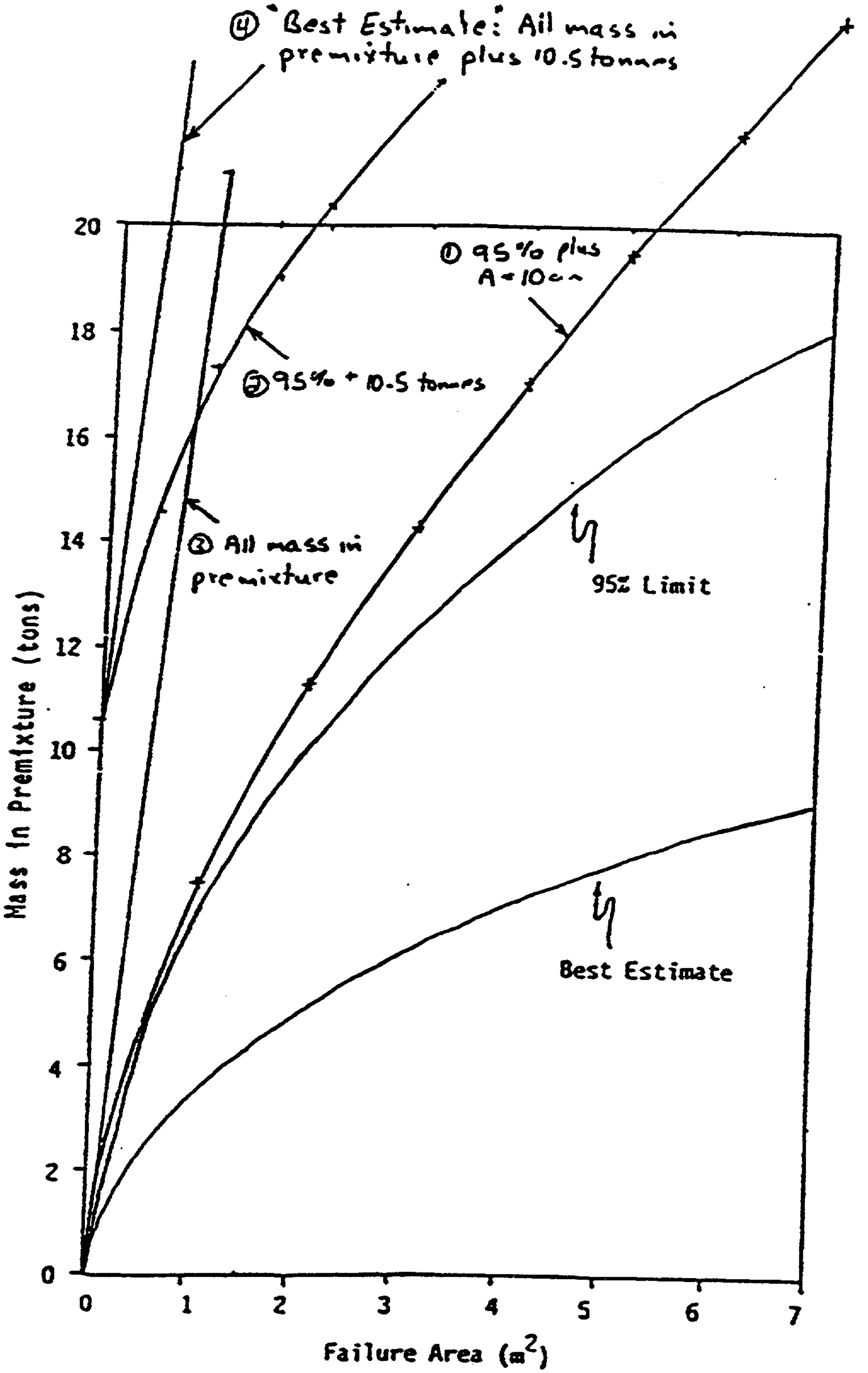

Figure 1. Probabilistic Functional Representation for the Correlation Between Mass of the Melt in the Premixture and the Size of the Core Support Failure Area.

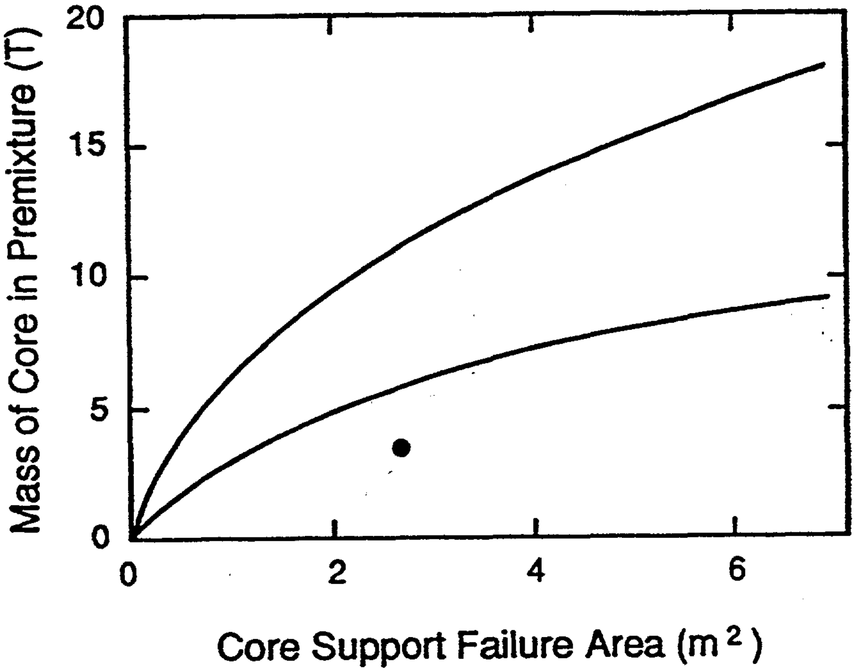

Figure 2a. CR1 according to NUREG/CR-5030. A flat distribution was assumed between the 5 and 95% limit lines shown. The point refers to a calculation presented later.

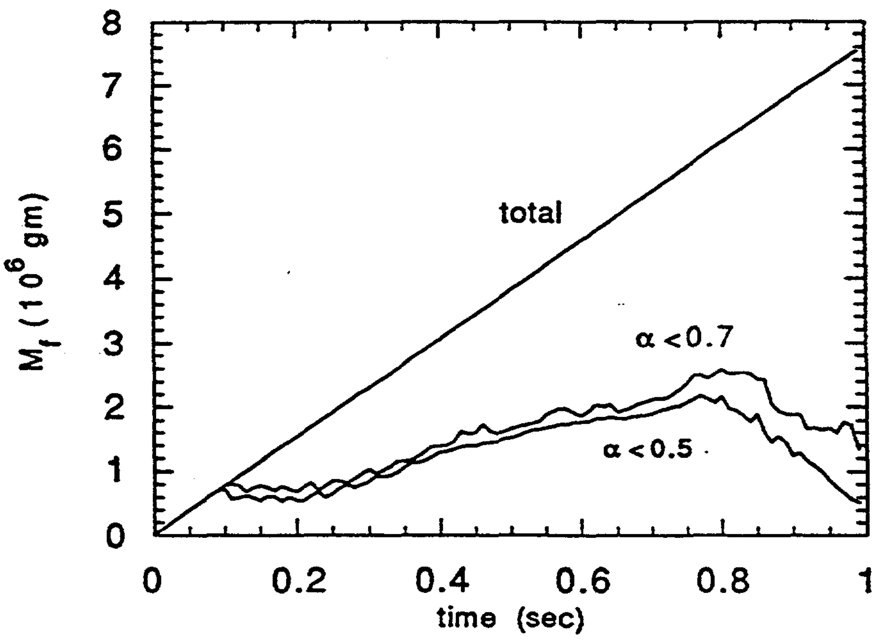

Figure 2b. Premixed mass transient compared to the total quantity of melt poured.

(c) Not applicable as far as I am concerned. The assessment initiated with Theofanous et al (1987) was not followed up in accordance with the ROAAM, mainly because after the UK work and the CSNI meeting (see item a), the issue did not appear to be pressing enough to do so. Moreover, there is the consideration made in item (b) above. If in this SERG-2 there is a substantial sentiment on a formal closure, I would recommend that the two previous assessments are integrated (generically) and followed up in the ROAAM manner to completion. This exercise could include a significant fraction of the SERG-2 praticipants in an *active* role, and it could naturally lend itself to several "standare problems" exercises that would appear to be attractive at this juncture, in any case.

2. Role and Status of Premixing

If one wishes to consider arbitrary size pours, then premixing plays a key role in addressing α-failure. We now have much better understanding that such massive pours cannot be expected. Also we have a lot of data from the MAGICO, MAGICO-2000, and MIXA tests that demonstrate the water depletion that limits the potential energetics from massive pours. We also have code-to-code comparison and data-experiment comparisons with the codes PM-ALPHA and CHYMES that render consistent predictions. (Note—nothing is, or can be, adjusted in these calculations.) More experiments that are well-defined are expected from France and Germany, and we expect them to be confirmatory. More code predictions from various places are expected also, and we expect them to be confirmatory, too.

If the characteristic dimension of the pour is large, we need to consider breakup. Again, compensating effects dominate. With slow breakup, the interfacial area needed for fragmentation is small, which limits energetics. Rapid breakup creates the interfacial area, but it creates voiding (water depletion) too. On this basis, it is important to recognize that breakup is not necessary to approach in a predictive attitude. Moreover, we do not think it is possible to do so in its fully dynamic character. We only need to exercise this degree of freedom in a more or less parametric sense, while at the same time show consistency with whatever limited experimental data are available (FARO, ALPHA, etc.).

3. Role and Status of Propagation

As explained in the introduction, propagation was not needed, and played no role in assessing α-failure, so far. I expect our present capability (ESPROSE.m) can be used to show much larger margins than those found in earlier assessments. But this will fall out from our lower head integrity study.

As explained in the introduction the subject of propagation gained a new status (predictive, that is) with the advent of the microinteractions model. This in conjuction with constitutive relations from it derived from large-scale explosion simulations in the SIGMA-2000 facility afford, for the first time, a rational approach to this long-standing problem. On this basis, integrated in 2D, and soon to be in 3D, in ESPROSE.m, loads on adjacent structures can be evaluated realistically, for any given premixture.

4. Role and Importance of Triggering

In Theofanous et al (1987), as well as in our present studies for the advanced passive plants, we are interested only in low pressure scenarios, and assume conservatively that an explosion will occur at the worst time in a premixing transient (typically, when the melt hits the floor). I agree with the very substantial assessment of triggering provided by Fletcher (1995), and agree also with the use of it in the UK α-failure assessment study (Turland et al, 1993).

In principle triggerability should be possible to evaluate in the SIGMA-ESPROSE.m framework currently used for propagation. However, it would be a much more arduous task as experimentation now must cover a much broader range of pressures (currently, we have no plans in this area). Some fundamental information is expected nevertheless from the planned experiments with oxidic melts. In these we would include also high initial premixture pressures to investigate the pressure cutoff question.

5. Role and Importance of Accident Progression

As noted under item 2, this is complimentary to the premixing argument. This is not needed for α-failure, since premixing limitations alone are adequate to cover large pours, but it is pursued for assessing lower head integrity in DOE/1D-10505.

6. Role and Consequence of Mechanical Energy Release

So far this has been done, for α-failure, in the studies referenced under 1(a), in a bounding manner (Thermodynamics). Work done now for lower head integrity is expected to demonstrate the extreme conservative nature of these early assessments. As far as damage-producing or mitigating events and the role of the upper internal structure we make reference to Lucas et al (1987). Especially the role of the massive core plate to "focus" the slug energy received by it, into a short interaction between it and the upper head should not be underestimated.

7. What is Failure Probability?

(a) Yes. Our conclusion in Theofanous et al, 1987, remains and with bigger margins than ever before, I conclude that α-failure is "Physically Unreasonable." I would hesitate to use a numerical extimate unless somebody told me what various such numbers mean. In ROAAM the extremely conservative nature of these early assessments. As far as damage-producing or mitigating events and the role of the upper internal structure we make reference to Lucas et al (1987). Especially the role of the massive core plate to "focus" the slug energy received by it, into a short interaction between it and the upper head should not be underestimated.

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8. Discuss Status of Analytical Tools

This was addressed in the introduction and in more detail in the appendices. My bottom line is that currently PM-ALPHA and CHYMES, (with subcooling capability, which I think was added recently) are both ready for use in assessing premixing, while I would use also THIRMAL or IKEJET for some added perspectives. In propagation, I would feel comfortable only with ESPROSE.m (due to the microinteraction feature).

9. Research for α-Failure vs. Localized FCIs

The "how much" is not really a well-posed question. As explained in the introduction, our research at UCSB is oriented to the dynamic loadings on structures. This work subsumes what is (or was since the job has been done) needed for α-failure, and is expected to reveal even larger margins.

10. Chemical Augmentation

In a power reactor accident any (or most) anoxidized zirconium is expected to separate out at the bottom core and form a blockage there. Any additional amounts in the melt pouring off from the side would be highly diluted, as dissolved in the metallic (steel) or oxidic phases. The chemical augmentation found in pure aluminum melts exploding in water (Theofanous et al, 1994c, Rightly et al., 1993) is not possible under diluted conditions. This is an interesting problem to determine the mechanism of coupling between the physical and chemical events (and hence determine the conditions under which they occur) but it is totally uninteresting in the LWR safety context.

we use a physically-based scale only as an interim tool to integrate among the various parts of the problem, and convert back to physical meaning the end result (using the same scale).

8. Discuss Status of Analytical Tools

This was addressed in the introduction and in more detail in the appendices. My bottom line is that currently PM-ALPHA and CHYMES, (with subcooling capability, which I think was added recently) are both ready for use in assessing premixing, while I would use also THIRMAL or IKEJET for some added perspectives. In propagation, I would feel comfortable only with ESPROSE.m (due to the microinteraction feature).

9. Research for α-Failure vs. Localized FCIs

The "how much" is not really a well-posed question. As explained in the introduction, our research at UCSB is oriented to the dynamic loadings on structures. This work subsumes what is (or was since the job has been done) needed for α-failure, and is expected to reveal even larger margins.

10. Chemical Augmentation

In a power reactor accident any (or most) anoxidized zirconium is expected to separate out at the bottom core and form a blockage there. Any additional amounts in the melt pouring off from the side would be highly diluted, as dissolved in the metallic (steel) or oxidic phases. The chemical augmentation found in pure aluminum melts exploding in water (Theofanous et al, 1994c, Rightly et al., 1993) is not possible under diluted conditions. This is an interesting problem to determine the mechanism of coupling between the physical and chemical events (and hence determine the conditions under which they occur) but it is totally uninteresting in the LWR safety context.

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(b) Consolidation of results and development of the PM-ALPHA and ESPROSE.m as codes, with my colleague Professor W.W. Yuen and S. Angelini (DOE ARSAP sponsorship).

(c) Development of the microinteractions concept, and implementation into the ESPROSE.*m* code, with Professor W.W. Yuen (DOE ARSAP sponsorship).

(d) Premixing experiments in MAGICO, with H. Amarasoorinya, S. Angelini, and the CRSS engineer, Mr. T. Salmassi (NRC RES sponsorship).

(e) Premixing experiments in MAGICO 2000, with S. Angelini and T. Salmassi (DOE and ARSAP sponsorship).

(f) Constitutive laws for microinteractions in SIGMA-2000, with X. Chen and T. Salmassi (DOE ARSAP sponsorship).

(g) Film boiling in the two-phase flow with C. Liu (DOE Office of Energy Research and DOE ARSAP sponsorship).

(h) Chemical augmentation threshold for Aluminum in SIGMA with P. Di Piazza, X. Chen, T. Salmassi, and M. Frey (DOE Office of Energy Research sponsorship).

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APPENDIX B-11

SERG-2 PANEL MEMBER RESPONSE

BY

DR. BRIAN TURLAND

AEA TECHNOLOGY

STEAM EXPLOSION REVIEW GROUP - 2: RESPONSE TO QUESTIONS AND ISSUES

B D Turland
AEA Technology

June 1995

The views expressed are those of the author and have not been endorsed by AEA Technology or any other organisation.

The format used here corresponds to that given in the letter of T P Speis, dated 10 May 1995. The questions and issues are given in *italic type* while the responses are in normal type.

A summary of the main conclusions and recommendations is given at the end of this response.

This version has been edited to take account of discussion at the meeting of the Review Group held on 15 and 16 June, 1995. However, there are no substantial changes from the draft version presented to the Review Group.

1. *In your opinion, what is the status of our understanding of the α-mode containment failure issue for the LWRs? Is it, in your opinion, resolved, ie of little or no risk significance.*

   (a) *If yes, cite the relevant references.*

   (b) *If essentially resolved, what additional confirmatory research is required, in your opinion, to fully resolve the issue?*

   (c) *If not resolved, ie if the residual uncertainties still remain large and/or if there are still unanswered questions about the α-mode failure, discuss specific additional research that will be needed to answer the questions and to address the uncertainties. Discuss the approach to research areas thus identified, potential benefits to be derived from the research, and indicate the time frame for accomplishing the research objectives.*

Using the definitions above as guidelines, my view is that the status of resolution lies on the (c) side of (b).

First we must consider what the target is that is equivalent to showing that the α-mode failure is of little significance. Given the potentially high releases and early failure time, I would seek to be assured that the probability of containment failure by this mechanism, given a core melt, lay below 0.01 with a good level of confidence, and was, preferably, at least one order of magnitude less than this.

Such a statement for the target, while expressed in probabilistic terms, does not preclude a more mechanistic approach if this can be defended. However, if we have to talk in terms of probabilistic targets (set at whatever level) we must face up to what is meant by the notion of probability as it is used in α-mode assessments. The 'target', as I have defined it, combines the notion of a frequentist target (1 in 100 or less), with the notion of confidence (unquantified: high level). In practice, α-mode assessments, at whatever level of complexity, have a strong subjective element, and the 'final probability' that is arrived at is in my view closest to the gambling odds that one would be prepared to take that given one core melt-down in the future there would not be a containment failure induced by a steam explosion. This may reflect an underlying belief that for real plants the actual likelihood is zero, whilst allowing for some uncertainty in one's convictions.

In these circumstances the issue should not be considered closed unless the subjective probability is significantly lower than 10^{-3}, representing some combination of a frequentist target (to take account of stochastic and sequence variations) and the element of confidence in the judgement. It is my belief that we are at about this level (still), so practical closure of the issue is close. However, this does rely on subjective judgements which can change. As a minimum, confirmatory research is desirable to give weight to the subjective assignments, as is continued dialogue between those active, or with experience, in the subject so that a consensus view may develop.

This confirmatory research should be focused on issues that can make a difference to the overall assessment. The major difficulty is that in a probabilistic assessment the α-mode failure probability is determined, in general, by the 'tails' assigned to (some of) the distributions for the usual input quantities (eg melt mass relocating, conversion efficiency, trigger likelihood) which represent the analyst's conclusions that while such values are unlikely they cannot be excluded with the current data. The quantification of these tails represents the greatest challenge in an assessment, and has the greatest effect on the calculated failure probability. Thus, based largely on heuristic arguments and some analysis, I have considerable confidence in low relocation rates, but scenarios can be envisaged (eg core disruption by an initiating interaction) that could produce a larger mass flow rates. Once recognised, I have to allow for this in the tail of the mass flow rate distribution (or have another branch that allows for the effect of pre-cursor interactions in the event tree). But how is this quantified? I am confident that such induced large mass flow rates are unlikely, but possible at the 10% level. To improve the overall α-mode assessment, I need to put firmer bounds on this, or the equivalent tail of other distributions. **NB. The fact that α-mode failure is the combination of a number of threshold events means that probabilities can only be used meaningfully when used to express the ranges of quantities, ie through the quantification of input distributions, and then evaluating the likelihood that the threshold is reached.** Some new understanding may come along and truncate the tail of one distribution sufficiently to eliminate concerns over α-mode failure (this has been the hope for pre-mixing and, at higher pressures, for triggering probability, but, so far, such firm conclusions cannot be justified by the available data and modelling).

Based on the assessment performed for the Sizewell 'B' PWR [1], the topics which might repay further study are (i) melt progression and relocation; (ii) determination of conversion efficiencies (including pre-mixing, the mixture characteristics that will support a propagation, and the venting of the interaction region) and (iii) triggering. The ameliorating effects of lower head failure might also be added to this list, at least looking at how the conditions required for lower head survival will constrain the loadings that can be delivered to the upper head.

Looking at what has been achieved in understanding so far, and the difficulties of model validation, I would not spend further effort specifically on triggering. Rather I would assemble a database of relevant information, which could be added to as new experiments are performed.

As far as melt progression and relocation is concerned, I would make this the primary aim of the continuing work in core degradation modelling (along with termination prior to relocation). There is likely to be the need for a few well-focused experiments for model validation and the production of suitable materials' data (eg crust properties).

For pre-mixing, I would curtail activities on solid particles, unless this is concerned with direct validation of a feature of the modelling code that is used in the assessment (eg if I wish to demonstrate that the steaming rate is self limiting, the known surface area of solid particles is a useful experimental constraint). Otherwise, I would concentrate on the break up of large (100 mm) diameter jets, with, unlike FARO as it is currently, sufficient diagnostics to determine what is going on, and perform FARO tests (see below) designed to test the limits to mixing hypothesis by ensuring sufficient surface area of melt droplets per unit cross-section of the vessel.

For propagation, understanding is still insufficient. Experiments with controlled external triggers are the best way to look at the circumstances in which escalation can occur and provide data for model validation. I support future activities in KROTOS with corium melts, but do not wish to see the facility depart from a one-dimensional geometry. KROTOS has highlighted the apparent ease with which corium melts undergo coarse fragmentation. This issue should be pursued in separate effects experiments, as should the dynamics of fragmentation in a pressure wave for real corium materials (akin to the SIGMA experiments).

It is possible that the topics discussed so far will give sufficient confirmation of low failure probability that work is not required in other areas. However, this may not be the case, and questions of conversion efficiency may need to be addressed. Some of this would be based on the 1-D propagation work, but there may be the need to argue that multi-dimensional explosions are less efficient at slug acceleration (as intuition and code calculations now imply). The prospect of performing meaningful multi-dimensional experiments with real materials for code validation (ie with high data requirements) are slight. It would be better to determine what aspect of the multi-dimensional calculation requires validation and design a simpler experiment for this purpose. This will most likely concentrate on the role of vent pathways, and the role of steam-rich regions.

Work should be focused by always considering the plant perspective first. This is best achieved by maintaining a current 'best guess' α-mode failure assessment. If this can be achieved at an international level, so much the better. It is my belief that a reliable integrated model is a pipe-dream with the resources that can reasonably be expected, so the current assessment methods based on combination of more or less reliable mechanistic calculations, scoping calculations, experimental data and engineering judgement will be needed for the foreseeable future. Hopefully, the work envisaged will be able to allow some judgements to be made with greater confidence and allow the ranges of some parameters to be reduced.

As far as timescale is concerned, it is important that there is a co-ordinated programme. The FARO-LWR Expert Group may form a basis for this, particularly as the majority of the experimental work could be performed at Ispra. However, it would be important for such a Group to have a broader remit derived from plant assessments and to be able to access and influence work in related areas, such as melt progression. Other nations, particularly Japan and Russia, who are not currently involved in FARO also have significant contributions to make, and arrangements for their involvement should be encouraged. The history of molten fuel coolant interactions has tended to be one of 'will o' the wisp' solutions, and I am reluctant to say that given two years effort we can close the issue for good. However, we do now have a good platform for the necessary work in a number of areas, and while the tasks that are desirable are still challenging, both from the modelling and experimental viewpoints, they are within current capabilities and will provide a greater level of assurance in steam explosion assessments.

2. *Discuss the role and status of premixing in addressing the α-mode failure issue.*

Premixing is the area where there has been the greatest investment in experiments and codes with a view to closure of the steam explosion issue. It is quite clear that early limits on the pre-mixture that could be formed were over-optimistic, but the area still has significant appeal because it may well be possible to demonstrate that the amount of core melt that can be well-mixed with water is only a few tonnes. If this is the case, high conversion efficiencies would be required for a containment threatening event.

While significant water depletion has been verified in the MAGICO tests and steam chimneys are apparent on the high speed videos for the MIXA tests that were performed under saturated conditions, this, by itself does not validate any particular claim for 'limits to mixing' even when the coarse mixing codes make reasonable simulations of these tests. A major question is "What does need to be demonstrated by the codes and the experiments to validate a 'limits to mixing' argument?" It has been suggested previously that regions of high void fraction could be eliminated from consideration (ie the liquid coolant should be a continuous phase, or heuristic limits were set at 70% or 90% void fraction). If such limits to what needs to be considered as the mixture region could be validated it would make the pre-mixing task significantly easier (70% void fractions have been achieved in MAGICO [2][1]); however there seems no firm basis for any limit and there is evidence from the JAERI ALPHA experiments of steam explosions occurring at a high overall void fraction (estimated at 70% for experiment STX021 [3]). It is possible that developments in propagation theory may be able to justify some void fraction cut-off in the future, but this is currently not the case.

One can either look for a simple limit to mixing - initially the flat plate critical heat flux was suggested, but this is far exceeded in the FARO-LWR tests [4], or one can look for an integral quantity in the mixing calculations. Any simple limit is likely to be linked to water fluidisation by the steam generation. The inferred steam generation rates in the FARO L-11 test were close to those anticipated to give water fluidisation, but there is no evidence that this provided a self-limiting process - indeed analysis indicates that there must have been good melt-water contact to produce this quantity of steam [5]. As discussed below, FARO experiments should be performed to attempt to demonstrate that self-limiting steam generation conditions can be reached.

Without the heuristic cut-offs on void fractions, integrals over the whole of the predicted mixtures need to be generated. It might be hoped that such integrals would indicate that there would be insufficient thermal energy transfer between melt and coolant, even if instantaneous local thermal equilibrium were reached, to produce a sufficiently damaging explosion irrespective of the pour characteristics. Results obtained so far for the large pours necessary to challenge the containment have indicated that considerable amelioration is expected through the relative distribution of melt and water. However maximum values obtained with CHYMES-2 (whose drag and fragmentation models are consistent with correlations for fluidisation) give typically 5 GJ (more if the initial melt length-scale is higher) [6]. These values are a cause for concern if the conversion efficiency approaches possible thermodynamic values. This is considered unlikely given the large steam voids predicted by the mixing calculations.

The set of calculations referred to were performed for initially saturated conditions, but allowed for the sub-cooling induced in the mixing region caused by its pressurisation because of the restricted vent areas. Rather surprisingly there was much less effect of initial pressure on the limits to mixing than had been anticipated; this is because induced sub-cooling is much more significant for the lower initial pressures and off-sets the higher fluidisation limits expected at higher pressures. Counteracting feedback effects on the melt inflow velocity were not taken into account, but neither was the possible swell of water into the melt release region. These considerations suggest that the full reactor system should be considered in premixing calculations rather than just the lower head region.

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1 Recent MAGICO tests with zirconia at 1500 C reported at the review group meeting by Theofanous have demonstrated local void fractions in excess of 80% [10].

Calculations and experiments indicate that making a 'limits to mixing' argument with significant sub-cooling would be much more difficult.

Finally, it is of interest that the highest values of potential thermal yield (greater than 15 GJ) came from jets that had not fully broken up, with the final melt length-scale still of order 100 mm. To eliminate such pours from consideration one has to argue that either melt will fragment to smaller length-scales or that there will be a significant reduction in explosion efficiency because of the large melt length-scale.

To conclude, while considerable progress has been made on pre-mixing and 'limits to mixing', it is my view that this will be insufficient, by itself, to close the steam explosion issue, even if it becomes possible to validate sufficiently the mixing codes in near prototypic conditions. Other arguments have to be used in association with 'pre-mixing' - these may relate to the low likelihood of the large pours usually assumed, heuristic void fraction limits to the region considered, conversion efficiencies (particularly in inhomogeneous media) and restrictions on the melt-lengthscale for efficient participation in an explosion.

3. *Discuss the role and importance of triggering (trigger availability and triggerability) in addressing the α-mode failure issue. Discuss the role of pressure threshold is suppressing the triggering.*

The difficulty of triggering alone could provide a satisfactory resolution of the α-mode failure issue. However, it has proved one of the most elusive areas in steam explosion assessments (see [7]). For some systems, in some conditions, triggering can almost be guaranteed (eg the JAERI ALPHA experiments with iron-alumina thermite at 1 bar). In other systems, including those with UO_2, triggering is more stochastic. For instance in experiments performed at Winfrith with UO_2/Mo melts, no triggering occurred in 7 of the 9 WUMT tests or 11 of the 14 HPTR tests (which had an external trigger) or in any of the 5 MIXA tests. However, explosions have occurred in a number of other experiments, often triggered, it seems, by base impact of part of the melt container, or in the case of one HPTR experiment (at 5.8 MPa ambient pressure!) by injection of cold water into the premixture. While it is possible to determine trends from the database (such as coolant sub-cooling increases the likelihood of triggering and melt dispersal makes it less likely), there is no firm basis for quantification for reactor melts at large scale.

In my view, neither arguments for early triggering at low pressure or no triggering above a pressure cut-off are defensible with sufficient certainty to preclude the possibility of α-mode failure. Heuristically both seem reasonable, and some credit was taken in the UK steam explosion study [1] for both effects. However, the paucity of prototypic data and the absence of any agreed model makes progress in this area very difficult. While many in the subject state that triggering at high pressure will not occur (despite the HPTR result at 5.8 MPa), I wonder how surprised people would have been if the leading melt blob in the FARO-L14 experiment had triggered some interaction when it arrived at the catcher, possibly encountering water with some (induced) sub-cooling there. The HPTR result would have been re-evaluated as would be the entrapment mechanism and views would have been revised. As it happened there was no interaction in this experiment, nor in the other 3 successful tests in FARO at 5.0 MPa initial pressure. Taking a Bayesian approach, such data may be used to discount the probability of triggering at this pressure of greater than 0.2 (even if 0.2 were the real probability the chance of obtaining the current set of experimental results is as high as 0.4). However, one may look at the data another way - so far in FARO less than 400 kg of melt has been poured into water, with no explosion; in the plant we are concerned, with typically 50 times this quantity, so we might reasonably expect the plant probability to be much higher than that in individual experiments. Indeed this is just the argument used to justify the high likelihood of early triggering at low pressures.

The best that can be done with triggering is to assemble the database and test it against various hypotheses, taking account of differences in materials and test conditions. It had been hoped to attempt such an approach for the UK study using a Bayesian method, and several different hypotheses regarding the likelihood of triggering (eg whether or not the likelihood scales with the mass flux), but effort was limited as, I suspect, are the data.

4. *Discuss the role and status of propagation in addressing the α-mode failure issue.*

The emphasis on pre-mixing has meant that there has been limited work only regarding propagation. If it is accepted that pre-mixing by itself does not allow the α-mode threat to be eliminated (a view that I subscribe to based on plant-scale mixing calculations - see above), then propagation issues have to be addressed. These may provide a limit to the richness of mixture through which propagation is physically possible, or give improved insights into the conversion efficiencies obtained in experiments and their applicability to larger scale interactions.

As discussed under the modelling question below, there have been some significant advances in the area of propagation in recent years, with an ability to broadly match some of the experimental data with simulants in one dimension. It is still not clear what benefits to an assessment will come from applications to corium in one-dimensional geometry. The principal issue is the escalation length, which will depend on the fragmentation laws, yet to be investigated experimentally for real materials in the regimes of interest.

Propagations in two dimensions have also been examined, with interesting results, which conflict with previous SIMMER studies - the new calculations show the benefit of void regions in lowering pressures, while the SIMMER calculations showed void regions being closed off. This is very important for the expansion phase and the question of the circumstances, if any, in which a coherent slug can be formed. However, as yet there is no validation of the propagation models in more than one dimension. Assuming that progress is made in one-dimensional systems for validating the basic propagation model, it should be possible to validate those multi-dimensional effects that are key to a steam explosion assessment by simpler experiments.

5. *Discuss the role and status of accident progression and melt relocation in addressing the α-mode failure issue.*

There is strong evidence that efficiencies in stratified geometry are limited, so the threat to the vessel and containment arise largely from the melt that is passing through the water. Without claiming credit for any additional limitations brought about by pre-mixing, the likelihood of a damaging steam explosion becomes substantially reduced for melt relocation rates of less than 1 te/s (or even 5 te/s). With a typical melt velocity of 5 m/s this corresponds to a flow area of about 0.024 m^2 (or 1.2 m^2 for the higher flow rate). This is equivalent to a pour diameter of 0.17 m (0.40 m for the higher flow rate). Depending on the reactor design and the melt relocation route, such relatively large diameter pours may be unlikely. The evidence from TMI-2, where relocation occurred through the bypass, supports significantly lower relocation rates.

In the UK we have attempted to look at the likely relocation route in some detail for our PWR, with the conclusion that low flow rates through the bypass are likely, but larger pours through the lower part of the core cannot be eliminated. The work drew attention to short-comings in even the most mechanistic codes that have a significant effect on the melt relocation rate:

1. The codes either assume that the melt retaining structure is intact or fails co-incidentally over a whole radial ring of the core, thus suddenly opening up large flow areas non-mechanistically.

2. The treatment of the lower fuel nozzles is of insufficient detail, as this is the most likely site of final crusting prior to melt release, if release is through the central part of the core.

3. Studies of relocation into the bypass should take account of the proper core cross-section. Scoping studies indicate that the anticipated melt superheat, when relocation into the bypass occurs, is significantly lower if the real cross-section is used rather than a cylindrical equivalent.

In my view none of these modelling issues, which would need to be accompanied by an improved understanding of crust behaviour, are more intractable than the details of mixing or multi-dimensional propagation behaviour. I believe, therefore, that accident progression and melt relocation studies have much to contribute to the α-mode failure issue. Development of SCDAP/RELAP5 should be oriented to provide models at sufficient level of detail for a realistic assessment.

6. *Discuss the role and status of mechanical energy release and damage-producing events in the context of the α-mode failure issue.*

It must be self-evident that the release of mechanical energy is an important component of this issue: no mechanical energy - no containment failure. There has been a tendency to associate this phase of the interaction with the propagation phase referred to above. Indeed, in the widely accepted Board-Hall model, it is the production of mechanical energy that drives the propagation. However, the expansion timescale, over which the mechanical energy is realised, is potentially much longer than that for propagation. Another viewpoint is that propagation determines the release of heat from the melt to heat in the coolant, while in the later expansion phase conversion to work occurs. There has been a tendency to have relatively simple models for the expansion phase, which do not reflect the likely disposition of materials or allow for possible dissipative processes.

A major issue is whether there is a suitable slug of material on which the mechanical work can be performed. The large steam voids calculated in plant-scale mixing calculations suggest that venting is likely to reduce the efficiency of slug acceleration.

In the plant, accelerating a slug with the potential to do damage to the upper head must occur over a period of time. Over the same period of time the high pressure bubble produced by the explosion can expand through any weaknesses in its constraints. Simple allowance for this was made in the UK study, and shown to be significant; indeed in some cases the back-pressure produced can begin to resist the slug motion that would otherwise occur.

There has been less work on the direct coupling of the shock waves to structures, on the grounds that most of the potential for mechanical work resides in the high pressure bubble rather than the leading shock structure. However, the propagation models could be used to drive a structural response code to investigate possible effects in more detail.

In a reactor accident, the kinetic energy impact on the upper head may be considerably less than that of the initial slug. Attempts have been made to quantify the energy absorbed in the deformation and failure of structures that the slug encounters. These use a combination of simple formulae, finite element analysis and model experiments. Into this must be input uncertainties on the state of a number of structures at this stage of the accident and the appropriate material properties. However the largest uncertainties probably result from the hydrodynamic behaviour of the slug; kinetic energy in the upward direction is lost if the slug is diverted sideways prior to structural failure, and energy is also lost as more material becomes associated with the upwardly moving slug (the coefficient of restitution arguments).

It is my view that the energy losses and the energies required to fail the upper head and containment for a large dry PWR (this will be plant specific) are reasonably well-bounded. While these energy absorption processes are sufficient to contain the majority of interactions expected (those with a mechanical yield of typically 1 GJ or less), the reactor vessel and the containment are not strong enough to resist the largest events that can currently be contemplated. Refining the treatment of energy absorption and dissipation processes is unlikely to have a major effect on the assessed containment failure frequency. I do, however, believe that there is potentially more to be gained by looking at whether slug energies of 1 GJ, or more, are really feasible, because of the venting potential.

In the UK study we did not claim lower head failure as a mitigating event. This was on the grounds that it was unclear that sufficient pressures would be generated to lead to lower head failure, and that the reason the upper head could fail with the lower head intact was that energy was extracted from the slug on a much shorter timescale than it was input (as in a gun). For this to be the case, a reasonably coherent slug must exist, which is the greatest uncertainty. Whether an in-vessel steam explosion can induce lower head failure is still uncertain. The high super-critical pressures necessary to fail the lower head have been found in experiments with alumina melts in KROTOS, but these would have to be applied to the lower head for some time to cause failure, implying that the explosion was well-tamped.

7. *In your opinion, is our current knowledge of premixing and propagation phenomena adequate for a better quantification of the α-mode failure? Based on your own knowledge, are you now able to assign a better probability (likelihood) measure to this failure mode?*

   (a) *If yes, provide your estimate(s) and the basis for it.*

   (b) *If no, do you think it is reasonable to expect that this will be possible sometime in the future? Provide your reasoning and indicate what key developments will be needed to meet the expectation.*

Better than what? More scrutable, I believe - which is important.

There are significant gaps that still have to be represented in an assessment by very subjective probability assessments. My colleagues and I prepared an assessment for the Sizewell B PWR, completing the work in 1991 [1]. Based on our assessment of the available information in the form of probability distributions for:

- Melt mass relocating
- Melt flow rate (conditional on mass relocating)
- Time to base contact
- Triggering distribution
- Equivalence factor for melt already pooled in the lower head
- Specific thermal energy of the melt
- Conversion efficiency (without venting)
- Slug energy (conditional on 'explosion energy')
- Energy to crush and fail structures
- Failure energy for the upper head
- Missile energy should the upper head fail
- Missile energy to fail the containment

containment failure probabilities of 3×10^{-4} at 0.1 MPa, 6×10^{-4} at 6 MPa and 2×10^{-4} at 15 MPa were obtained. Subsequently, on the same basis an evaluation was made for 1.0 MPa, which produced a value of 1×10^{-3}. All these probabilities are conditional on a large core melt having occurred. Sensitivity studies were also performed taking a more pessimistic view of the assessed data. This led to probabilities up to one order of magnitude higher. It would have also been possible to take a more optimistic view of the data (eg by assuming that triggering was impossible at 15 MPa, thus reducing the probability to zero), but in our view the data and understanding were currently not sufficient to justify such quantifications.

There is an element in this assessment of having input probability distributions that the analyst feels comfortable with (the subjective element). The need to defend such judgements tends to make them more rather than less conservative (ie to give a higher value for the failure probability). It should be recognised that our interpretation of the results of this study is that there are no grounds yet to say steam explosion induced containment failure is physically impossible; rather the argument depends on not generally getting a combination of circumstances that could, in principle, lead to containment failure.

It is interesting to note that this assessment was performed before much of the detailed mixing studies had got underway, before the FARO-LWR tests had been performed, and before the recent progress in propagation modelling. The study has been reviewed annually, and, so far, it has been concluded that these new data and interpretation do not have a significant impact on the judgements made earlier (note that a propagation model was not used in the quantification, because of concerns over its validation at that time).

The interpretation of the FARO-LWR experiments [4,5] supports the view taken for the assessment that stringent limits to mixing could not be justified, and recent modelling with induced sub-cooling [6] has tended to support that view further. The effect of this is likely to raise the low pressure probability with respect to those for higher pressures.

Limits on melt mass relocating played a major role in the assessment. If relocation were confined to the bypass route the probability would be much lower; however current assessments indicate that the released melt may not have enough superheat to reach the lower head by this route. This topic though merits further study, and indicates how performing an integrated plant assessment may give new indications of what really are the key issues.

The assessment referred to was performed for a specific plant. As the discussion of melt relocation indicates, the results are plant specific and may not carry over to other plants (eg this plant has a secondary core support system, making global low core plate failure highly unlikely).

8. *Discuss the status and capabilities of the analytic tools/computer codes available to address various components of the FCI methodology or to perform integral FCI assessments. How much verification have these analytic tools had? Are there well defined experiments against which a number of these tools can be assessed? Provide your recommendations regarding the need to perform a "standard" problem, preferably one in conjunction with an integral evaluation.*

The status of validation of the various codes used to address the components of a steam explosion are, in general, insufficient for mechanistic best estimate calculations. In many cases the results can be used to develop engineering judgement, while there are some cases where an over-reliance on codes can be misleading. In my view a steam explosion assessment covers all aspects from melt relocation through to structural response. The areas will be taken in turn (some of the comments have been made previously, when referring to the specific phenomena).

Melt relocation: The system codes are currently unable to make predictions of the conditions under which melt would relocate from the core to the lower head that are directly useable in a steam explosion assessment. This is because they do not treat the geometry in sufficient detail, the treatment of crust behaviour is non-existent or simplistic, and they assume simultaneous behaviour over a whole sector. I **recommend that specific objectives be set for the 'mechanistic' core degradation codes to address these deficiencies.** The superheat of released melt is currently very uncertain, and may have a major impact on the likelihood of a steam explosion. It is possible to use core degradation predictions to guide the likely melt relocation conditions (eg when does melt spread to the periphery of the core?), and there are some separate effects models (such as PLUGM) which may be used to look at whether melt that has been released is likely to reach the lower head.

Melt jet break up: The melt might be released in streamlets less then 10 mm in diameter, if the lower fuel nozzles remain intact. However it is more likely that the characteristic pour diameter will be, initially, in the range 20 - 100 mm, corresponding to holes in the below core plate(s). If the pour is through a limited number of holes these may be further ablated with time (reasonable models with some degree of validation are available for this based on studies related to high pressure melt ejection, although they are not currently used in the core degradation codes).

A number of models (eg TEXAS, THERMAL, IKEJET) have been developed to address melt jet break-up; in addition correlational approaches are available. These models and correlations are based on a variety of proposed mechanisms. Often only limited break-up of the melt is predicted in passing through, typically, 2 m of water. These models have not performed well when compared with the FARO-LWR data for 100 mm diameter jets (but only of short duration), which indicate (from the observed steam generation) rapid break-up of the melt jet. It has been suggested that in reality, break-up may occur close to the entrance, through atomization or other processes. Everyday observations indicate that entrance conditions have a significant effect on whether large diameter jets remain coherent, or form rivulet structures.

The lack of model validation implies that in an FCI assessment jet break-up should currently be treated in a scoping manner. The common assumption that the typical droplet size produced by melt jet break-up is determined by a critical (external) Weber number is supported by the experimental data, although there appear to be some, as yet unexplained, differences between the behaviour of alumina and corium melts in the KROTOS experiments. While a number of the coarse mixing codes claim to have models for jet break up, these have not been demonstrated in practice. The mixing codes tend to induce fragmentation as the melt falls under gravity - this may be a numerical artefact, but might also represent physical reality if the jet consists of smaller diameter rivulets.

Coarse Mixing: It is here that most effort has been deployed, and where we would expect to see the greatest progress. Unfortunately much of the effort has been duplicated in different organisations and different countries. Amongst the models developed are IFCI, PM-ALPHA, MC-3D, CHYMES-2, COMETA and IVA-3. All these codes use a transient multi-fluid representation in at least two dimensions. They have varying levels of sophistication in terms of constitutive physics, allowed geometries, and numerical algorithms. With the recent upgrading of CHYMES all handle sub-cooled conditions. Some of these codes can be applied to the later stages of the steam explosion, although a different formulation of the fields may be desirable for this application.

When the first mixing codes, such as CHYMES, were developed the intention was to examine the water depletion phenomenon. In the UK the intention was to perform scoping calculations that allowed for the uncertainty in the constitutive physics and then to determine what range of melt-water mixtures could be possible. More recently there has been much more emphasis on detailed validation of the codes, with specific sets of experiments undertaken for a number of the codes (MAGICO for PM-ALPHA; MIXA for CHYMES; QUEOS and PREMIX for IVA-3; BILLEAU for MC-3D). Most of these experiments, along with similar tests performed at Oxford University, use heated or isothermal solid spheres. The MIXA tests use a high temperature melt in droplet form. In addition there are the results from a number of earlier test series, the JAERI ALPHA experiments, and most importantly the FARO-LWR tests, with up to 150 kg of prototypic melt (also some interesting pre-mixing information from the smaller-scale KROTOS tests).

While the mixing codes tend to give reasonable qualitative predictions, and all can be made to perform creditably against FARO data, there are significant quantitative differences between experimental data and code simulations even for isothermal systems. These differences may be attributed to a number of causes, including experimental effects that are not modelled (eg air entrapment in a pour - this can be taken account of, but may require relatively detailed treatments of bubble behaviour), physical processes that are not accounted for (eg turbulence) and numerical effects. The most obvious numerical effect is numerical diffusion at the leading edge. Some codes seem to suffer from this more than others; it is now clear that a Lagrangian treatment rather than the usual Eulerian approach is desirable to track the leading edge. Numerical diffusion, here, feeds through into particle fractions and hence the drag. This then determines the likelihood of flow separation around the falling particle stream and the induced lateral spreading at the head. However, while it may give confidence in the use of the codes to predict such behaviour (which is seen for narrow streams of particles), the evidence is that spreading of streams of melt droplets occurs by other processes. There is evidence of such spreading in the visual records of the MIXA tests, and, by inference, in the FARO-LWR data.

The FARO-LWR inlet conditions are insufficiently well-defined for the tests to provide good data for code validation. While the ability to predict steam space and water temperatures away from the melt stream may give some confidence in the predicted overall flow, what is of fundamental importance is the void fraction in the region of melt droplets. For significant 'limits to mixing' this has to be very high (greater than 90%) and such conditions have not been demonstrated with lower temperature simulants. Unfortunately all that FARO-LWR provides is an average void fraction (much lower than this). Inferences drawn from the heat transfer data, show that there was significant heat removal from the melt during its fall, implying that the melt droplets had good access to the water. Thus the ability of the codes to match reasonably well FARO-LWR data, when a judicious choice of input conditions is made, cannot be taken as validation of 'limits to mixing' in plant applications. However, one of the FARO tests (L-11) produced steam superficial velocities near that expected for the flooding limit and flooding limitations may well have been achieved in the narrower KROTOS facility.

The situation may be improved in a number of ways:

1. Performing FARO tests at lower pressure will lower the flooding limit.

2. Tests in a vented system would suppress the induced sub-cooling effect and give potentially higher void fractions.

3. Prefragmentation of the melt streams would ensure that a high melt surface area is available for heat transfer, and thus give a better indication of when any limits are becoming important.

4. A narrower vessel should be used to investigate limits to mixing.

5. Visualisation of the melt entry should be attempted.

Some of these ideas will be pursued in the future programme for the facility, but direct measurement of void fraction seems unlikely given the very hostile conditions in the region of interest.

On a more positive note, because the codes are able to make reasonable predictions of the steam generation/pressurisation for FARO and other tests, it is reasonable to place some confidence over their predictions of water depletion in plant applications even though this involves a degree of extrapolation.

I expect that this is the topic for which a "standard problem" might be considered. Indeed, I am aware that CSNI has accepted the FARO-LWR test L-14 as an International Standard Problem, subject to sufficient support. For the reasons outlined above, I am sceptical that much will be learnt from such an exercise. It is clearly of interest for each code to be compared with such experimental data (in general this has already been done for L-14), but the inlet conditions are sufficiently unknown and the conditions in this test insufficiently stringent to give a good test of the modelling. Ideas on how this situation may be improved were given above.

At this stage I would prefer to see a concerted effort on specimen plant applications. This will better focus on how the codes can be used in an assessment, and should lead to a better definition of the validation requirements for these purposes.

Triggering: Apart from models of external hydrodynamic triggers, there are no satisfactory models available for triggering that could be used, for instance, with a coarse mixing code to predict the initial stages of an interaction.

Propagation: Until the last few years models of propagation following an initial trigger had reached an impasse, because without artificial modifications to input conditions or fragmentation laws, observed propagations in tin-water systems could not be replicated by the codes. Part of the 'artificial' modifications had been to reduce the amount of coolant involved (ie to get more pressurisation per kJ of heat transfer). A formal way of doing this, supported by experimental data, has been proposed by UCSB, through the introduction of the "microinteractions" field which entrains both droplet fragments and coolant [8]. This allows events to escalate more rapidly, while later entrainment of coolant can lead to a subsequent quenching of the microinteractions region and restrict the predicted overall mechanical energy release of the interaction.

The SIGMA (constitutive physics) and KROTOS experiments provide some validation for this approach, at least for tin-water systems. A feature of molten tin is its low thermal capacity compared with prototypic materials; thus it is more readily quenched. The same models that had difficulty predicting any propagation in a tin-water mix readily predict propagation through corium-water mixtures, even at high void fractions. Experiments in the SIGMA facility and elsewhere have indicated that the droplet fragmentation cannot be simply related to droplet properties or the flow conditions, and is material dependent [9]. It is conjectured that, as the shock wave develops, hydrodynamic fragmentation takes over which is dependent on a simpler combination of material properties. I believe this to be more a conjecture than based on comparison experiments with different materials, but if fragmentation is sufficiently rapid it probably does not matter. However, caution should be applied in using a code validated only against tin-water experiments to predict reactor melts.

A recent welcome development is the production of two-dimensional (rather than one dimensional or spherically symmetric) models. These models may be used to investigate the effects, to some extent, of inhomogeneities in the mixture, including vent pathways. However, there is no validation of the models in two dimensions and real explosions will always be three-dimensional.

Because of the difficulties of establishing initial conditions, and the difficulties in making sufficient measurements for code validation, care should be taken before embarking on a significant programme of work for validation of the propagation codes. The KROTOS facility is able to provide experiments in a one-dimensional geometry for a variety of melts. So far it has not been found possible to trigger escalating events in corium melts, partly, it seems, because of the difficulty of getting the melt into the facility. It is intended to make the facility wider to encourage melt ingress, but this will further complicate the initial conditions for any propagation event. I favour trying to generate as one-dimensional conditions as possible, with triggers used to study escalation (or otherwise) for validation of the one-dimensional codes.

For the interpretation of these one-dimensional tests, there is the need to generate equivalent melt fragmentation data to that obtained in SIGMA for tin for the other melts investigated. This should include varieties of corium, preferably with a variety of initial void fractions in the coolant.

Beyond this, careful consideration needs to be given to how multi-dimensional models will be used in a steam explosion assessment. It is generally believed that one-dimensional conditions represent a worst case - if propagation is only weak in one-dimension then there may be no further need for multi-dimensional work [a word of caution - the likelihood of chemical detonations increases with channel width; we do not know what the structure of a fully-developed steam explosion detonation would look like]. It is most likely that applications of multi-dimensional codes will highlight the role of inhomogeneities, particularly regions of high void content. Specific experiments may be needed to validate this if it is claimed as an ameliorating feature. Consideration should be given to approaches that do not include the melt, but look at the effect of a shock on a pre-setup multi-phase coolant configuration. Such data may already be available outside of reactor safety studies.

Energy Conversion and Slug Acceleration

Beyond the propagation calculations, which model the early stages of energy conversion, there has been the tendency to address slug acceleration using a simplified model for the explosion region. Losses in such a model come about if the bubble breaks through before the slug has been fully accelerated (this was found to happen when the SEURBNUK-EURDYN code was used for LWR applications), or through normal fluid losses in the slug motion. As far as the impact on the upper head, or other structures, is concerned, there may be an effective loss of damage potential if the slug arrives at different times over different areas. However, the calculations that have been performed so far do not take account of the geometrical complexity of the plant, and so are of limited use. For the UK study a 'leaky slug' model was developed using simple mechanics to account for the possible venting of the bubble region while the slug was being accelerated. Such a model is relatively robust, provided one has a reasonable idea of the vent areas available.

Dissipation of the Slug Energy

This topic has largely been treated by model experiments and heuristic arguments. There has been no concerted model development.

Energy Absorption in Structures

Structural codes, such as ABAQUS, can be used to look at the energies required to fail the structures. So far only axisymmetric calculations have been performed, giving axisymmetric failures, while reality is likely to be more complex. Calculations performed so far are in broad agreement with engineering-based correlations. The major issue here is likely to remain the form of the loading rather than the accuracy of the predicted response.

Probabilistic Analyses

A number of tools are available to perform the probabilistic analyses required in most approaches. As the analysis methods get more sophisticated it is important that these tools are also subject to verification. For the UK assessment the SEEP code was developed for the probabilistic evaluation, and careful verification was undertaken. In addition the code was used to evaluate the effect of input distributions developed by Theofanous et al: the results agreed reasonably well with the final frequencies and distributions evaluated by Theofanous et al. This gives good confidence in the mechanics of the probability evaluation by both teams.

9. *How much of the research performed (both experimental and analytical) in support of the α-mode failure issue is also applicable to "localized" FCIs (eg, an energetic FCI next to a structural boundary where there is a need to evaluate the dynamic loading on the structure)?*

Localized FCIs as described here should not pose any new difficulties. Depending on the geometrical configuration, a three dimensional analytic capability may be desirable. There is nothing intrinsically difficult about performing coupled fluid structure interaction calculations, although this may require some modification to the usual boundary conditions in the propagation/expansion model.

10. *Discuss the possibility and importance of chemical augmentation to energetic FCIs. Discuss the impact of chemical augmentation on the dynamic loading of structures.*

For PWRs the principal energy source is likely to be the thermal energy of a predominantly oxidic melt, and this is the only area of interest in the UK. Other reactors may have higher inventories of unoxidised zirconium in the melt (or as a separate melt) and the use of aluminium in fuels has also been considered. For single drops, a transition in the behaviour of aluminium has been demonstrated in experiments at UCSB, indicating the link between rapid fragmentation and oxidisation.

Calculations for oxidation of the zirconium component of a PWR melt during both coarse mixing and a possible steam explosion have tended to show only limited additional oxidation, but this cannot be taken as a rigorous conclusion. Differences in the pre-mixing behaviour between the FARO-L11 (with Zr) and FARO-L14 (without Zr) have been attributed to the modest amount of Zr in L-11. This may well be the case, but the published conclusion of full oxidation of the Zr in L-11 should be treated with caution as it is not based on measurements of hydrogen generation. In addition it has been conjectured that the oxidation reaction in L-11 caused the observed greater degree of melt fragmentation and pressurisation. Again this may well be the case, but it may also have occurred because of the result of different discharge characteristics in the two tests or because the presence of zirconium modified the melt properties in a manner that encouraged greater fragmentation. These questions are best pursued in small-scale well-instrumented tests. If one accepts the interpretation of these FARO tests it is still not clear what the effect on the likelihood of a steam explosion would be: greater break-up may reduce the likelihood of a damaging explosion and in small-scale systems the presence of non-condensible gases has inhibited triggering.

What is important is that steam explosions are material-sensitive and sufficient experiments should be performed with the range of prototypic materials to cover the compositions of interest in plant applications.

SUMMARY OF MAIN CONCLUSIONS AND RECOMMENDATIONS

1. The assessment of α-mode failure probability still depends on a large amount of engineering judgement, so any evaluations have a large subjective element. This is particularly the case for an event such as this which depends on the tails of a number of input distributions that are difficult to quantify. Current assessments produce probabilities typically in the 10^{-3} to 10^{-4} region given a large core melt, similar to earlier evaluations. While many may feel the real probability is much lower, I do not believe there is the degree of validation of models or hypotheses to support such a quantification. Indeed, unless something new can be demonstrated, even if the current calculational tools are better validated, I do not see the assessed probability being substantially reduced.

2. Given the subjective nature of the assessments and the potentially high consequences of the event, the current probabilities are of the order where one could declare the issue closed, but not by a significant margin. It is my view that, at this level of assessment, the issue should remain monitored and that additional work to provide greater confidence and consensus in assessment is desirable. This is best achieved by co-ordination at an international level, providing the best means of peer review in this subject.

3. Any additional work should be strongly focused on plant assessment and the behaviour of prototypic materials. It should consider the steam explosion assessment as a whole, taking melt progression and relocation into account. Effort should be undertaken to avoid duplication at the international level.

4. Specific objectives related to relocation route and rate should be placed on the developers of core degradation codes. A limited number of experiments to validate such modelling would be desirable.

5. The absence of suitable triggers (or conversely the plethora or early triggers) provides potentially the most straight-forward way of eliminating concerns over steam explosions. However current data and understanding are insufficient to support such assertions at the level of confidence required, and there is no obvious way forward apart from the systematic collection of relevant data.

6. Melt progression studies and coarse-mixing studies offer the best hope for (partially) validated models that provide limits to the energy release. However, it is almost certainly the case that coarse-mixing, by itself, will not provide the

desired level of confidence in a low probability. Recent work has highlighted the importance of (induced) sub-cooling which makes mixing limits less stringent. Future work should be oriented to demonstrating limits to mixing experimentally with prototypic materials. Such experiments are potentially possible in a modified FARO facility. In addition, the initial break-up of large diameter (~100 mm) jets merits more investigations. Here, current models perform poorly and there is interest both from the steam explosion and coolability viewpoints.

7. The conditions under which a triggering event causes propagation are still poorly understood, and proposed heuristic limits cannot currently be supported. Progress has been made understanding propagation in tin-water systems, by a combination of model development and separate effects experiments. Further work is required for corium systems, where propagation appears less easy to obtain. The use of well-characterised triggers to initiate a possible propagation is desirable, as is maintaining a one-dimensional geometry. Supporting experiments, akin to SIGMA, should be performed to study the break-up of individual corium droplets in prototypic pressure/velocity fields.

8. Multi-dimensional effects in propagation and expansion are expected to have a strong mitigative role in energy conversion, which is currently difficult to quantify. Code developments here are welcomed, but they remain unvalidated. Validation experiments should be designed for the additional effects predicted in multi-dimensional propagation that are claimed in plant assessments.

9. Dissipation of slug energies and energy absorption in structures have been estimated for plant applications. While uncertainties exist in these quantities, the scope for having a significant effect on estimated failure probabilities is small, and so future work in this area should have a low priority.

10. Small-scale separate effects experiments on the role of Zr in corium compositions are desirable. These could be combined with the SIGMA-like experiments referred to in 7 above.

11. The topics of stratified and multiple explosions have not been discussed in any detail (partly as a result of the questions asked). Based on current experimental data it is generally believed that explosions starting from a stratified configuration are weak; this topic needs to kept under review, as if this were not the case, it could impact assessments significantly.

12. The probabilistic frameworks developed at UCSB and in the UK represent the only practical way to perform steam explosion assessments. The concept of an integral 'mechanistic' calculational package for steam explosion studies is not a worthwhile objective.

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APPENDIX C

SUMMARY OF LEAD PANELISTS ON MAJOR FCI PHENOMENOLOGICAL ISSUES

APPENDIX C-1

SUMMARY OF LEAD PANELIST

PROBABILITY OF α-MODE FAILURE

BY

DR. HANS K. FAUSKE

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Summary of α-Mode Containment Failure Probabilities

The first SERG meeting held 10 years ago concluded that the occurrence of a steam explosion of sufficient energetics that could lead to α-mode containment failure has a low probability. A central feature of the quantitative responses among the 1985 panel members was a mechanistic treatment of various stages of the steam explosion sequence, with emphasis on estimation of the mass of melt participating in the explosion. It follows that the low probability of early containment failure suggested by SERG-1 resulted largely from the belief that the fuel mass participating in a potential steam explosion in the lower vessel plenum following fuel relocation from the core region is quite limited.

The limitation in fuel participating in a possible steam explosion was related both to the likelihood of a large, coherent pour of melt into the lower plenum as well as the subsequent potential of molten fuel/coolant mixing. While the estimates among the SERG-1 members varied over a wide range, the estimates were generally lower than the 20,000 to 40,000 kg of molten fuel that must relocate from the core region and subsequently mix with the water in the lower plenum, all within a few seconds time interval, in order to generate a condition capable of challenging the reactor vessel and containment. Probability (likelihood) estimates provided by SERG-1 members that also participated in SERG-2 are summarized below.

α-Mode Failure Probability (Likelihood) Estimates Following a Core Melt Accident		
	SERG-1 (1985)	SERG-2 (1995)
Bankoff	$< 10^{-4}$	$< 10^{-5}$
Berthoud	--	$< 10^{-3}$
Cho	< WASH-1400*	$< 10^{-3}$
Corradini	10^{-4} - 10^{-2}	$< 10^{-4}$
Fauske	Vanishingly small	Vanishingly small
Fletcher	--	$< 10^{-4}$
Henry	--	Vanishingly small
Jacobs	--	Probably low likelihood
Sehgal	--	$< 10^{-2}$
Theofanous	$< 10^{-4}$	Physically unreasonable
Turland	--	$< 10^{-3}$
*WASH-1400 best estimate $< 10^{-2}$		

Substantial confirmatory research has been completed since the first SERG meeting. Especially, the new data obtained in the water depletion phenomenon and its quantification, have substantially reduced the previous wide range of estimates offered at the SERG-1 relating to the potential to intermix large quantities of molten fuel and water. The additional confirmatory research completed during the last ten years is clearly reflected by the revised probability estimates provided by the SERG-1 members that participated in the SERG-2 as well as in the estimates provided by the new members.

The above probability estimates reflect the general consensus among the SERG members that the magnitude of potential pre-mixing in assessing the α-mode failure issue is of primary importance and is quite limited. The energetics of the vapor explosion, if it occurs, is commonly taken to be directly proportional to the extent of the corium melt/water mixing zone at the time that the vapor explosion is initiated. Once the extent of the mixing zone is determined, an upper bound to the mechanical energy release, can be calculated by multiplying the thermal energy "stored" in the corium component of the mixture by an appropriate thermodynamic conversion ratio. The work required to fail the upper head of the reactor pressure vessel is generally calculated to be of the order of 1000 MJ. As such, other details and remaining uncertainties related to triggering, fine scale fragmentation, escalation and propagation of steam explosions are not considered essential in assessing the α-mode containment failure probability.

In summary, based upon the new knowledge gained since the first SERG meeting and reflected by the SERG-2 members probability estimates, the α-mode containment failure can be considered a resolved issue representing no significance to risk. It is noted that several SERG members expressed strong need for additional research to further improve the understanding of the steam explosion phenomenon.

APPENDIX C-2
SUMMARY OF LEAD PANELIST

PREMIXING
BY
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PREMIXING

B D Turland
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July 1995

INTRODUCTION

The topic of premixing, here taken to cover the interaction between melt stream(s) from the core region and water prior to any explosive interaction, plays a key role in steam explosion studies. It determines (i) the quantity of melt that is in sufficient proximity to the coolant to participate efficiently in any explosion and (ii) the medium through which the explosion must propagate. Some participants believed that premixing by itself is sufficient to exclude steam explosions sufficient to damage the containment, while others were more cautious in their assessment.

There can be considered to be two limits involved in premixing:

> That of an unfragmented, or poorly fragmented, jet in which the surface area of the melt-water interface is limited, restricting the quantity of melt that could be involved in an explosion because of the difficulties of mixing over distances greater than a few millimetres in a short time period; and
>
> That where the melt is fragmented into sub-centimetre-sized particles, giving potentially a very large heat transfer, which is sufficient to generate large volumes of steam that forces water from the interaction zone.

The first limit is determined by considerations of jet break-up, the second by processes involving melt droplets. In recent years effort has concentrated on the second limit, which is seen as indicating that mixing of melt and water is self-limiting.

The importance of premixing according to the various contributors is summarised in the following section, followed by the contributors' views on whether enough was now known for use in steam explosion assessments. The topics of jet break-up and droplet mixing are then reviewed, followed by the conclusions reached by the reviewer.

IMPORTANCE OF PREMIXING

The importance of pre-mixing was universally recognised by the contributors. To a large extent, the assessment of the role of mixing depended on the individual's confidence that large-scale steam explosions could be eliminated on the grounds of the improbability of forming a premixture alone (at least for some pressure ranges).

At one extreme it was stated that the depletion phenomena would restrict the amount of melt involved efficiently in any explosion to no more than (a few) hundred kilogrammes, while others considered that if there was an explosion all the melt would be involved, to some extent, and that the importance of premixing was in determining the initial conditions for any explosion, which would then limit the efficiency of mechanical energy release.

The statement by Corradini that:

> "Fuel-coolant mixing with corium and water will naturally result in a mixture which has a large void fraction with limited amounts of corium fuel mixed with liquid coolant, and that under these mixture conditions an explosion is possible but will be relatively weak in energetics and not capable of generating a solid missile to threaten containment."

is close to the central position that most participants would associate themselves with. Participants differed in the extent to which they considered that this had already been sufficiently demonstrated.

DO WE HAVE SUFFICIENT INFORMATION ON PREMIXING?

Many of the participants thought that sufficient work had been performed to demonstrate that water depletion would place sufficient limits on the possible energetics of a steam explosion, at least for low pressures. (A number of contributors pointed out that melt relocation scenarios also limit the amount of melt that could be involved, often to values lower than those given by limits to mixing derived from the pre-mixing codes.)

Cho suggested that the range of pressure that was likely to apply in reactor accidents was greater than 0.1 MPa, due to elevated containment pressures, and considered that further work was necessary for the 0.2 - 0.4 MPa pressure range. Likewise, Fletcher noted that steam voiding of water from the premixture is essentially a low pressure phenomena. Bankoff said that an approach based on application of flooding correlations was generally sufficient to provide limits on the mixture, but was concerned that a preliminary explosion may cause catastrophic failure of the lower core support plate and more rapid mixing for a second explosion. Theofanous referred to recent PM-ALPHA calculations indicating that, even for large pours, less than 15 te of melt could be well-mixed; this was consistent with CHYMES-2 calculations referred to by Turland.

Most participants, when referring to codes for pre-mixing, introduced concepts such as "sufficiently validated" or "demonstration of fitness for purpose". This is seen as an ongoing activity, where confidence in the predictions of pre-mixing codes gradually improves as the comparison with the experimental database is extended. There was a desire for more data in near prototypic conditions with good instrumentation for code validation.

Fletcher drew attention to the fact that only CHYMES and PM-ALPHA of the current generation of pre-mixing codes have been applied to plant analyses. Jacobs took the view that such applications are premature. Berthoud indicated that they expect to be able to perform plant calculations with sufficient justification of the pre-mixing modelling in France in about 2 years time.

THE UNDERSTANDING OF JET BREAK-UP

Jet break up was discussed by most contributors. It was generally recognised that this was a topic for which improved understanding was desirable, although several contributors wondered whether it was essential, or indeed possible, to obtain a detailed model for jet break-up, particularly as once it occurred one would have to consider the full melt topology from a coherent core to small fragments.

Only Bankoff made claims that large diameter jets (~0.5 m) would not break up because of vapour blanketing. However, others, including Berthoud, stated that unfragmented jets would not contribute to any explosion.

The FARO-LWR tests were quoted by a number of contributors (Berthoud, Turland) to indicate that jet fragmentation was not well understood.

There were differences of opinion on whether treatments of melt jet break up were essential for α-mode assessments. Jacobs stressed that there was a requirement, because, in his view, it is not clear how the phenomena could be covered conservatively. Some other participants, while stating that a model was desirable, thought that jet fragmentation could be handled in a scoping manner. Sehgal considered that jet fragmentation kinetics should be evaluated further as current demonstrations of coolant voiding were for discrete particles or droplets. Fletcher drew attention to the likely complexity of jet behaviour in the plant because of interactions with internal structures. Turland thought jet behaviour was more important for coolability considerations rather than for α-mode assessment.

THE UNDERSTANDING OF DROPLET MIXING

It was generally agreed that the understanding of the mixing of melt droplets with coolant is better developed than that of jet fragmentation. Most contributors drew attention to the development of the transient multi-phase, multi-dimensional computer codes that have been developed to model droplet mixing. These codes are based on the fundamental conservation laws for mass, momentum, and energy, but contributors differed over the status of the constitutive physics (drag laws, fragmentation laws and heat transfer relations) embodied in the various codes and the level of validation that could be claimed for the models. Berthoud pointed out that these had often been derived from two-phase models applicable at lower temperatures than those of interest in steam explosion studies.

It was agreed that separate effects experiments such as MAGICO and MIXA give a reasonable picture of pre-mixing that confirms the initial concept of water depletion, and that FARO-LWR data were broadly consistent with post-test code calculations provided early break up of the melt jet was assumed. The most successful attempts at code validation were presented by Theofanous based on comparisons of PM-ALPHA with MAGICO data. These experimental data were particularly important in providing (relatively) local void fraction measurements in excess of 80%, which compared well with the code predictions. This is the strongest experimental evidence so far for water depletion. Other participants referred to problems in code validation such as over-predicting the rate of downward progression of narrow particle streams and underprediction of radial spreading.

It was argued that exact agreement with experiments involving fragmentation of melt streams was not to be expected, but the codes could be used to show that they bracket experimental behaviour and provide an upper bound to mixture characteristics for the plant application. Jacobs said that he saw a need for fully mechanistic pre-mixing calculations.

Corradini drew attention to the need for advanced instrumentation to provide data for code validation, but also indicated that pre-mixing information could be backed out of experiments investigating propagation.

CONCLUSIONS

I have found it impossible to split this material into a consensus (meaning everyone would agree) position and a list of open issues. In most cases, as I have tried to indicate, there is a spectrum of opinion. However, I will attempt to draw some general conclusions:

1. Pre-mixing is important and is a major component in α-mode assessments at low pressure.

2. The development of pre-mixing codes which are transient, multi-fluid and multi-dimensional provides a good way of addressing scaling concerns in applying the concept of water depletion in α-mode assessments.

3. Experiments have demonstrated the water depletion phenomenon, and some of the codes have been successfully compared with experimental data for low and high temperature materials entering water in particle or droplet form. Measurements of high local void fractions in the MAGICO-2000 tests and their consistency with PM-ALPHA predictions are a significant step forward. However uncertainties still exist in whether the constitutive physics in the current versions of the codes is sufficient to adequately represent the interactions involving a high temperature fragmenting melt stream. On the other hand, the applications to FARO-LWR do not show any obvious inadequacies in the codes provided early jet break-up is assumed.

4. Pre-mixing, by itself, may not be sufficient to eliminate α-mode failure, particularly at elevated pressures, but provides some constraints on the mixture at all pressure ranges.

5. The fragmentation of melt jets is poorly understood and current models have little predictive capability. For α-mode failure assessments it may be possible to use the current code with conservative assumptions about the initial melt droplet size to scope the effect of uncertainties in melt jet fragmentation. However, an improved understanding of jet break-up is desirable, particularly for coolability studies.

6. It is desirable that more plant applications of the pre-mixing models are published and subject to review. These should include the feedback from the rest of the primary circuit, including induced sub-cooling and water swell into the lower core regions.

APPENDIX C-3
SUMMARY OF LEAD PANELIST

TRIGGERING

BY

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Discussion Group Summary for SERG-2 Workshop

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Discussion Issue: Triggering

Discussion Leader: D. H. Cho

Discussion Summary:

1. Questions and Issues

In his May 10, 1995, letter, Dr. Speis asked the Panelists to address a number of questions and issues for the SERG-2 Workshop. The questions and issues pertaining to triggering were stated as follows:

"Discuss the role and importance of triggering (trigger availability and triggerability) in addressing the α-mode failure issue. Discuss the role of pressure threshold in suppressing the triggering." In this statement, the issue of triggering was divided into two subissues, namely "trigger availability" and "triggerability". This division of the issue was found to be very useful in facilitating the discussions.

Generally, "trigger" means pressure and/or flow perturbations that may initiate an explosion in a melt/water mixture. A number of mechanisms that could potentially serve as a trigger may arise naturally in reactor accident situations ("natural" triggers). Examples include: mechanical impact such as might be caused by falling objects or collapsing structure; bubble/void collapse due to condensation following cold water injection; pressure disturbances and flow turbulence associated with mixing of large masses of melt and water; and the vaporization of water entrapped at solid surfaces. The question then is whether any one of these potential triggers could be effective in bringing about a large-mass explosion. This is the issue of triggerability.

The issue of triggerability is very complex and poorly understood. It may well involve the escalation of a relatively small pressure disturbance to a threshold level which is responsible for a propagating interaction. The response of a melt/water mixture to a triggering event would most likely depend on the trigger strength as well as on the mixture condition. The condition of a melt/water mixture is determined by a number of variables. Among them are; melt mass, contact mode, system pressure, water subcooling, melt superheat, and melt composition. All these variables are expected to influence the triggerability of a melt/water mixture. A given trigger may or may not be effective in producing an explosion, depending on the melt/water mixture condition. For example, the triggerability of a stratified system would be different from that of a well-mixed system. Also, available data indicate that the triggerability would be a function of system pressure. In fact, the triggerability may become practically zero at pressures above a certain threshold level. This is the so-called "pressure threshold" effect.

2. Trigger Availability

In general, the Panel members agreed that the availability of some sort of a trigger in reactor situations could not be ruled out. However, there appeared to be a wide range of opinions as to the type and strength of a trigger that might arise naturally in reactor situations. One member suggested that an appropriate trigger pressure pulse to be considered in code calculations would be of the order of 1 kPa (0.15 psi) over 1 msec. This is an extremely weak trigger. Some other members felt that much stronger triggers might be available in reactor situations. Also, it may be noted that available triggers for ex-vessel interactions could be different from those for in-vessel interactions.

3. Triggerability

For low-pressure accident scenarios (say, for pressures less than 1 MPa), most Panelists felt that the triggerability would be relatively high without identifying the particular triggers that may be available. A majority of the Panelists seemed to be accepting the high probability numbers assigned to triggering in recent assessments of the α-mode failure for low-pressure scenarios (e.g., 0.7 or even 1.0). However, two Panel members felt that the trigger probability could be much lower even at pressures as low as a few tenths of 1 MPa. Also, a few Panelists felt that the triggerability of real reactor materials could be lower than that of the various simulants used in experiments, although the supporting evidence is far from being adequate.

All the Panelists shared the feeling that the triggerability would decrease as the system pressure increases. For high-pressure accident scenarios (say, for pressures greater than 10 MPa), the triggerability would likely be an order-of-magnitude lower than that for low-pressure scenarios. There appeared to be some differences in opinion as to the adequacy of the supporting evidence. Many Panelists seemed to believe that the concept of a "pressure threshold" for triggerability is physically reasonable. However, no consensus was reached regarding the exact level of pressure above which the triggerability would become essentially zero.

4. Recommendations for Future Research Efforts

Opinions regarding the need for future research work were diverse. These diverse opinions are briefly summarized below.

- Before deciding what needs to be done about triggering, it would be useful to assemble the existing database and test it against various hypotheses. Also, the question of what kinds of "realistic" or "natural" triggers may be available in reactor situations should be addressed.

- For low-pressure scenarios, there is no urgent need to consider further work on triggering, since the α-mode failure probability is already very low based on other considerations such as premixing. (In the context of "localized" interactions, however, there may be a need to look at the question of triggerability more carefully.)

- For high-pressure scenarios, there may be a need to consider further work of an experimental nature. (The importance of high-pressure scenarios in the context of overall safety assessments is another matter to consider.) Exactly what kind of experimental work would be needed was not fully discussed. But the need appears to be to confirm the very low triggerability for high-pressure scenarios, hopefully to establish the pressure threshold for zero triggerability.

APPENDIX C-4
SUMMARY OF LEAD PANELIST

PROPAGATION
BY

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SUMMARY OF THE PROPAGATION PHASE DISCUSSIONS AT SERG2

The discussions at SERG2 focused on the three stages of the vapor explosion: i.e., mixing, triggering and propagation. In these discussions the propagation phase was defined to involve the spatial and temporal growth of the rapid vapor production and attendant fuel fragmentation, as well as its quasi-steady movement through the fuel-coolant mixture and eventual energetics produced by the vapor expansion. Thus, the propagation phase contains the escalation, spatial propagation and energetics of the explosion. Historically, this phase was first identified in a thermodynamic manner by Hicks-Menzies [1985} and Board-Hall [1975] and later by the development of parametric models [e.g., Cho-Wright for LMFBR in 1974, and Oh-Corradini for LWR in 1985]. These approaches were spatially lumped models and spatial propagation was not considered. This is in difference to more recent mechanistic models being developed for both mixing and propagation [see attached Tables]. After discussions, the following summary comments can be made.

1) The current state of knowledge for the FCI propagation phase [i.e., escalation, spatial propagation and energetics] is sufficient for use in the alpha-mode failure analyses being performed by many safety analysts. All members of the SERG2 were in general agreement with this conclusion, although certain members felt specific improvements in models were needed for continued alpha-mode safety analyses.

2) Prof. Bankoff suggested that the explosion propagation process should be considered with large pours and the possibility of multiple explosions. A few of the SERG2 members agreed that such physical events need to be considered, but emphasized that without further data, the consideration of this is somewhat problematic, but may be bounded by conservative estimation for alpha-mode failure applications.

3) Most of the SERG2 members felt that the vapor explosion propagation physics could be treated conservatively. In this setting conservatively is defined as being able to model the propagation process [i.e., escalation, spatial effects and energetics] in a manner that provides upper bounds to the particular effect. In alpha-mode issues this effect would involve the impact energy to the upper head. In local pressurization issues this effect would involve the dynamic pressure in the lower plenum or cavity and the attendant damage to the nearby structures. There was not agreement on which conservative approach was preferable.

4) Many of the SERG2 members felt that the causal relationship between the explosion shock propagation wave and the associated fuel fragmentation process is not well established. For example, one may ask the question - does the fuel fragmentation process occur ahead of the shock passage, during the point of shock wave passage or after the shock passes the fuel-coolant mixture. The former possibilities may imply that the fuel fragmentation process is a direct result of the flow behind the shock wave. The linkage between the explosion escalation and the spatial propagation process has yet to be well understood.

5) As a follow-up to the previous conclusion the same SERG2 members felt that there is not enough well-characterized experimental data for the explosion escalation and spatial propagation processes to help discern model differences. Because of this lack of data, all current models are at best semi-empirical and still quite tentative in their qualification.

6) A few SERG2 members, particularly Cho and Corradini, felt that the propagation process can be very useful in understanding the fuel-coolant mixing process, the explosion escalation process and the formation of void in the fuel-coolant mixture. One example may be that by observing the propagation characteristics one can ascertain the initial mixture conditions. Another example is that the observed behavior with different fuel compositions and with coolant additives could be very useful in understanding the fundamental propagation process.

7) Many of the SERG2 members felt that the linkage between the fuel-coolant mixing, void fraction and fuel fraction distribution in the mixture, and the explosion escalation [given a trigger of known perturbation] is the key for better understanding of the escalation propagation and associated energetics. The reason for this belief is that all explosion mixing/propagation models [e.g., TEXAS or ESPROSEm] clearly indicate that the mixture composition has the dominant effect on the predicted explosion behavior; i.e., fuel diameter, void fraction, fuel distribution. In fact, the experiments presented by the JRC Ispra researchers from the KROTOS tests clearly indicated that the mixing process was the main effect on if the explosion was triggered or if the explosion escalated under prototypic fuel conditions.

8) Prof. Theofanous pointed out that propagation models must demonstrate a 'fitness for purpose' for use in safety calculations. This means that explosion models must be critically evaluated as they are applied to answer specific regulatory issues: e.g., alpha-mode failure.

9) Most of the SERG2 members also agreed that chemical augmentation of the explosion propagation and energetics must be considered when the fuel has some metallic components. Some of the SERG2 members felt that the contribution would be modest due to the expected small amount of metal in the prototypic melt compositions. Still others felt this area an open question to be answered by the current ZrEX tests at ANL.

10) Finally many of the SERG2 members felt that there was a continued need to consider specific propagation experiments in a '1-D' experimental apparatus:
a) Standard problem from certain 1-D experiments with tin, alumina and corium fuels as the major variables in the tests.
b) Use of coolant additives to promote explosion suppression and thereby determine the mixing conditions from test mixing results.
c) Use of these tests to empirically determine scaling of the propagation.
d) Perform experiments with pre-existing void to observe its effect on the explosion propagation process; i.e., simulating larger scale pool condition.
e) Examine the initial fuel to coolant mixture volume effect on energetics.
f) Consider single droplet experiments with corium melts and zirconium for understanding the triggering process for prototypic conditions.

TABLE I

FUEL-COOLANT MIXING COMPUTER MODELS

- Simulate the transient process of melt penetration into a water pool
- Provide estimates of fuel spatial and temporal distribution as well as steam production and pressurization during mixing phase

MODELS	REMARKS
CHYMES (Fletcher et al, C ulham)	2-D with discrete particles
IVA3 (Kolev et al, KFK)	3-D with discrete particles
MC-3D (Berthoud et al, CEN)	3-D with discrete particles
PM-ALPHA (Theofanous et al, UCSB)	2-D with discrete particles
TEXAS-V (Corradini et al, UW)	1-D Lagrangian and Eulerian, dynamic fragmentation (Chu/Yang)
IFCI* (Young et al, SNL)	2-Eulerian with dynamic fragmentation (Pilch model)
THIRMAL (Sienicki, Chu et al, ANL)	1-D Lagrangian in a pool of water, dynamic fragmentation (Chu)

[IFCI, TEXAS and THIRMAL dynamic fragmentation models simplified from analytic derivations]

*NRC supported

TABLE II

EXPLOSION/DETONATION COMPUTER MODELS

- Provides estimates of the dynamics of explosion, pressure and velocities
- Simulates the explosion expansion process and work output

KROTOS/WFCI provide benchmark data for comparison of models

MODELS	REMARKS
IFCI* (Young et al, SNL)	2-D parametric fragmentation model
CULDESAC (Fletcher et al, Culham)	1-D parametric fragmentation heat transfer rate
ESPROSE (Theofanous et al, UCSB)	2-D hydrodynamic fragmentation
IDEMO (Carachalios et al, IKE)	1-D Eulerian assorted mechanistic fragmentation models
TEXAS-V (Corradini et al, UW)	1-D Lagrangian/Eulerian combined jet mixing and thermal fragmentation model

[ESPROSE, IDEMO and TEXAS have semi-empirical fuel fragmentation models)

*NRC supported

APPENDIX C-5
SUMMARY OF LEAD PANELIST

MECHANICAL WORK

BY

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Summary of Considerations for Mechanical Energy Loads

Once the magnitude of an explosive interaction is characterized, the capabilities of delivering work to the surrounding structural boundaries must be addressed. In particular, for the α-mode failure considerations, the work required must be sufficient to fail the upper head of the reactor pressure vessel. There was substantial agreement among the members of the Steam Explosion Review Group-2 regarding the issues of assessing mechanical loads. These included:

1. The work required to fail the upper head of a reactor pressure vessel is of the order of 1000 MJ.

2. Several members of the group felt that there are analytical tools available to assess the structural response once the explosion is characterized. All members also felt that it is important to separate the mechanical loads considerations for BWRs and PWRs since the vessel designs and the upper plenum structures are substantially different. Some members of the review group believe that the existing tools need to be validated before deriving specific conclusions from the mechanical energy calculations.

3. There is a consensus in the group that the only material that could be considered as a "slug" and accelerated through the RPV to impact on the upper head is the remainder of the core material.

4. When considering the forces acting on the remainder of the core material and accelerating it upward toward the RPV upper head, venting of steam through the downcomer (shroud region for the BWRs) is an important consideration for assessing the work delivered to any overlying "slug".

5. It is important to consider the forces acting on the structural boundaries and not just the energy required to cause failure. This is intended to simplify the assessments of the work necessary to fail the RPV upper head.

6. Since the material that could be conceived as a "slug" is the remnant of the damaged core, the upward movement of this debris would quickly impact on the structures in the upper plenum region. For PWRs this would be the control rod guides and their supporting structures and for BWR designs this would be the shroud head, separators and dryers. Since these structure-structure interactions would occur with relatively small movements of the postulated "slug", these interactions need to be considered for two reasons. Firstly, the structure-structure interactions

could potentially focus a substantial energy release on a relatively small part of the RPV upper head. This could result in failures at lower slug energies than are considered for a global impact of the slug on the upper head. Secondly, since the structure-structure interactions are progressive in nature and the deformation of structures in the upper plenum region absorb energy, these structures could substantially reduce the energy transferred to the RPV wall. Thus, the structure-structure interactions could either decrease or increase the potential for failing the upper head. It was the collective opinion of the review group that these structure-structure interactions should not be ignored when considering the mechanical energy transferred to the upper head. Also, these interactions would be expected to differ for BWRs and PWRs, hence, it is important to separate the considerations for the different designs.

This summarizes the discussions related to the mechanical energy conversion to the RPV upper head. When these were presented to the group on the morning of the second day there were no additional points added to the list.

APPENDIX C-6
SUMMARY OF LEAD PANELIST

ISSUE RESOLUTION
BY

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PATH TO ISSUE RESOLUTION

Summary of Group Discussion led by T. G. Theofanous

This group discussion was the last one in the meeting. It took place as an extension of the morning session (without lunch), and as a consequence it was terminated prematurely, without reaching any firm conclusions.

The group leader introduced the subject, along the lines of the viewgraphs shown in Figure 1. Besides the old question of α-failure, the problems of Lower Head Failure (mostly for PWRs) and Lower Drywell Failure (mostly for BWRs), were identified as being of current interest. Potential approaches to addressing these issues were then introduced. With reference to Figure 1, the "Defacto, Over Time" approach is to take sporadic, small nibbles at the problem which over a long time, thus, diminishes in interest, and eventually is considered effectively closed. This is pretty much what happened to the α-failure problem to a considerable degree (loss of interest) so far, and it will continue to be the case if nothing "organized" is done. The CSAU approach was developed in conjunction with the revision of Appendix K rule for the Large Break LOCA problem. It is basically a deterministic calculational approach, and is especially applicable when the event in question can be approached in the well-defined manner typical of Design Basic Accidents. The PRA Expert Opinion methodology is exemplified by the NUREG-1150 work. Experience has shown that it is less oriented to resolution, and much more to the identification of issues. The Risk Oriented Accident Analysis Methodology (ROAAM) actually originated in an early effort to address α-failure (Theofanous et al, 1987), and it was also employed (except for the external peer-review part) in the UK study of the Sizewell plant (Turland et al, 1993). The methodology was developed further through completed applications to the Mark I Liner Attack and Direct Containment Heating problems. A further application to the in-vessel retention severe accident management scheme is currently in progress for the AP600. It was noted that while the 1987 study originated ROAAM, the process was not pursued to closure.

The subject of closure was illustrated by Figure 2, and in it the 1987 study can be seen to have advanced the problem to Phase II. At the time of the UK study there were some initial results from the experimental work on premixing which did not play as strong a role in it as it did for the 1987 US study. Still, due to the lack of involvement of external experts, and the limited amount of experimental verification, the UK study can probably be classified also in Phase II. Meanwhile much progress has been made on the experimental front and it appears feasible now to carry out Phases IV and V in rapid succession.

Several panel members (including the leader of this discussion) in their individual presentations and during the discussions of the meeting, expressed the wish that the α-failure be brought to an orderly closure. Several members, as well as other cooperative bodies (CSNI), expressed the wish to see comparative studies and the use of standard problems for this purpose. It appears that this is an opportune time to combine these two wishes in an international effort. Specifically, the discussion leader put forth the proposal that the 1987 US and the 1993 UK studies be combined and extended to closure through the involvement, and integration of all available, world-wide expertise.

The floor was then opened for discussion. Several group members felt that at this "stage" the problem of α-failure does not deserve the commitment of any further resources, while at least one member felt that current understanding and capability fall short of what is needed to provide a reliable closure. There wasn't much explicit support in favor of the proposal, voiced during the discussion, which, however, was interrupted to close the meeting, as many group members had to catch planes.

APPENDIX D

ADDITIONAL COMMENTS AND CONTRIBUTIONS BY SERG-2 PANEL MEMBERS

Concerns Related to Evaluations of Propagation and Localized Failure Analysis

R. Henry
Fauske & Associates, Inc.

During the SERG-2 meeting, some of the discussion was focused on propagation of an initiating event through a potentially explosive mixture of high temperature molten core debris and water. As part of these discussions it was clearly stated that some of the physical processes were represented in a conservative manner to assess the potential for explosive interactions to threaten the integrity of the RCS upper head (α-model failure). Moreover, those modeling assumptions that were considered as being conservative were appropriately noted.

In the Friday morning session, Mike Corradini led the discussion related to propagation of an explosive interaction. He listed a possible conclusion that current models were insufficient to assess event propagation and localized failures. This generated extensive dialogue related to whether (1) event propagation is appropriately calculated and (2) whether the information resulting from these calculations were sufficient to assess localized failures. Examples of such failures would be the RPV lower head or localized challenges to the containment wall in the case of an ex-vessel steam explosion. During this discussion it was unanimously concluded that propagating events can be calculated once a significant external trigger is postulated and imposed on the premixed configuration of molten core debris and water. It was not clear whether current models are sufficient to model the escalation of a very small trigger, for example 1000 Pa pressure increase for 1 ms, and thereby demonstrate how this could result in a propagating interaction. Herein lies my concern.

I believe that the observation of "high pressure cutoff" is due to the fact that localized triggers can no longer escalate into explosive events. Consequently, it is my belief that localized events (triggers) are always occurring when high temperature molten fuel is poured into water, regardless of whether the water is subcooled or saturated and regardless of whether the pressure is 1 bar, 10 bars or 100 bars. Therefore, while propagating interactions can be calculated given a sizeable trigger, in my view, these are conservative estimates of the actual event since a significant explosive interaction must be postulated before propagating event can be calculated. Assessing the potential for localized failures requires a well characterized analytical model with no conservatisms built into the assessments for propagation. Conversely, conservatisms are appropriate when determining which structural members <u>will not</u> fail as a result of a propagating event. In this latter case, those structures which successfully withstand a conservative representation of the propagating event clearly can be viewed as sufficiently strong to withstand a more realistic event.

Before committing to a conclusion that localized failures can be adequately characterized, I believe that two key experimental observations must be represented by the calculational models. First, the models must demonstrate that a small, innocuous, trigger due to localized contacts, can escalate into a major explosive interaction. Secondly, the calculational tools must demonstrate that an event which can escalate into an explosive condition at a low pressure, for example 1 bar, does not escalate when the pressure is elevated to 10 bars. Both of these experimentally observed behaviors should be demonstrated by the calculational tools before the potential for localized failures can be adequately assessed using the tools for local propagation.

Additional Comments
on
the Steam Explosion Induced α-Mode Containment Failure Issue

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1. What Is the Meaning of All Those Probability Estimates?

Several estimates of the conditional probability of the α-mode containment failure were given at the meeting. My estimate happened to be higher in value than those of the other experts, except that Prof. Theofanous preferred to provide the estimate as 'physically unreasonable'.

It was not clear (1) whether the numerical estimates provided by experts were considered as strictly frequentistic and (2) what level of confidence the experts placed on the values they quoted. The levels of confidence for the quoted estimates were not discussed at the meeting, and, perhaps, this should be clarified in the final summary of the meeting.

Regarding my numerical estimate of the α-mode containment failure probability of $1 \cdot 10^{-2}$, I place very high confidence on this number. I could state that I am 99.9 % confident (3σ) that the chance of failing the PWR containment due to an in-vessel steam explosion, given a core melt, is less than 1 in 100.

I, personally, do not understand values of 10^{-6} to 10^{-5}, advanced in the meeting. One can very well state that the α-mode failure is impossible. When I state that I am positive (highly confident) that the α-mode failure probability is $1 \cdot 10^{-2}$, it is physically unrealistic to assume that such a failure will occur.

2. Should Other Consequences of a Steam Explosion Be Considered?

I believe the NRC did not want to deal with this question in the framework of severe accidents. I made a case for conducting research to explore these. The α-mode failure, being an early containment failure, is of primary concern; however accident termination and accident management are also of concern. A strong in-vessel steam explosion (which does not cause containment failure) could cause considerable damage (e.g., lower head failure), and the management of the accident according to the currently, or soon to be devised, procedures may not be possible or efficient.

3. Should the α-mode Containment Failure Be Investigated Further?

This is a tough question. On the one hand the estimates on the conditional failure probability are so low that all NRC safety criteria are satisfied and the benefit of pursuing further work on this particular topic seems to be ephemeral. On the other hand, the methodology of treating the various phases of the in-vessel steam explosion accident has matured to the point that the failure probability estimates may be certified and the issue closed for ever. I, personally, support the latter course, i.e., further investigations, since it has many side benefits. For example, a rigorous review of the methodology developed will result. This course will also be required if in near future NRC decides to deal with the other consequences of an in-vessel steam explosion.

Further investigations, based on the focused ROAAM-type approach may not appear to be of large benefit for the α-mode failure issue, but they will help in the assessment of the risk of the other consequences of an in-vessel steam explosion.

4. What About Ex-Vessel Steam Explosions and Their Loads?

The containments of the advanced LWRs, i.e., SBWR and the AP-600 (if in-vessel retention fails), are subject to ex-vessel steam explosions. Perhaps, the ice condensers will be similarly prone. The Swedish BWRs have the accident management scheme of flooding their drywells in the event uncovering of core occurs. Thus, ex-vessel steam explosions and the loads they may impose on the containments should be of concern. The methodology developed for the premixing, propagation and expansion phases of a steam explosion should be applicable and exploited for assessment of ex-vessel steam explosion loads. The work on this issue would also derive benefit from the further investigations recommended above.

5. Are There Any Important Phenomena Which Have Not Been Considered?

Except for the contribution of chemical energy, I believe all the possibly important phenomena have been considered. For the TMI-2 type core melt scenario, the zirconium content of the melt jet will be minimal. However, for a scenario in which the core melt is discharged from the bottom of the core, the zirconium content could be large. I believe experiments using mixtures of oxidic and metallic melt could delineate the contribution of chemical energy. The majority of the chemical energy should be delivered during the expansion phase. KROTOS facility could be used to obtain pertinent data with prototypic melts.

6. How Could the Hazards of Steam Explosions in Reactor Accidents Be Shown to be Small?

I believe the difficult explosivity of UO_2-ZrO_2 mixture is the key. The KROTOS experiments have found this to be the case. This should be pursued further. The property or properties, and the physical phenomena responsible for such behavior, should be identified and assessed. If it can be established that the prototypic UO_2-ZrO_2 melt requires a massive trigger to explode, or does no explode, it may resolve the steam explosion hazard issue. In this context, experimental research on triggerability, as recommended in my presentation, should be beneficial.

Contribution to the Discussion on
Propagation and Dynamic Loads from Steam Explosions

T. G. Theofanous

I took issue with Corradini's proposed conclusion that current capability is insufficient to assess the magnitude of local dynamic loads from steam explosions, because it is not correct relative to our capability at UCSB. On the contrary, I think we should make such a conclusion on the affirmative, and following Hans Fauske's suggestion, by specific reference to ESPROSE.m. I welcome specific observations on our approach, and our code, but I think it would not be appropriate to summarily dismiss it (as the conclusion attempts to do) nor ignore it (as the proposal made at the meeting, to simply delete this conclusion, would effectively do).

Now going to my discussion with Bob Henry, I think it can be summarized as follows. His position is that our calculation is conservative, so that it is appropriate if the results imply structural integrity, but it cannot be accepted if the results imply failure. My position is that while the codes, and whole modelling approach is based on best estimate physics, it is in the nature of this problem that one tries to determine a <u>reasonably</u> conservative envelope of premixture conditions at the time of trigger, and, unless it can be shown otherwise, that one assumes that an effective trigger occurs to produce a large scale steam explosion. Further, our intent in safety analyses, is, preferably, to show that the structures can take the resulting loads. So, in fact, for all intents and purposes we agree.

Where we would potentially disagree is if our calculations show failure. He would interpret such a result as "inconclusive," and as far as I can tell his main reason would be that in actuality the effective trigger (assumed in the calculation) may not occur. We certainly agree that in an actual realization an explosion may, in fact, not occur. However, except for high initial pressures, where there seems to be general agreement that spontaneous explosions are in general not to be expected, I think one would be hard pressed, at this time, to place odds for or against such an occurrence. Moreover, this is likely to remain an area of uncertainty for some time to come. Because of this, we, and I think most safety people, see no other choice but to assume that an explosion will occur. Moreover, we, and I think most safety people, find it reasonable to postulate that the timing, and the premixture of such an explosion, are chosen so as to reasonably envelope premixture uncertainties, regarding especially the breakup aspects of the problem. This means, then, that we are prepared to accept the consequences of these assumptions, even if failure is implied—unless, of course, some relief is found in terms of some other aspects of the assessment (i.e. pouring rates) that can be counted on. All this is standard procedure in issue resolution, according to my own experiences, and I feel there is no need to make special qualifications about the "conservative nature of the calculations" in the very limited sense described above.

It could be noted, however, as a separate conclusion, that so far there has been an apparent difficulty (in some limited tries) to obtain explosions with oxidic (ZrO_2/OO_2) reactor materials. However, this cannot be used to assume that such explosions cannot be triggered in reactor geometries, before identifying a robust mechanistic cause for it. Similarly, but to a much lesser degree (due to the much more extensive empirical evidence available) we need to identify the mechanistic cause for the high pressure cutoff. Incidentally, we are working on both of these aspects now in the SIGMA facility, at UCSB.

POSTSCRIPT

The summary by Fauske (Appendix C-1) gives a tabulation of the alpha-mode failure probability estimates by the SERG-2 members. Subsequent to this summary, three members - Berthoud, Jacobs and Sehgal - modified their estimates and views. The modifications are reflected in Table 1 in the main body of the report.

Berthoud and Jacobs provided a few comments on the Premixing summary by Turland (Appendix C-2). In response to the comments, Turland suggested certain modifications. The original summary is retained in Appendix C-2, and the suggested modifications are noted here for completeness.

1. Bottom of page 2: Replace sentence starting "Berthoud indicated ..." by "Berthoud indicated that some plant calculations were performed in France but were not reported in the open literature."

2. Conclusion 3. third sentence, add "on the reactor scale."

3. Conclusion 3. after "assumed", add (however, the break-up may be less pronounced at lower pressures than those in the FARO experiments).

4. Conclusion 5. Replace the second sentence with: For alpha-mode failure assessments it may be possible to use the current codes with a range of assumptions on initial melt drop size, fragmentation and heat transfer to scope the effects of uncertainties in melt jet fragmentation.

Theofanous' additional comments (see Appendix D, pages D-5 and D-6) were prompted, in part, by an item in Corradini's summary on Propagation (discussed during the workshop) in which it was stated that the current state of knowledge of the propagation phase was considered sufficient by the experts for use in the alpha-mode failure analysis, but insufficient for use in the local dynamic load calculations. The printed summary (Appendix C-4), on the other hand, makes no statement concerning an insufficient knowledge for local dynamic load calculations. The summary, however, makes a point that the vapor explosion propagation physics could be treated conservatively with the current state of knowledge.

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10. SUPPLEMENTARY NOTES

This is a report of the Second Steam Explosion Review Group (SERG-2) Workshop held June 15-16, 1995 at Annapolis, MD.

11. ABSTRACT *(200 words or less)*

This report summarizes the review and evaluation by experts of the current understanding of the molten fuel-coolant interaction (FCI) issues covering the complete spectrum of interactions, i.e., from mild quenching to very energetic interactions including those that could lead to the alpha-mode containment failure. The experts' review and evaluation took place in the form of a Second Steam Explosion Review Group (SERG-2) Workshop, held in Annapolis, Maryland, on June 15 and 16, 1995. The first such workshop (SERG-1) took place in 1985.

Extensive discussions took place at the SERG-2 workshop on the alpha-mode failure issue, based on the experts' responses to the questions raised, and consensus opinions on the status of resolution of the issue emerged from the discussions. Of the eleven experts polled, all but two concluded that the alpha-mode failure issue was resolved from a risk perspective, meaning that this mode of failure is of very low probability, that it is of little or no significance to the overall risk from a nuclear power plant, and that any further reduction in residual uncertainties is not likely to change the probability in an appreciable manner.

To a lesser degree, discussions also took place on the broader FCI issues such as mild quenching of core melt during non-explosive FCI, and shock loading of lower head and ex-vessel support structures arising from explosive localized FCIs. These latter issues are relevant with regard to determining the efficacy of certain accident management strategies for operating reactors as well as for advanced light water reactors. The experts reviewed the status of understanding of the FCI phenomena in the context of these broader issues, identified residual uncertainties in the understanding, and recommended further research (both experimental and analytical) to reduce the uncertainties.

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