FOURTH CSNI SPECIALIST MEETING ON FUEL-COOLANT INTERACTION IN NUCLEAR REACTOR SAFETY

Bournemouth, United Kingdom
2-5 April 1979

Hosted by the UNITED KINGDOM ATOMIC ENERGY AUTHORITY ATOMIC ENERGY ESTABLISHMENT WINFRITH

PROCEEDINGS

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS OECD NUCLEAR ENERGY AGENCY
38, boulevard Suchet, 75016 Paris, France
FOURTH CSNI SPECIALIST MEETING
ON
FUEL-COOLANT INTERACTION IN
NUCLEAR REACTOR SAFETY
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## CONTENTS

### VOLUME 1

<table>
<thead>
<tr>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>19</td>
</tr>
<tr>
<td>21</td>
</tr>
<tr>
<td>22</td>
</tr>
<tr>
<td>52</td>
</tr>
<tr>
<td>54</td>
</tr>
<tr>
<td>80</td>
</tr>
<tr>
<td>81</td>
</tr>
<tr>
<td>89</td>
</tr>
<tr>
<td>90</td>
</tr>
<tr>
<td>111</td>
</tr>
</tbody>
</table>

- Abstract
- Programme Group of the Meeting
- List of Participants
- Welcoming Address: H Cartwright CBE Director, AEE Winfrith
- Introductory Remarks: K B Stadie Head, NEA Nuclear Safety Division

### SESSION I

**Introduction**
Chairman: J G Tyror

A Summary of Open Key Issues in the Science of Fuel–Coolant Interactions and Vapour Explosions
H J Teague: Chairman of a CSNI Group of Experts

Discussion on Session I

### SESSION II

Theoretical Modelling of FCI Phenomena
Chairman: W B Hall

FCI4/P1 Multiphase Thermal Detonation for a UO₂–Na System
G Berthoud and E Scott

Discussion on Paper FCI4/P1

FCI4/P2 Calculations on Propagating Vapour Explosions for the Aluminium/Water and UO₂/Sodium Systems
T P Fishlock

Discussion on Paper FCI4/P2

FCI4/P3 Thermodynamic Predictions for the Maximum Interaction Pressures
G Scarano

Discussion on Paper FCI4/P3

FCI4/P4 Hydrodynamic Fragmentation in a Dense Dispersion
M Baines

Discussion on Paper FCI4/P4
<table>
<thead>
<tr>
<th>Session III</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCI4/P8</td>
<td>The Influence of Solid Boundaries in Inhibiting Spontaneously Triggered, Small-Scale, FCIs T A Dullforce</td>
<td>180</td>
</tr>
<tr>
<td>FCI4/P9</td>
<td>Base Triggered FCI in copper/water systems F M Page</td>
<td>192</td>
</tr>
<tr>
<td>FCI4/P10</td>
<td>Molten tin/water interactions, a description of the experimental apparatus and preliminary heat transfer results G Boxley and F M Page</td>
<td>203</td>
</tr>
<tr>
<td>FCI4/P11</td>
<td>Film Boiling Experiments at Karlsruhe L Caldarola and R Ladisch</td>
<td>216</td>
</tr>
<tr>
<td>FCI4/P12</td>
<td>Importance of the Coolant Impact on the Violence of Vapour Explosion H M Kottowski and M Mol</td>
<td>224</td>
</tr>
<tr>
<td>FCI4/P13</td>
<td>The Injection of Liquid Sodium into Stainless Steel: A report of further experiments NA SS/4, Na SS/5 and Na SS/6 R C Asher, L Bradshaw, D Davies, J E Perry, S J S Sangwine and G J Vaughan</td>
<td>269</td>
</tr>
</tbody>
</table>
FCI4/P14  The Effect of Pressure on NaCl-H₂O Explosions
H Hohmann, H E Henry and H M Kottowski

Discussion on Paper FCI4/P14

General Discussion on Session III

VOLUME 2

SESSION IV  Specific and Well-characterized Integral FCI
Experiments
Chairman : R E Henry

FCI4/P15  Experimental Observations of Propagating Thermal
Interactions in Metal/Water Systems
C J Fry and C H Robinson

Discussion on Paper FCI4/P15

FCI4/P16  Melt/Water Interactions in Tank Geometry : Experimental
and Theoretical Results
R Benz, W Schwalbe, H Hohmann and F Toselli

Discussion on Paper FCI4/P16

FCI4/P17  Steam Explosion Triggering and Efficiency Studies
L D Buxton, L S Nelson and W B Benedick

Discussion on Paper FCI4/P17

FCI4/P18  Out-of-Pile Studies of Power Burst Energetics
T G Theofanous and D VanZandt

Discussion on Paper FCI4/P18

FCI4/P19  Fuel-Coolant Interaction Studies with Water and
Thermite Generated Molten Uranium Dioxide
M J Bird and R A Millington

Discussion on Paper FCI4/P19

FCI4/P20  Observations of Tin/Water Thermal Explosions in a
Long-Tube Geometry; their Interpretation and
Consequences for the Detonation Model
R W Hall, S J Board and M Baines

Discussion on Paper FCI4/P20

FCI4/P21  A Comparison of the Sodium-U₃O₈ Results with the
Spontaneous Nucleation Theory
R E Henry

Discussion on Paper FCI4/P21
SESSION V

FCI Studies Directly Related to Reactor Conditions
Chairman : L Caldarola

FCI4/P22

UO₂–Na Interactions : The CORECT 2 Experiment
M Amblard and B Berthoud

Discussion on Paper FCI4/P22

FCI4/P23

Simulation of the CORECT II Experiment No 18 with
the MURTI Computer Program
H Jacobs

Discussion on Paper FCI4/P23

FCI4/P24

Fuel–Sodium Thermal Interactions in the Camel
TOP Safety Tests
B W Spencer, D R Armstrong, L Bova, G T Goldfuss
R E Henry and D Raridon

Discussion on Paper FCI4/P24

FCI4/P25

Prompt Burst Energetics (PBE) Studies
K O Reil and M F Young

Discussion on Paper FCI4/P25

FCI4/P26

A Study on Pressure Generation Caused by Actual
Fuel Failures in the NSRR Experiments
T Fujishiro, T Hoshi, S Yanagihara, M Ishikawa

Discussion on Paper FCI4/P26

SESSION VI

Implications of FCI for Reactor Safety Studies
Chairman : H J Teague

FCI4/P27

The Effect of Uncertainties in Thermophysical
Properties of UO₂ and Sodium on MFClS
D A MacInnes, D Martin and G J Vaughan

Discussion on Paper FCI4/P27

FCI4/P28

The Influence of MFCl Modelling on the Predictions
of Accident Codes used in the WAC Group Comparative
Exercise
D E Billington

Discussion on Paper FCI4/P28

FCI4/P29

A Model for the FCI in a Multichannel
K Mehr, H M Kottowski and H Goldammer
FCI4/P30  Mechanical Energy Yields and Pressure Volume and Pressure Time Curves for Whole Core Fuel/Coolant Interactions
P Coddington

Discussion on Paper FCI4/P30

FCI4/P31  Fuel-Coolant Interactions in LWRs and LMFBRs: Relationships and Distinctions
R B Duffey and G S Lellouche

Discussion on Paper FCI4/P31

FCI4/P32  Fuel Operation with UO₂ Melting and Zircaloy Sheath Temperatures to 1600°C
A S Bain, R R Meadowcroft, V J Langman and S M Leung

Discussion on Paper FCI4/P32

FCI4/P33  The FCI Potential of Oxide and Carbide Fuels: Results of the Prompt Burst Series at Sandia Laboratories
M F Young, K K Murata, J T Hitchcock and W J Camp

Discussion on Paper FCI4/P33

General Discussion on Session VI

SESSION VII

Part 1  First Panel Discussion: Science of Fuel Coolant Interactions
Chairman: J G Tyror

Introductory Remarks to Session VII, Part 1
Chairman's Report for Session II
Chairman's Report for Session III
Chairman's Report for Session IV
Chairman's Report for Session V
Chairman's Report for Session VI
General Discussion on Session VII, Part 1

Part 2  Second Panel Discussion: Reactor Safety Implications
Chairman: E V Gilby

Introductory Remarks to Session VII, Part 2
Discussion of Session VII, Part 2
General Discussion
Need for a Fifth Fuel Coolant Interaction meeting
FCI Newsletter
Continuation of Specialist Groups
Standard Problem Exercise
SESSION IV

Specific and Well-characterized Integral

FCI Experiments

Chairman:  R E Henry
Secretary:  R J Maddison
Paper for presentation to

OECD-CSNI

Fourth CSNI Specialist Meeting on
Fuel-Coolant Interaction in Nuclear Reactor Safety
Bournemouth, UK: 2-5 April 1979

EXPERIMENTAL OBSERVATIONS OF
PROPAGATING THERMAL INTERACTIONS IN
METAL/WATER SYSTEMS

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March 1979
EXPERIMENTAL OBSERVATIONS OF PROPAGATING THERMAL INTERACTIONS IN METAL/WATER SYSTEMS

C J Fry and C H Robinson

1 Introduction

The THERMIR experimental facility at AEE Winfrith was set up in 1975 in order to study on a large scale, thermal interactions between molten metals and water. Experiments in THERMIR have used both tin and aluminium as the molten metal and have covered a wide range of temperature conditions, geometry, and triggering arrangements.

During these experiments three types of interaction have been observed:

i Coherent interaction of a large mass of metal/water mixture.

ii Localised interaction in which a separate drop of metal or a small region of metal/water mixture interacts, producing local expansion but not triggering any interaction of the surrounding materials,

iii Incoherent interaction of a large mass of metal/water mixture, in which a sequence of small interactions at different locations is observed to develop in the metal/water mixture. This sequence can either die out or continue until all the mixture has been involved.

Coherent interactions have been observed to involve the usual sequence of

a Coarse but quiescent mixing of molten metal with water,

b A trigger event to initiate interaction,

c Propagation of the interaction through the coarse mixture.

The main aim of recent work has been to observe the propagation stage, and these experiments have confirmed that propagation can be identified with passage of a pressure wave through the mixture. This work is discussed in sections 3 and 4.

The characteristics of incoherent interactions are discussed in sections 5 and 6, in which it is suggested that such events could be involved in the escalation of a trigger event into coherent propagation. A simple mathematical model of the response of a single drop to an impulse is used to illustrate the possible relationship.

A number of experiments have been conducted with low temperature tin, (300°C), to investigate whether any obvious changes in phenomena resulted from the reduction of the initial interface temperature between metal and water to a value well below the spontaneous nucleation temperature for water. Unexpectedly, propagation of a coherent interaction was observed in some cases, and these results are discussed in section 7.
The THERMIR Facility

The THERMIR facility at AEE Winfrith has been described in detail by Briggs (1). Briefly, it consists of a strong test cell, designed to contain a 10 MJ energy release and located in a cleared area of 200 m radius. The test cell contains a gas heated muffle furnace in which 20 kg of metal can be heated to 800°C. This molten metal is then dropped, through the base of the furnace, into a reaction vessel containing water which can be heated and circulated to maintain a uniform temperature. Many of the reaction vessels have been fitted with transparent sides through which the events have been filmed with a high speed camera. The pressure in the vessel is measured with piezo electric pressure transducers. The operations are controlled from a building outside the cleared area which also contains the magnetic tape recorders used for the transient pressure data.

Experimental Evidence of Propagating Thermal Interactions

3.1 Experimental Details

Ten experiments have been carried out in which results relevant to the characterisation of a propagating thermal interaction have been obtained. The experiments have been carried out in three different types of reaction vessel and have been obtained using both tin/water and aluminium/water mixtures. High speed cine film was used to observe these experiments, which are listed in Table 1.

Five of the early tests were carried out in an open, rectangular vessel which is shown, with interior dimensions, in figure 1. The transducers in these vessels were on the centre line of the vessel and were therefore about 15 cm away from the front of the vessel and the perspex window through which the interaction was filmed. The propagation velocity was measured from these film records. With one exception, these interactions were triggered spontaneously. In the one exceptional test an early incoherent interaction lifted the vessel from its support structure. The observed interaction which is discussed in this paper was triggered by the mechanical blow when the vessel fell back to the support structure, (see Table 1). Results from some tests of this type have been reported previously (1).

In the next series, cylindrical vessels were used to provide stronger confinement and improved locations for pressure transducers. Two sets of data were obtained in tests with these partially roofed cylindrical reaction vessels, shown in figure 2. The main test used a vessel with a steel body; the second had a perspex body to allow filming of the events. In this experiment the propagation velocity was very high and the interaction front could only be observed in one frame of the film; consequently the propagation velocity could not be directly measured from the film. In both of these tests the interactions were triggered by a very strong pressure pulse from a detonator attached directly beneath the centre of the base. The propagation velocity has been calculated from the pressure transient records, assuming that the interaction originated at the time that the detonator was fired. This gives a minimum value for the velocity.
As can be seen from the figure, the transducers were not all the same distance from the assumed origin of the interaction. Nevertheless, there was good agreement in the velocity calculation using the data from individual transducers and this suggests that any underestimate of propagation velocity, due to an assumption about the time of origin, was small.

The third series of experiments were carried out in the vessels shown in figure 3 which were made very narrow (80 mm) in comparison with the depth and width, so as to obtain an essentially two dimensional system. The front and rear walls were transparent. The metal from the furnace was spread equally through the vessel by a heated distributor and was collected on a false base, the catch tray, some 50 mm above the true base. The interaction was triggered by firing a detonator, attached to the side wall of the vessel, when the molten metal had collected so as to produce an interaction propagating horizontally through the metal/water mixture on the tray. A row of seven pressure transducers were bonded in a horizontal line on the transparent front face of the vessel so that they were in the same reference plane as the events recorded on the high speed cine film. Most of these transducers were immersed in the metal/water mixture at the time of the interaction. The specific aim of these tests was to determine the relation between an observed propagation front and pressure transients measured in the vessel. The results are discussed in detail in section 4, but an example of the type of data obtained is shown in figure 4, which shows that the observed front coincides with a rapid increase in pressure. The propagation velocity was obtained from these comparisons of pressure transducer and film data.

3.2 Experimental Results

The results are summarised in Table 1, in which the type of reaction vessel and the metal used are identified together with the initial experimental conditions. The amount of metal present in the vessels at the time of the interaction is an estimated value obtained from flow calibration tests of the furnace and distributor system. The maximum pressure measurements are average values taken from the appropriate pressure transient measurements, as are the pressure rise times. However, in those cases where the pressure transducers were not fully covered by the metal/water mixture, the pressure rise time measured at the transducers is likely to be greater than the pressure rise time in the propagating front, due to the higher speed of sound in water. The methods of determining the propagation velocity, which were different in each of the three series of experiments, have been discussed above.

The debris collected after each experiment was sieved and the sieve fractions weighed. The particle sizes ranged from about 2 mm to less than 45 microns. This data has been presented in Table 1 as an apparent specific surface area which has been calculated assuming that each particle is a sphere. It is, therefore, not the true surface area, since the particles are, almost universally, coke-like. It is, however, indicative of the size distribution in that
a high apparent specific surface area indicates a greater percentage of fine particles.

Some measurements of the true surface area of samples of debris have been made using gas adsorption techniques. These measurements show that the surface area of the tin debris is in the range from 10 to 200 $m^2/kg$ and that for the aluminium debris is about 1000 $m^2/kg$.

The high speed cine film records of the metal/water mixture just before the interaction show no fine detail but suggests that the surface is smooth and in the form of a number of roughly spherical and interconnecting bulges. The enclosing volume is large showing that the volume of water or vapour trapped in the mixture is considerably greater than the volume of metal; the value of the total volume is quoted in Table 1.

In some experiments with aluminium, where no interaction has been triggered, the development of the mixture has been observed on film from its first formation until it has solidified. No changes in the exposed surface can be observed as the metal freezes and it is probable that the frozen metal adequately represents the state of the molten metal in the mixture. One of these objects has been sectioned and a photograph is shown in figure 5. It has a relatively thick base, about 1 cm thick, above which a large number of cells, with thin walls, form the body of the structure. There are, however, throughout the body numerous accretions of the metal, which have thicknesses of the order of 1 cm. The cell walls are typically less than 1 mm thick.

The cine film records of two of the experiments (numbers 107 and 109 see Table 1) with the type 3 vessel have been analysed to determine the particle velocity in the region immediately behind the front. The measurements can be carried out on only a few, relatively large (2-3 mm) features which had a greater reflectivity than their surroundings because the films show no fine detail. In the 10 measurements which have been made the measured velocities ranged from 31 m/s to 13 m/s with an average of about 25 m/s. These measured velocities are likely to be low both because of the size of the particles and because of their proximity to the wall.

4 The Characteristics of the Coherent Propagating Thermal Interaction

4.1 The relationship between visual observation and pressure records

One of the main aims of the third series of experiments has been to relate the visual observation of the passage of a front through the metal/water mixture with the concurrent measurement of the pressure transient related to the front by pressure transducers mounted in the plane of observation. Results from one of the more satisfactory tests of this kind are shown in figure 4. In this experiment tin at 800°C was released into water at 85°C (see Table 1 for other data on experiment 107). The figure shows both the pressure transients measured at seven locations across the vessel, and the time at which a front was seen on the cine film, to cross
each transducer location. The uncertainty of $\pm 0.25\ ms$ on this time mainly represents the difficulty of precisely defining the position of the front on each frame of the film, but also covers synchronisation of the film with the pressure transients.

On film, the front does not have a sharp boundary, but is recognised by disappearance of detail. Ahead of the front the film shows relatively static detailed features with highlights produced by reflection, whereas behind the front the detail is either blurred or disappears to give a grey region which expands rapidly. The absence of streaking behind the front indicates that the blurring is not due to rapid motion of the material, hence it is assumed that it results from a combination of the collapse of any vapour present and fragmentation of the metal, both of which would change the appearance of the mixture. The resolution available makes it difficult to relate the front to the detailed shape of the pressure transients, but in most cases the data are consistent with the peak pressure occurring at the observed front. In a few cases the observed front appears to be ahead of the peak pressure and in others the interpretation is complicated by regions of water adjacent to a transducer in which case the higher speed of sound in the water leads to distortion of the pressure transient. However, in general there is no increase in pressure ahead of the front, confirming that it is moving at least at sonic velocity through the initial system. In the example shown in figure 4, the total rise time of the pressure pulse is of order 0.2 ms to a peak pressure in the range 1 to 2 MPa, although the transducers on the far side of the vessel, which the film shows to be well immersed in the mixture show a main pressure rise which is more rapid. The velocity of the front is approximately 80 ms$^{-1}$.

Another feature of this experiment was the delay between the trigger pulse being applied, by the firing of a detonator, and the apparent initiation of the thermal interaction. Extrapolation of the position of the front backwards to the edge of the catch tray, at a velocity of 80 ms$^{-1}$, yields a delay of 1.5 to 2 ms. Of this only 30 $\mu$s is required for the pulse to be transmitted, through water, from the wall of the reaction vessel to the tray. In a repeat of this experiment a stronger trigger pulse was achieved by using two detonators simultaneously. No delay between the trigger pulse and the start of propagation was observed in this case although the other results were generally similar.

4.2 The Velocity of Propagation

Examination of the results of all the experiments which have been discussed here, shows that the propagation velocity is strongly influenced by the maximum pressure in the front. These data are given in Table 1 and plotted in figure 6. For aluminium/water tests the velocities varied from 76 to 409 ms$^{-1}$, and the figure shows that the peak pressure varied from 1.2 to 40 MPa. For tin/water experiments the values show a similar variation, although there is a wider scatter and the velocity range is lower (35 to 120 ms$^{-1}$). Figure 6 has logarithmic scales, and the slope of the guide line plotted shows that the points indicate a variation of velocity as
the square root of the peak pressure.

The velocity of a shock front in a homogeneous mixture of materials may be expressed as

\[ D = V_1 \sqrt{\frac{P_2 - P_1}{V_1 - V_2}} \]

where subscripts 1 and 2 refer to the status before and after the shock and V is the specific volume.

For a mixture of incompressible liquid and vapour this has been written as

\[ D = V_1 \sqrt{\frac{P_2 - P_1}{\Delta V}} \]

where \( \Delta V \) is the volume of vapour per kilogram of mixture in the initial state (2). If \( P_2 \gg P_1 \) this approximates to \( D = V_1 \sqrt{\frac{P_2}{\Delta V}} \).

Hence for constant \( V_1 \), the propagation velocity is expected to be proportional to \( \sqrt{P_2} \). Although the composition of the initial mixture has not been accurately determined, in the broadly similar conditions achieved in these experiments it is unlikely that the variation in these quantities would be greater than, say 2:1. Hence over a sufficiently large range of pressure variation the effect of pressure would be dominant. The trend which is observed in the experimental results is therefore some confirmation that the observed propagation has the characteristics of a shock front.

4.3 The Composition of the Initial Mixture

The composition of the mixture through which an interaction propagates must be determined if any detailed analysis is to be possible. In these experiments the quantity of metal involved is known from the flow rate from the furnace and distributor and the volume of metal water mixture can be estimated from the films. These data are given in Table 1, and imply that the average metal density in the interaction zone was of order 1 kg/l for aluminium and 2 kg/l for tin. These values imply that the volume fraction of H₂O was of order 58% and 70% respectively, but do not provide any direct information on the relative volumes of liquid water and steam.

Examination of the solidified form of aluminium which did not interact suggests that large vapour volumes are produced, since the metal contains many large cavities probably produced by steam pressure. Examination of films confirms that large volumes of vapour are produced, but does not allow any quantitative estimate to be made. However, an approximate estimate of the vapour fraction has been made from the observed correlation of peak pressure with propagation velocity. In the previous section it was shown that the observed variation of propagation velocity D with pressure rise was consistent with the relation \( D = V_1 \sqrt{\frac{P}{\Delta V}} \). From measured values of D
and P this can be evaluated, and for both tin and aluminium the approximate value of the initial specific volume of vapour is given by \( \Delta V_1 = 250 V_1^2 \) where \( V_1 \) is measured in m³/kg. This condition defines the volume fractions of steam and water in the known total volume fraction of H₂O. The nominal values of volume fraction obtained for typical aluminium/water mixtures are 40% aluminium 40% water and 20% steam. In the case of tin the typical mixture has volume fractions of 30% tin, 60% water and 10% steam. Differences between these metals would be expected because of the large differences in both density and heat transfer properties. The lower volume fraction of tin is consistent with its higher density, whereas the higher steam fraction in the aluminium case probably derives both from the higher metal to water ratio and the better heat transfer properties of aluminium. This is consistent with films of the initial contact phase in which larger vapour volumes are produced by aluminium even when the initial sub-cooling is high. It is concluded that the average volume fraction of vapour at the time of interaction was of order 10 to 20%. Variations in this fraction would be expected in individual experiments because of differences in the sub-cooling of the water, and the surface area of metal in the mixture.

The velocity of sound in a complex three phase mixture would be expected to depend to some extent on the vapour fraction present. No measurements have been made in such systems but values as low as 20 ms⁻¹ have been reported for two phase bubbly mixtures with vapour contents of order 10% and upwards (3). From extrapolation of the measured shock velocities to low pressure, it seems likely that the sound velocity in the initial mixtures in THERMIR was also of order 20 ms⁻¹.

4.4 Fragmentation of the mixtures

The metal debris which has been recovered after each of the experiments has been highly fragmented. The mechanism causing this fragmentation cannot be determined from the debris or from the film records. However, it is of some interest to evaluate the rate of fragmentation to be expected if hydrodynamic forces resulting from differential velocity are involved.

A recent study by Patel and Theofanous (4) shows that, in liquid-liquid systems the breakup time for droplets can be correlated by

\[
t_b = 1.5 \left( \frac{R_d - \frac{1}{2} \frac{\rho_d}{\rho_s}}{v} \right) \left( \frac{\rho_s}{\rho_d} \right)^{1/2}
\]

where \( r_d \) is the droplet radius,

\( v \) is the differential velocity

Bo is the Bond number

and \( \rho_d \) and \( \rho_s \) are the density of the droplet and the surrounding liquid.
The Bond number may be calculated from

$$Bo = \frac{3 C_D \sigma r_d v^2}{8 \sigma}$$

where $C_D$ is the drag coefficient, usually taken as 2 for spheres, and $\sigma$ is the interfacial tension. On this basis it is possible therefore to estimate the break-up times if the droplet size and the differential velocity can be determined.

In the case of aluminium, the size of the droplet may be assumed to be between 0.1 and 1 cm based on the evidence of the frozen debris from tests in which no interaction occurred, referred to above. The calculations have been carried out using a value of 1 cm, which leads to a high value of break up time.

For the case of the experiments with tin there is no evidence to identify the detailed structure within the mixture. However, a value of 1 cm has been assumed to also apply in this case, since the appearance of the metal during the mixing phase is similar in the two cases. An estimate of the differential velocity can be made by assuming it to be equal to the velocity change through the front. This can be evaluated, assuming a homogeneous mixture, from the propagation velocity and measured pressures, thus:

$$v_1 - v_2 = \sqrt{(P_2 - P_1) (V_1 - V_2)}$$

$$v_1 = v_1 \sqrt{\frac{P_2 - P_1}{V_1 - V_2}}$$

and hence

$$v_1 - v_2 = \frac{v_1}{v_1} (P_2 - P_1)$$

Results of these calculations are given in Table 2. The calculated values of Bond number are also given, and are seen to be within the range covered by the experiments of Patel and Theofanos. In the case of experiments 107 and 109 some estimates of velocity of particles behind the front were made from the cine films, which indicated value of the order of 20 ms$^{-1}$. The calculated values of velocity difference were significantly lower.

These calculations can only be indicative since they assume that the metal water and vapour were homogeneously mixed. It is probable that some separation takes place, with the higher density component sinking to the base in which case the specific volume of the mixture at the higher levels will be greater than has been assumed. Nevertheless, these calculations are useful in indicating that break up times of order 0.1 ms are plausible in these experiments, and that the width of the fragmentation region is likely to be of order 1 cm as is shown in the column of break up distances in Table 2. This is not inconsistent with the cine film of these events, and is generally small compared to the vessel dimensions.
4.5 Summary

Observations of thermal interaction in aluminium/water and tin/water mixtures have identified the propagation observed on film with the passage of a pressure wave. The variation of propagation velocity with peak pressure was found to be consistent with simple shock wave theory. On this basis it was possible to estimate that the volume fraction of vapour present in these systems was of the order 10 to 20%. Approximate estimates of the break up time expected from differential velocity effects indicate that fragmentation might be expected within about 1 cm of the shock front, which is not inconsistent with cine films of these interactions.

5 Experimental Evidence for Incoherent Thermal Interactions

5.1 Observed properties

Incoherent interactions between molten tin and water have been observed to propagate in a manner which has quite different characteristics to coherently propagating interactions. Characteristics of incoherent interactions are:

i. No clearly defined propagation front, either visually or on pressure records

ii. A slow general increase in pressure

iii. A fairly large number of separate interaction centres.

The mass of molten tin involved in these interactions ranged from a few hundreds of grammes to over ten kilogrammes, with pressures ranging from less than 0.1 MPa to over 1 MPa.

5.2 Experimental details

A series of experiments were carried out in which up to 20 kg of molten tin at 800°C was released through a distributor into a vessel of the type illustrated in figure 3. Three alternative distributors were used with different outlet nozzles to produce metal/water volume ratios of approximately 1:10, 1:7 and 1:4. No catch tray was fitted in the vessel, as the aim of these tests was to trigger an interaction in the falling metal by firing a detonator placed on the end wall of the vessel. This arrangement did not result in coherently propagating interaction, but did produce a number of incoherent interactions. Further details of experimental conditions are listed in Table 3, which shows that in most of these tests the initial water temperature was raised to avoid excessive spontaneous interaction. The details of five tests carried out with low temperature tin (300°C) are also given in the table.

Transient pressures inside the vessel were measured by a horizontal row of 7 transducers, spaced 50 mm apart on the rear face of the vessel, and high speed cine films were taken of the events in the vessel.
5.3 General observations

The molten tin was observed in each test to start to enter the water 0.8 s after release of the metal was initiated and to fall through the water with a fairly constant velocity of around 1.0 m/s. The detonator was fired about 1.3 s after release of the metal. The tin was still entering the water at this point since it took about 1.4 s for all the metal to fall through the distributor. The interactions triggered by the detonator were all incoherent. However, in some cases later interactions were triggered spontaneously, and in some cases these later interactions were coherent. Details of the types of interactions observed are given in Table 3.

The incoherent interactions were generally observed to start near the detonator where the trigger pulse would be the strongest. Several drops of metal would show rapid expansion in the order of 100 µs after the firing of the detonator and this would then cause further expansions in neighbouring drops of metal after a delay which varied from a few hundred microseconds to several milliseconds. This chain reaction was then continued through the remaining unreacted material.

The incoherent interactions were not observed to propagate through the tin/water mixture under conditions of constant velocity and pressure but instead either to increase steadily in strength or to decay gradually. From observation of the high speed films each of the incoherent interactions has been identified as either escalating or decaying and this is related to the initial metal/water ratio and the initial tin and water temperature in figure 7.

It can be seen that for a metal/water ratio of 1:10 all the interactions decay but with a 1:4 ratio they all escalate.

The three tests which used the 1:7 metal/water ratio all had tin temperatures of about 800°C with water temperatures of 80, 93 and 81°C respectively. The first and last tests gave escalating incoherent interactions whilst the second produced an interaction which decayed away very quickly. This suggests that increasing the water temperature, and hence increasing the thickness of the vapour film, caused the incoherent interaction to decay rather than escalate.

In addition to the main series, five tests were conducted with the tin at a temperature of 300°C, (68°C above the melting point), and with the water at only slightly below saturation temperature. In two of these tests a spontaneous trigger upon the falling metal resulted in incoherent interactions shortly after the tin first entered the water. The remaining tests in this series are discussed in section 7.
6 Analysis of Incoherent Propagation

6.1 Examples of Incoherent Interactions

For each test the pressure records and high speed film have been synchronised and the events visible on the film correlated with the measured pressures. In relating the records to the film, it has to be remembered that events away from the transducers will appear weaker and will be delayed in time on the records relative to the film due to the low sonic velocity and high attenuation in the two phase mixture. Further discrepancies of the order of up to 1 ms may arise due to the pressures being measured on the rear face of the vessel and the film observing events on the front face.

Figure 8 shows the pressure records from test number 75. The seven transducers were spaced 50 mm apart in a horizontal line. A detonator on the right hand side of the vessel is fired at 1.3 ms and it can be seen that the resulting pressure pulse is largest (1.1 MPa) on the adjacent transducer. The first small pressure pulse on the left hand side corresponds to a velocity of around 4000 ms\(^{-1}\) which indicates that it is directly transmitted through the walls of the vessel. The rapid attenuation of the detonator pressure pulse can be seen between positions 7 and 6. The various times and areas of the most easily visible local expansions have been measured from the film and are marked on figure 8. It is possible to correlate some of the recorded pressure pulses with these observed events. No propagation front was observed and the localised expansions continue producing small pressures for over 8 ms after the interaction is initiated.

A second example of the transient pressures during an incoherent interaction is shown in figure 9. These were obtained from test number 80 in which the interactions was judged from the film to be escalating. In this case the rear window was broken 7 ms after the interaction was initiated. No records were obtained from the transducers in positions 2 and 7. However it can be seen from figure 9 that the major events observed on the film can be correlated with some of the features of the pressure records.

6.2 Transition to Coherence

The transducer furthest from the trigger pulse in test number 80 (position 1 in figure 9), shows a transient pressure at 4.5 ms which is similar in shape to those observed in a coherently propagating interaction (eg figure 4) rather than an incoherent interaction (eg figure 8) with a very sharp initial pressure rise followed by a sustained pressure. This suggests that an incoherent interaction may develop into a coherently propagating one. A propagation front is not observed on the film but all the drops of metal on the extreme left hand side are observed to expand at the same instant which again suggests some coherence.
6.3 Evidence of drop oscillation

In small scale experiments it has often been observed that the interaction escalates in a series of oscillations with a period of a few milliseconds (eg Board (5), Dullforce (6)) and this has been explained as successive growth and collapse of the vapour blanket. For coherently propagating interactions these oscillations cannot occur since the fragmentation and heat transfer must be much faster to sustain propagation. These oscillations however could be present in the weaker incoherent interactions. Oscillation of individual interaction centres cannot be directly observed from the high speed films, since resolution is probably not adequate. However, the pressure records for most of the incoherent interactions show successive delay periods of about 2 ms between pressure pulses. A time of apparent quiescence separates the pressure pulses and this can be clearly seen following the firing of the detonator in both figures 8 and 9. The 2 ms period is very similar to that measured by Board and Dullforce and determined theoretically by Buchanan (7) for the oscillations of an interaction upon a single drop. This suggests that such oscillation may be occurring at local expansion centres producing an apparent delay of several ms between the trigger pulse and the expansion pulse. If this is the case, then variation in the time between initial disturbance and final expansion could be contributing to the apparent incoherence in the response of the system as a whole to the trigger pulse.

6.4 Effect of Impulse Variation

In those tests in which the interaction was triggered by the firing of the detonator both the pressure pulse from the detonator and the resulting pressures produced by the nearby drops of tin are observed by the pressure transducers. For selected cases in which both are clearly defined the pulse from the detonator has been integrated to obtain an impulse per unit area and the delay between this pulse and the start of pressure production by the drops has been measured. For all the tests measured the tin and water temperatures were around 800 and 80°C respectively. The results are shown in figure 10. It can be seen that time delay decreases with increasing impulse. Below a threshold of about 2 Ns m$^{-2}$ the impulse is insufficient to cause a prompt effect, but an expansion is observed a few milliseconds later which may be due to oscillation of the vapour film, initially disturbed by the pressure pulse from the detonator.

The minimum time delay measured between the two pressure pulses was 100 μs. But much of this measured delay may be due to the expansion centre being a small distance away from the transducer and hence causing a time delay between pressure being produced and being observed. The true time delay between a drop experiencing a pressure pulse and subsequently expanding may thus be significantly less than the measured values. This comparison of initiating impulse and delay time is only possible for the detonator pulse since its sharpness enables the initiating impulse to be clearly defined from the pressures produced by the expansion centres.
6.5 Discussion

An incoherent thermal interaction may be formally modelled by assuming the metal/water mixture to be a collection of separate drops of metal suspended in the water and then considering the behaviour of each drop.

For a given drop the time and magnitude of the major and final expansion is assumed to be related to the initiating impulse. The relationship will be a function of drop diameter, metal and water temperatures, and the metal and water physical properties. This relationship would be expected to be continuous except in the region in which oscillations occur. For strong input impulses the dominant fragmentation mechanism will vary depending upon the strength of the initiating impulse.

A possible general form of these relationships is shown in figure 11 and figure 11(b) can be related to figure 10 which is the measured relationship between initiating impulse per unit area and delay time for these experiments. For small input impulses the action is that of a trigger, and the response is nearly independent of the size of the trigger. For larger input pulses, it is assumed that the output increases with input because of some direct response.

Consider the situation of two drops of molten metal in water.

Let drop number 1 produce impulse \( I_{out(1)} \)

Then impulse detected by second drop \( I_{in(2)} = I_{out(1)} \cdot \frac{a}{r_{12}^2} \) where \( a \) is a constant and \( r_{12} \) is the distance between drops 1 and 2.

If the impulse response function for drop 2 is denoted by \( f \)

\[
I_{out(2)} = f(I_{in(2)})
\]

\[
= f(I_{out(1)} \cdot \frac{a}{r_{12}^2})
\]

A comparison of \( I_{out(1)} \) and \( I_{out(2)} \) demonstrates whether the interaction is escalating or decaying

\[
\frac{I_{out(1)} \cdot \frac{a}{r_{12}^2}}{I_{out(1)}} > 1 \quad \text{escalation}
\]

\[
\frac{I_{out(1)} \cdot \frac{a}{r_{12}^2}}{I_{out(1)}} < 1 \quad \text{decay}
\]

\[
\frac{I_{out(1)} \cdot \frac{a}{r_{12}^2}}{I_{out(1)}} = 0 \quad \text{localised interaction}
\]

If the same relation applies in an array of drops then increasing the metal/water ratio would correspond to a decrease in average drop separation, and this relation predicts a tendency to escalation. The condition for escalation can be written in terms of average values as \( f(I_{in}) > I_{in} \cdot \frac{a}{r_{12}^2} \).

This relation does not explicitly show the effect of variation with time, but it could represent either spatial propagation or escalation with time in a given region. Coherent propagation could be expected to develop if the escalation resulted in the response function tending to short response times.

342
Interactions with Tin at Low Temperatures

One important parameter in predicting the behaviour of a mixture of liquids is the initial interface temperature. It has been established that there is a threshold temperature below which energetic large scale interactions have not been observed experimentally. This threshold has been identified with the spontaneous nucleation temperature (8). One advantage of using tin in the THERMIR programme was that its low melting point allowed a range of temperature conditions to be studied, including cases in which the initial interface temperature was about 240°C and therefore well below the homogeneous nucleation temperature for water, which is 300°C. The results of these experiments with low temperature tin are summarised in this section.

Five of the experiments listed in Table 3 used low temperature tin at a nominal temperature of 300°C, poured into water at 95 to 98°C. In two further experiments the water temperature was such that the test conditions were within the Temperature Interaction Zone (9). These experiments both resulted in numerous weak localised interactions. This was as predicted since experience with large scale tin/water experiments at AEE Winfrith has shown that the TIZ criterion is as applicable to large masses of metal as to single drops. This is shown in Figure 12, which includes data from many experiments in THERMIR besides those reported in this paper and which shows that, with few exceptions, spontaneously triggered interactions usually occurred, on the falling column, if the initial temperature conditions were inside the TIZ. If the initial temperature conditions were well outside the TIZ the interaction usually occurred on the base.

In three tests interactions occurred which appeared to propagate coherently through the metal/water mixture. These tests were carried out with the water at \( \sim 96°C \), corresponding to a calculated instantaneous contact temperature at the interface of 243°C.

In one of the experiments the interaction was triggered spontaneously on the base, and a propagating front was observed to travel upwards through the column of material with a velocity of about 80 metres per second. The passage of the front was followed by an expansion phase. In this test the metal had been introduced into the vessel by way of a distributor and therefore covered much of the width of the vessel. The expansion in this case was observed uniformly across the column. In experiment 84 which was part of an earlier series, but which is included here for convenient reference, 5 kg of tin at 300°C had been released through a single nozzle into a similar vessel filled with water at 300°C, and this also had resulted in an interaction triggered on the base of the vessel propagating upwards. In this case, the column was relatively slender and the expansion behind the front was radially away from the column.

The pressure records of both these tests show a pressure rise to about 1 MPa followed by a slow decay.

In the remaining test in this group the interaction was triggered by a detonator attached to the side of the vessel. The falling column extended over most of the width of the vessel and the interaction front recorded on the high speed film is observed to enter the column at right angles to the flow direction. As the front passes through the column, however, it is refracted so that it is travelling upwards through the column.
as it leaves the reaction vessel. As in the previous tests, the passage of the propagation front was followed by an expansion phase.

These tests indicate that a coherently propagating interaction can occur in a tin/water system where the instantaneous contact temperature is well below the homogeneous nucleation temperature. However, the surface conditions at a molten tin water interface have not been investigated, hence the possibility that spontaneous nucleation could have occurred at the interface remains untested.

8 Conclusions

Selected results from the THERMIR programme have been presented which illustrate some characteristics of metal/water thermal interactions. The main conclusions of this work are:

i In a coarse mixture with a high proportion of metal to water, coherent interactions have been observed in which a front identified with fragmentation propagates through the mixture. This front has been shown to have the characteristics of a shock front, in so far as it corresponds to a rapid increase in pressure with an amplitude, (in the range 1 to 40 MPa), which is proportional to the square of the propagation velocity.

ii In more dilute mixtures of tin and water coherent propagation has not been observed. However, a trigger pulse from a detonator has stimulated incoherent interaction throughout the mixture. Peak pressures of order 1 MPa have been observed, but the estimated yield from this type of interaction has been low (of order 100 J). Some results suggest that this type of incoherent interaction could develop into coherent propagation, and hence that it could be involved in an escalation phase.

iii A number of tests with low temperature tin, (300°C), were carried out to investigate phenomenological changes when the interface temperature is well below the homogeneous nucleation temperature for water. For low sub-cooling of the water (≈4°C) coherent propagation was observed in three experiments.
REFERENCES


3. HENRY, R E, GROMES, M A and FAUSKE, H K: Pressure pulse propagation in two phase, one and two component mixtures. ANL 7792, March 1971

4. PATEL, P D and THEOFANOUS, T G: Fragmentation Requirements for Detonating Vapour Explosions. PNE-78-122, January 1978


### TABLE 1

Summary of Experiments involving Coherent Interaction

<table>
<thead>
<tr>
<th>Expt</th>
<th>Vessel (Ref Fig)</th>
<th>Metal Type</th>
<th>Metal Temp °C</th>
<th>Metal Charge kg</th>
<th>Water Temp °C</th>
<th>Vol of Mixture Litre</th>
<th>Max Pressure MPa</th>
<th>Prop Rise Time µs</th>
<th>Propagation Velocity m/s</th>
<th>Debris Analysis Apparent Surface Area m²/kg</th>
<th>Remarks</th>
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<td>9.1</td>
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<td>800</td>
<td>120</td>
<td>5.2</td>
<td>Spontaneous trigger</td>
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<td>8</td>
<td>8.3</td>
<td>1.2</td>
<td>1600</td>
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<td>4</td>
<td>44</td>
<td>.37</td>
<td>750</td>
<td>35</td>
<td></td>
<td>Mechanical blow. Earlier interaction No volume, charge or debris measurements.</td>
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<td>8.8</td>
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<td>106</td>
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<td>7</td>
<td>76</td>
<td>1.05</td>
<td>510</td>
<td>109</td>
<td></td>
<td>Leakage at tray end. No detonator. No charge or volume measurements</td>
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<td>800</td>
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<td>85</td>
<td>3.2</td>
<td>1.7</td>
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<td>2.8</td>
<td>3.4</td>
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<td>800</td>
<td>4</td>
<td>32</td>
<td>3.9</td>
<td>1.65</td>
<td>160</td>
<td>83</td>
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### TABLE 2
Calculation of break up times and distances

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<th>Run</th>
<th>Metal</th>
<th>Velocity Difference ms</th>
<th>Bond No</th>
<th>Break-up Time μs</th>
<th>Break up Distance cm</th>
<th>Remarks</th>
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<td>7,200</td>
<td>54</td>
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<td>1,100</td>
<td>220</td>
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<td>28,000</td>
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<td>14,000</td>
<td>33</td>
<td>1.0</td>
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<td>1.1</td>
<td></td>
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<tr>
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<td>TIN</td>
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</tr>
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<td>TIN</td>
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<td>920</td>
<td>200</td>
<td>2.4</td>
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TABLE 3

Test Conditions

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<tr>
<th>Test No</th>
<th>Tin Temp °C</th>
<th>Water Temp °C</th>
<th>Metal/Water vol ratio</th>
<th>Interactions observed</th>
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<tr>
<td>72</td>
<td>804</td>
<td>17</td>
<td>1:10</td>
<td>I, I*, I, I</td>
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<td>I*, C, C</td>
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<td>75</td>
<td>806</td>
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<td>I, I, I, C</td>
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<td>74</td>
<td>1:4</td>
<td>L, I*</td>
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<tr>
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<td>C</td>
</tr>
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<td>93</td>
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<td>94</td>
<td>800</td>
<td>74</td>
<td>1:4</td>
<td>I, I*</td>
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<td>302</td>
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<td>1:4</td>
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<tr>
<td>100</td>
<td>302</td>
<td>95</td>
<td>1:4</td>
<td>I</td>
</tr>
</tbody>
</table>

L - Localised interaction
I - Incoherent interaction
C - Coherently propagating interaction
* - Triggered by detonator
@ - Tin was not distributed through the water
LIST OF FIGURES

Figure 1  Square THERMIR Vessel

2 Strong Cylindrical THERMIR Vessel

3 Large Narrow THERMIR Vessel

4 Pressure records from test No 107 showing observed propagation front

5 Aluminium solidified after mixing with water

6 Variation of propagation velocity with peak pressure

7 Initial conditions of escalating and decaying interactions

8 Pressure records from test No 75 showing observed events

9 Pressure records from test No 80 showing observed events

10 Initiating Impulse against delay time for drops of tin at 800°C in water at 80°C

11 Typical form of impulse response function and delay time function

12 Conditions of spontaneous interactions
FIG. 2 STRONG CYLINDRICAL THERMIR VESSEL.
FIG. 3 LARGE NARROW THERMIR VESSEL.
FIG. 7 INITIAL CONDITIONS OF ESCALATING AND DECAYING INTERACTIONS.
FIG. 10 INITIATING IMPULSE AGAINST DELAY TIME FOR DROPS OF TIN AT 800°C IN WATER AT 80°C
FIG. II  TYPICAL FORM OF IMPULSE RESPONSE FUNCTION AND DELAY TIME FUNCTION.
T G Theofanous
I have one short question and a comment.
How much lower was your calculated interface temperature than the spontaneous nucleation limit?

C H Robinson
The interface temperature was calculated as 240°C. This was calculated from the initial temperature of the tin and is therefore an upper limit. However, this is still some 60°C below the homogeneous nucleation temperature for water.

T G Theofanous
And now my comment. I would suggest that your experimental observation concerning interface temperature conforms with the conclusion of my paper yesterday. Specifically if Taylor waves are responsible for breakup, the coolant temperature in these waves is much higher than the interfacial temperature calculated on the basis of two stagnant semi-infinite media. Hence spontaneous nucleation limit could still have been reached in your experiment (as I believe is the case). I believe this to be necessary to obtain the rapid pressure feedback that you would need for successful propagation.

C H Robinson
I agree that a mechanism which entraps the cooler liquid within the hotter one must give a coolant temperature higher than that calculated by the classical method we used. In our experiment the tin temperature was not greater than 300°C and, even if the water reached the temperature of the tin it would not exceed $T_{HN}$.

H Jacobs
In Fig. 4 of your paper a pressure event can be seen behind the pressure wave, which is coherently recorded by three pressure transducers. Is this a coherent interaction in that region?

C H Robinson
This apparent pressure signal affected the three pressure transducers on the left-hand side of the reaction vessel, the cables from which shared a common conduit to pass the cables from the transducers to the exterior of the vessel. It did not effect the other 4 transducers which used a different conduit. It is believed that these signals originated in mechanical damage to the transducer leads, probably from the movement of the catch tray. This experiment was typical of the majority of large scale events in that the reaction vessel windows broke within a few milli-seconds of the interaction.
Melt/Water Interactions in Tank Geometry: Experimental and Theoretical Results

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Introduction

A large number of FCI-experiments has been conducted with simulant materials in many laboratories to study basic phenomena, important for the understanding of thermal interactions. To investigate the process of thermal interactions between molten reactor core materials and water, an experimental program has been executed during the last years in the Ispra tank facility. It has been intended to deduce from the results of these experiments the risk of FCI during a core melt down accident in light water reactors.
To analyse the experimental results a theoretical model as well as a code have been developed by the IKE at the University of Stuttgart. Both activities were sponsored by the BMFT/Germany.

Experimental Facility

In the Ispra tank facility /1/ melts of reactor fuel or structural materials of masses up to 4 kg and temperatures up to approximately 3000°C can be mixed with water. The principal scheme of the facility is shown in Fig. 1. Inside a crucible of adequate material (tungsten, aluminum-oxide, etc.) the probe is heated in an inertgas (argon, helium) or vacuum atmosphere in a radiation furnace up to the desired temperature. The crucible is placed inside the cylindrical tungsten heater, which is connected to an electrical power supply of 0.13 MW maximum. The furnace can be operated at slight overpressures, only. After reaching the desired temperature, the crucible is dropped through a guide line of 3 m length, which connects the furnace with the interaction tank. Fast operating spherical valves in the guide line separate the furnace from the tank after the crucible has passed.

Fig. 2 shows the interaction tanks which are used. The vessel V 1 has a volume of 350 l and allows a maximum static operating pressure of 4 MPa. The water mass is approximately 200 kg in all the tests in order to simulate small melt to coolant volume ratios, as for instance about 1 : 1000. The melt can be inserted into the vessel in two different ways: One possibility is to catch the crucible and fix it in a catcher device, mounted on the top flange of the vessel. After pressure balance between the tank and
the fall guide, the melt is poured into the water by turning the catcher device automatically. Otherwise, if furnace and tank pressure are the same, the melt can be dropped directly into the water by destroying the bottom of the crucible by means of a mechanism which substitutes the catcher device.

To perform experiments using reactor relevant conditions with respect to molten fuel to coolant volume ratios after a core melt down accident, a PWR scaled down reactor vessel can be mounted within the large tank (see Fig. 2). The dimension of the vessel was defined by the mass of the melt, e.g. 4 kg, which has to simulate 70% of the mass of the core material. Thus, the small PWR vessel has a volume of about 6.5 l. The fuel to coolant volume ratio can be varied from 1:2 up to 1:5 in this small vessel. In all experiments of this kind the melt has to be dropped directly into the water, because the pouring device could not be attached. Therefore, experiments at system pressures higher than 0.1 MPa cannot be performed in this vessel.

Pressures, temperatures and strains generated during the interaction can be measured at different positions along the vessel walls and registered by means of a tape recorder. Additionally, in the large tank the progress of the interaction can be visualized by means of a high speed camera, with a maximum framing rate of 10 000 frames/s.

**Experimental Program**

The influence of different experimental parameters on the interaction was studied within the following range:
- fuel materials: stainless steel, $\text{UO}_2$-granulate, $\text{UO}_2$-melt;

- fuel masses (maximum): $\text{SS} \ 3 \ \text{kg}, \ \text{UO}_2$-granulate $1.5 \ \text{kg}, \ \text{UO}_2$-melt up to $4.0 \ \text{kg}$;

- temperatures of the melt: $1500^\circ\text{C} - 1800^\circ\text{C}$ (steel),
  $1200^\circ\text{C} - 1800^\circ\text{C}$ ($\text{UO}_2$-granulate),
  $\approx 2850^\circ\text{C}$ ($\text{UO}_2$-melt);

- ambient pressures: up to $2.5 \ \text{MPa}$;

- water temperatures: $20^\circ\text{C}$ and $80^\circ\text{C}$ at $0.1 \ \text{MPa}$
  $20^\circ\text{C}$ and $230^\circ\text{C}$ at $2.5 \ \text{MPa}$;

- fuel to coolant volume ratios: from $<1 : 1000$ to $1 : 2$;

- inertgas atmosphere: nitrogen, argon, helium;

- gas content of the water: saturated or degassed.

About 75 experiments combining the above mentioned parameters have been performed, about 50 could be finished successfully; part of them are used for analysis.

**Theoretical Model**

For the interpretation of the measured pressure history a theoretical model and code (TANDEM, Tank-Dampfexplosions-Modell) have been developed /2/. The model is applicable to non explosive heat transfer processes in a constant, thermally insulated volume with water as coolant, different melts and various gas atmospheres.
The fragmentation process of the melt is not treated in the model. However, the distribution in size and the shape of the fragmented melt is simulated by means of 4 or more groups of spheres, representing the melt particles with different diameters. These spheres correspond to experimentally obtained fragmentation data, e.g. sieving data, or empirical correlations. This concept assumes implicitly that fragmentation is a significantly faster process than the cooling of the fragments by heat transfer. Thus, the model is restricted to non explosive phenomena. By means of the above mentioned partition of the melt into groups, the different cooling behavior of small and large fragments can be described more precisely.

Inside the fuel particles the transient heat transfer equation has been solved taking the boundary condition from the boiling curve in the following way (see Fig. 3): The heat transfer process of all particles starts with film boiling, which is described by a model of Frederking and Clark /3/, extended to subcooled boiling and to small particle sizes; the latter is done by application of Langmuirs /4/ correction, which is effective for spheres of 1 cm and less in diameter. The transition from film boiling to the violent boiling regime is assessed by Henrys minimum film boiling correlation /5/. The critical heat flux is calculated by a correlation of Kutateladze /6/ for subcooled boiling, extended to spherical geometry by a correction following Lienhard and Dhir /7/, which takes into account the increase of the heat flux with decreasing sphere diameters. The heat transfer coefficient during transition boiling is obtained by interpolation between the critical heat flux and the heat flux at the minimum film boiling temperature. The surface temperature of the melt at critical heat flux is estimated according to an own
correlation, based on quenching data of metal spheres /2/. Nucleate boiling is treated following Chens /8/ correlation, including an empirical term for convection on spheres by Michejew /9/. Pure convection is dealt with Michejew's correlation only.

For the calculation of the pressure history inside the tank it is assumed that a certain mass of water is heated by the melt. The vaporization follows the thermal equilibrium state. Thus, the calculated pressure in the vessel equals the saturation pressure of the heated part of the coolant - which increases with time - plus the pressure of the inert gas, which is heated to the same temperature. The increase of the mass of the heated water was fitted using the pressure history of one experiment by means of an empirical constant.

As an illustration of the model a characteristic result is shown in Fig. 4. In this case the fuel (UO₂-granulate) was subdivided into 4 groups, each one represented by one sphere. The different cooling behavior of the particles can be demonstrated. The small particles are cooled down to the water temperature very fast, whereas the larger particles still remain in film boiling. The resulting pressure history is indicated too.

Results

A large number of experiments has been performed in both, the large tank and the scaled down "PWR" vessel and analysed by the theoretical model. All experiments have been made without triggering. The main result is that no explosive interaction has taken place, but a rapid evaporation with a rather weak pressure rise up to 0.2 MPa in the large vessel and
2.5 MPa in the "PWR" mock-up as maximum values. The
time of this pressure rise is approximately 2 s, the
condensation time some 10 s in all experiments. The reason
for these mild interactions can be seen on the high speed
movies and from the sieving data of the fragments. The
movies show that a remarkable part of the fuel is cooled
down under film boiling conditions over a long time.
Additionally the fragmentation is rather poor as compa-
red to other fragmentation data taken from the literature
(e.g. /10/, s. Fig. 5). In the case of molten UO₂ and SS
approximately 60 % of the mass had particle diameters of
more than 4000 μm (s. Tab. 1). Additionally, in the small
tank the melt has been collected on the bottom as a
large lump with a relatively small surface area; thus the
mild interactions can be understood.

In the following, some experiments will be presented in
more detail (data s. Tab. 2). The behavior of UO₂ with a
well known particle size distribution in contact with water
has been studied by the UO₂-granulate experiments. Fig. 6
and 7 show the measured and the calculated pressure history
in case of 30° C and 80° C water temperatures and UO₂-granu-
late at 1800° C. In the figures only the excess pressure is
indicated. Due to the large measuring range of the trans-
ducers and the rather small measured pressures, a background
noise cannot be avoided sometimes. The measured excess
pressure is very low in both experiments, which differ in
the water temperature mainly. Because of the lower energy
for evaporating water of 80° C initially, compared to the
other case, the maximum pressure is a little higher. The
 correspondence between the experimental and the theoretical
results give confidence in the physical model used to con-
struct the code.

369
Similar pressure histories can be obtained in the SS experiments. Again, two examples with hot and cold water are plotted (see Tab. 2, Fig. 8 and 9). Because of the lack of sieving data for these two experiments, mean distribution values from the sieving of adequate experiments (no. 30, 33, 34, 36; see Tab. 1) have been taken as input data in the model in order to calculate the pressure trace. The effect of the higher water temperature, which leads to a higher maximum pressure normally, is balanced partly by a larger fuel mass in experiment no. 39 compared to experiment no. 28.

The UO₂-melt/water experiments may be represented by experiment no. 79. The ambient pressure was about 0.03 MPa higher than the diagram (Fig. 10) indicates, due to a pressure balance during the introduction of the melt. Thus, the pressure rise, caused by the interaction, still remains approximately 0.12 MPa, a normal value, compared to the other experiments with UO₂-granulate or molten SS. The model input values on fragmentation can be taken from the sieving data directly in this experiment.

At last experiments with the scaled down "PWR" vessel will be presented. In Fig. 11, an UO₂-granulate experiment with water of 20°C (experiment no. 90) is shown. Due to the smaller free volume and the large volume ratios compared to the experiments in the large tank the excess pressure is much higher; in this experiment approximately 2 MPa. Nevertheless, this also is not a significant excess pressure. The time scale of the pressure history corresponds to those of the large tank, the time of the pressure rise is about 1.5 s, the condensation time more than 20 s. The simulation of this experiment by the model was a little difficult, because more and more of the granulate has settled.
on the bottom of the vessel. Thus the heat transfer area decreases during the experiment, an effect, which could not be described by the model. Therefore the code is calculating a higher maximum pressure and a faster pressure decrease due to the better heat transfer. The faster decrease of the real pressure at the end of the process (> 8 s) results from the heat transfer through the bottom of the vessel, which has not been accounted for in the model.

The SS experiments in the small tank show another effect: Complete depressurization was not achieved even after a long time (s. Fig. 12) due to hydrogen production, which is of significant influence in this case, because of the small volume of the vessel. This effect cannot be seen in experiment no. 90 because of the lower UO₂-granulate temperature (1200 °C) compared to that of the molten steel (1685 °C). Additionally, hydrogen production may be higher in the steel experiment due to the stronger oxidation of steel compared to UO₂. A long time after the experiments have been finished nearly 1 MPa excess pressure can still be measured. Due to this phenomenon and the less fragmented melt, which has been collected again as a large lump on the bottom of the vessel, this kind of experiments could not be analysed with the model. Nevertheless the pressure history seems to be explained sufficiently.
Conclusion

With the reactor materials UO\textsubscript{2} and SS a large number of experiments has been conducted in a closed tank to study thermal interactions. For that purpose the parameters have been varied over a wide range with respect to temperatures (fuel: 1200° C to 3000° C; water: 20° C to 230° C) and ambient pressure (<0.1 MPa to 2.5 MPa). In none of the experiments a real vapor explosion has been observed, but an evaporation process with a rather mild pressure rise.

Maximum pressures up to 0.2 MPa in the large tank and up to 2.5 MPa in the small one could be measured, the time of pressure rise in all experiments is approximately 2 s. The fragmentation was found to be weak compared to other experimental data mentioned in the literature. Triggering of the interaction has not been performed. For the analysis of these non-explosive interactions a model has been developed, which calculates the pressure history as a function of time. The agreement between the experimental and theoretical pressure histories was good, except the UO\textsubscript{2} melt experiments in the large and the SS experiments in the small vessel. In the latter cases the hydrogen production becomes important to the pressure rise, due to the small volume of the vessel and the high temperature of the molten steel. This effect could not be simulated using the model TANDEM. The differences between the measured and calculated pressure trace of the UO\textsubscript{2} melt experiment could not be explained finally.
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Tab. 1: Particle size distribution of some experiments, performed in the Ispra tank facility. (Data in kg; the values in brackets indicate mass percent)

<table>
<thead>
<tr>
<th>exp. no.</th>
<th>fuel</th>
<th>particle size / μm</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&gt;4000</td>
</tr>
<tr>
<td>30</td>
<td>SS</td>
<td>-</td>
</tr>
<tr>
<td>33</td>
<td>SS</td>
<td>-</td>
</tr>
<tr>
<td>34</td>
<td>SS</td>
<td>-</td>
</tr>
<tr>
<td>36</td>
<td>SS</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>exp. no.</th>
<th>fuel</th>
<th>particle size / μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&gt;4000</td>
</tr>
<tr>
<td>52</td>
<td>UO₂⁻⁻⁻Granul.</td>
<td>0.3406</td>
</tr>
<tr>
<td>54</td>
<td>UO₂⁻⁻⁻Granul.</td>
<td>0.3225</td>
</tr>
<tr>
<td>79</td>
<td>UO₂⁻⁻⁻Granul.</td>
<td>0.735 (59.3)</td>
</tr>
<tr>
<td>90</td>
<td>UO₂⁻⁻⁻Granul.</td>
<td>-</td>
</tr>
</tbody>
</table>
Tab. 2: Data of analysed experiments

(Particle size distribution: see Tab. 1)

<table>
<thead>
<tr>
<th>exp. no.</th>
<th>fuel</th>
<th>melt temperat. °C</th>
<th>mass of melt kg</th>
<th>water temperat. °C</th>
<th>ambient pressure MPa</th>
<th>tank volume m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>SS</td>
<td>1725</td>
<td>1.65</td>
<td>80</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>39</td>
<td>SS</td>
<td>1755</td>
<td>2.6</td>
<td>20</td>
<td>0.015</td>
<td>0.2</td>
</tr>
<tr>
<td>52</td>
<td>UO₂ - granulate</td>
<td>1800</td>
<td>1.58</td>
<td>80</td>
<td>0.048</td>
<td>0.2</td>
</tr>
<tr>
<td>54</td>
<td>UO₂ - granulate</td>
<td>1800</td>
<td>1.5</td>
<td>30</td>
<td>0.016</td>
<td>0.2</td>
</tr>
<tr>
<td>79</td>
<td>UO₂</td>
<td>≈ 3000</td>
<td>1.24</td>
<td>20</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>82</td>
<td>SS</td>
<td>1685</td>
<td>1.74</td>
<td>25</td>
<td>0.1</td>
<td>6.5 \times 10^{-3}</td>
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<tr>
<td>90</td>
<td>UO₂ - granulate</td>
<td>1200</td>
<td>1.53</td>
<td>20</td>
<td>0.21</td>
<td>6.5 \times 10^{-3}</td>
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</table>
Fig. 1: ISPRA FCI tank facility: flow scheme
Vessel V1
(Volume: 350 l)

"PWR" scaled down vessel
(Volume: 6.5 l)

Fig. 2: Interaction vessel geometries
Fig. 3: Heat transfer correlations of the TANDEM model
Fig. 4: Typical cooling behavior of the fuel and the corresponding pressure history calculated by TANDEM (fuel: UO$_2$ granulate; initial temperature of the fuel 1500° C; initial water temperature 30° C)
Fig. 5: Particle size distribution of the Ispra tank experiments compared to other experimental data
Fig. 6: Excess pressure versus time in the large tank (V1) during the \( \text{UO}_2 \)-granulate experiment no. 54 (water temperature \( 30^\circ \text{C} \))

Fig. 7: Excess pressure versus time in the large tank (V1) during the \( \text{UO}_2 \)-granulate experiment no. 52 (water temperature \( 80^\circ \text{C} \))
Fig. 8: Excess pressure versus time in the large tank (V1) during the SS experiment no. 39 (water temperature 20°C)

Fig. 9: Excess pressure versus time in the large tank (V1) during the SS experiment no. 28 (water temperature 80°C)
Fig. 10: Excess pressure versus time in the large tank (V1) during the $\text{UO}_2$-melt experiment no. 79 (water temperature $20^\circ\text{C}$)
Fig. 11: Excess pressure versus time in the scaled down "PWR" vessel during the UO$_2$-granulate experiment no. 90 (water temperature 20° C)

Fig. 12: Excess pressure versus time in the scaled down "PWR" vessel during the SS experiment no. 82 (water temperature 25° C)
Discussion on Paper FC14/P16

P Coddington
How did you calculate the water mass, and did the mass of water change with time?

R Benz
The heated water mass increases as a function of time. The empirical correlation describing this increase contains one constant, which was calculated by fitting the measured and the calculated pressure histories of the experiment no. 52. The same value of this constant was used in order to calculate the pressure trace of the other experiments.

L Caldarola
How many adjustable parameters have you got in your theoretical model?

R Benz
The model is fully, phenomenological except the correlation describing the increase of water participating in the interaction. In this correlation one empirical parameter was used to fit the pressure trace of one experiment. (exp no 52). Then all other experiments are simulated using the same parameter.
STEAM EXPLOSION TRIGGERING AND EFFICIENCY STUDIES\textsuperscript{+}

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Sandia Laboratories, Albuquerque, NM, 87185 USA

INTRODUCTION

When the Reactor Safety Study\textsuperscript{1} on the assessment of accident risks in light water reactors (LWR) was performed, it was noted that much of the basic data required to realistically evaluate the probability of occurrence of containment breaching steam explosions did not exist.\textsuperscript{2} Consequently, the U. S. Nuclear Regulatory Commission (Fuel Behavior Research Branch, Division of Reactor Safety Research) initiated a program at Sandia Laboratories to provide relevant data on the interaction of molten LWR core materials with water. Two different subtasks were established to achieve this goal. The first was the performance of laboratory-scale experiments to investigate the ability to trigger steam explosions for realistic LWR core melt simulants under a wide range of initial conditions. The second was the performance of field-scale experiments to investigate the efficiency of converting the thermal energy of the melt into mechanical work in much larger steam explosions.

\textsuperscript{*This work was supported by the U. S. Nuclear Regulatory Commission.}

\textsuperscript{+Prepared for the OECD (NEA) Fourth CSNI Specialist Meeting on Fuel-Coolant Interaction in Nuclear Reactor Safety, April 2-5, 1979, Bournemouth, United Kingdom.
TRIGGERING STUDIES

More than 300 laboratory experiments were conducted over the last three years in which 10-37 g samples of various LWR core material simulants were arc-melted in an atmosphere of argon in the apparatus shown in Fig. 1 and then flooded with approximately 1.5 liters of water. In most of the experiments, the melt/water system was additionally subjected to a short duration, impulsive pressure transient in an attempt to initiate a steam explosion. The majority of the experiments used transients generated by an exploding bridgewire. Pressure, temperature, hot liquid motion and cold liquid motion were monitored during the experiments. Morphological and chemical analyses were performed on selected debris.

The four primary materials studied were: stainless steel; four-component Corium-E (iron-rich) simulants made from Fe, O, U, and Zr; four-component Corium-A (uranium-rich) simulants; and two-component Corium-E simulants (iron oxides). A few experiments were performed with molten aluminum, silver and cobalt oxide. A topical report was published which contained detailed results from the early studies on stainless steel, aluminum, and silver. The essential results for the metals were that benign freezing of the melt was observed when no pressure transient was applied, but considerable fragmentation of the stainless steel melts could be initiated with applied transients. Rapid steam production was not observed to accompany that fragmentation. No further mention of the metals experiments will be made here. Instead, the remaining triggering study discussion will focus on the observations made for the various oxide material simulants.

Simple flooding (no applied transient) never produced explosive interactions for the Corium-E or iron-oxide melts. However, multi-stage, pressure producing interactions were readily triggered for the more highly oxidized
FLOODABLE ARC MELTER FOR STEAM EXPLOSION STUDIES

FIGURE 1: FLOODABLE ARC-MELTING APPARATUS USED FOR TRIGGERING EXPERIMENTS
Corium-E simulants, iron oxides and cobalt oxide. The debris produced in those steam explosions was a powder containing both spherical and "mossy" particles as depicted in Fig. 2. The more vigorous explosions which were triggered were usually two-stage, with the second stage normally exhibiting pressurizations of less than 1.5 MPa maximum magnitude and 1 millisecond duration. A representative pressure trace from an iron-oxide experiment is shown in Fig. 3. In one experiment, a pulse having a peak pressure of 5.7 MPa was recorded. The impulse contained in that pulse was not unusually large, however.

It should be noted that the processes causing the stage 1 and stage 2 pressure excursions indicated in Fig. 3 are believed to be extremely rapid fragmentation of the melt accompanied by enhanced heat transfer to the water and subsequent steam production at explosive rates. The possibility that the observed excursions might be the direct or indirect result of localized hydrogen production via chemical reactions in the Fe–O–H₂O system has been rejected since, at the temperatures involved, the volume of hydrogen produced should not be more than about one percent of the steam volume.³ This hydrogen/steam ratio is well outside the flammability limits, irrespective of the amount of oxygen which might be present.⁴

Threshold initial oxygen concentration levels, below which steam explosions could not be triggered using bridge-wire-generated transients, were observed for the four-component Corium-E simulants and the iron oxides. That observation is graphically displayed in Fig. 4 which shows the peak pressures measured in several Corium-E simulant explosions plotted versus the oxygen content in the unmelted samples. The threshold level for cessation of explosions was slightly lower for the iron oxides. Combined with the information gained from debris analyses,
FIGURE 2: SCANNING ELECTRON MICROGRAPHS OF CROSS SECTIONED CORIUM-E DEBRIS PRODUCED IN A TRIGGERING EXPERIMENT.
FIGURE 3: PRESSURE RECORD OBTAINED DURING TRIGGERING EXPERIMENT WITH AN IRON OXIDE MELT.
FIGURE 4: EXPLOSION GENERATED PEAK PressURES VERSUS OXYGEN CONTENT OF THE UNMELTED SAMPLES FOR A FOUR-COMPONENT CORIUM-E SIMULANT.
that result is consistent with an impulse initiated gas release mechanism\textsuperscript{5,6} as the explanation of the multi-stage explosive events observed for the two-component and four-component Corium-E simulants. By analogy to the iron-oxide system, the gas release hypothesis implied that cobalt oxide would also explode and, in fact, multi-stage explosions were triggered for that system.

However, recent data (obtained using an oxygen analyzer in the argon exit line from the arc melter to directly measure the time-dependent evolution of oxygen prior to flooding) indicate that only modest quantities of oxygen could be released during the actual explosions. Work is currently underway to quantify more exactly the amount of oxygen which might be able to participate in an impulse initiated gas release fragmentation mechanism. Work is also underway on alternative hypotheses involving thermo-physical property changes caused by melt compositional changes.

Most of the explosions occurred in experiments for which the chamber atmosphere was nominally argon at 0.083 MPa ambient pressure. Multi-stage explosions were also initiated for ambient pressures as high as 0.5 MPa with no apparent change in the explosion's character. However, a decrease in the time window during which the initiating impulse could be successfully applied was noted as the pressure was increased. This shrinking "window" is consistent with the fact that all attempts to initiate explosions at chamber pressures of 0.75 and 1.0 MPa failed.

Experiments studying the effect of increased water temperature (reduced subcooling) indicated that the use of hot water inhibits the triggering of explosions by bridgewire-generated transients for the Corium-E (iron-rich) simulants. Figure 5 illustrates that effect for a single initial Corium-E composition. The peak pressures generated in the interactions are plotted versus the
FIGURE 5: EXPLOSION GENERATED PEAK PRESSURES VERSUS WATER SUBCOOLING (AND WATER TEMPERATURE) FOR A FOUR-COMPONENT CORIUM-E SIMULANT.
bulk water temperatures measured just prior to initiation of flooding (the subcooling scale was calculated using $T_{\text{Sat}} = 368$ K). A slightly lower subcooling threshold was observed for the iron oxides using bridgewire initiation. The threshold is also transient dependent as indicated by a recent iron oxide experiment in which a detonator was used to generate an explosion at an even lower subcooling.

Experiments in which flooding was performed with simulated seawater (3.5 w/o NaCl) and borated water (3000 ppm B as $\text{H}_3\text{BO}_3$) produced explosions with both iron-rich simulant melts; there were no major differences from the experiments with pure, deionized water.

Several experiments with oxidized Corium-A (uranium-rich) simulants yielded coarse fragmentation of the melt spontaneously upon flooding. Later application of a bridgewire-generated transient had no effect on the interaction. In one experiment with a highly oxidized Corium-A simulant, there was a fragmentation event approximately 4 msec after the bridgewire fired; a pressure pulse with a 0.14 MPa peak was generated. The difficulty of triggering explosions with these uranium-rich simulants is consistent with the gas release hypothesis if it is assumed that the iron oxide in the melt is the primary driving potential for the explosion. The cause of the spontaneous fragmentation upon flooding for Corium-A is presently unknown.

**EFFICIENCY STUDIES**

Forty-eight field experiments involving metallo-thermic-reaction-generated mixtures of molten aluminum oxide and iron have been performed in the past year. Compared to the small-scale triggering tests, these large-scale, open geometry tests were relatively unsophisticated in instrumentation and design. The melt generator, initially containing up to 27 kilograms of a mixture of iron oxide ($\text{Fe}_3\text{O}_4$) and aluminum powders, was suspended above the
interaction vessel containing between 175 and 840 kilograms of water. To perform an experiment, a chemical (thermite) reaction was electrically initiated in the mixed powders at the top of the melt generator. The reaction then proceeded downward through the mixture, producing a melt with a temperature of about 3000 K. The generators for most of the tests utilized a melt plug in the bottom which failed when the thermite reaction was complete, causing a simple pour to be initiated. The last few tests used a trapdoor arrangement on the bottom of the generator.

The primary diagnostics in these experiments were cinematography and reaction energy measurements by means of crushable aluminum honeycomb placed underneath the interaction vessel as shown in Fig. 6. Plastic deformation of the interaction vessel walls was also monitored. Some of the last experiments which were performed incorporated lithium niobate and/or quartz pressure gages.

Explosions were observed in 37 of the 48 experiments. Most of the explosions occurred spontaneously at seemingly random delays from pour initiation. Spontaneous explosions occurred as early as 0.16 seconds and as late as 3.34 seconds after pour initiation. Both single and multiple explosions were produced. Sometimes a single explosion emptied the interaction vessel, leaving no water for later explosions even though the pour continued for a few more seconds. When multiple explosions occurred, they were separated in time by hundreds of milliseconds and one was frequently more energetic than the others. The spontaneous triggering mechanism is unknown, but it is strongly suspected to involve contact of the melt with the interaction vessel walls or similar surfaces, at least for the slower pour rates. Coating the interaction vessel walls with lard significantly reduced the incidence of spontaneous explosions for slow pours. Using certain other coatings or merely smoothing the wall surfaces was ineffective. At
FIGURE 6: ARTIST'S CONCEPTION OF INTERACTION VESSEL WITH HONEYCOMB BLOCKS AND MELT GENERATOR INSTALLED.
extremely high pour rates, explosions were sometimes observed to occur shortly after the melt/water contact was initiated, before the melt had time to contact a solid surface. Explosions were also artificially initiated using high explosive detonators, even when the tank walls were coated with lard. No enhancement in efficiency was seen for the artificially triggered explosions.

The debris generated in the field-scale efficiency experiments looks quite similar to the debris produced in the laboratory-scale triggering experiments. Figure 7 shows that both hollow spheres and "mossy" debris with a high surface area to volume ratio were found. This suggests that the same mechanism may be responsible for the explosions in both the field and the laboratory. Sieve analyses on partial samples of the debris recovered from some of the experiments indicated that the more efficient explosions produced the finer particulate.

A limited number of direct pressure measurements and other indirect evidence implies peak pressures between 5 and 10 MPa were generated in the explosions. Most of the actual pressure traces which were obtained indicated peak pressures between 2 and 7 MPa which decayed over several milliseconds. Narrow spikes to higher pressures were seen. Figure 8 is a trace recorded during one of the later tests in the series. It is seen that the initial rise time is extremely fast but the peak pressure did not occur until about 0.4 ms later. The shape of the pressure pulses are not what would be expected from a continuous, coherent interaction. Instead, it appears that the explosions might involve several much smaller explosions which are only loosely coherent in time. The brisance of the steam explosions is certainly less than that for standard chemical high explosives, but atmospheric shock waves appear to have formed in at least some of the explosions.
FIGURE 8: PRESSURE RECORD OBTAINED DURING EFFICIENCY EXPERIMENT WITH A THERMITE MELT.
By using the cinematography to estimate the height to which the water and other heavy material were blown into the air, the amount of work performed on the water slug by the expanding steam was determined for each experiment. The amount of work performed in crushing the aluminum honeycomb and plastically deforming the interaction vessel walls was also determined. The explosion efficiency was then determined by comparing the total work estimate to the amount of thermal energy available (assumed to be 3.1 kJ/g) in the melt which poured into the tank before the explosion. The largest thermal-to-mechanical energy conversion efficiency estimate obtained using this procedure was 1.34 percent for experiment No. 42. The next largest was 0.96 percent for experiment No. 15. The other explosions all had estimated efficiencies less than 0.6 percent.

As shown in Fig. 9, the most efficient explosions all occurred with full tanks of water. This was probably caused by the tamping effect (inertial confinement) provided by the additional water above the explosion zone, assuming the explosions all occurred near the bottom of the tank. The most efficient explosion had even more tamping in the form of a heavy steel plate placed just above the tank in that particular test. It is unclear exactly how much increased efficiency can be attributed to the additional tamping provided by this projectile, however, since the plate might have just allowed a much better diagnosis of the water slug energy by holding the slug together longer and thereby reducing its breakup due to atmospheric drag.

Figure 10 is a plot of the explosion efficiencies versus the amount of melt estimated to be in the tank at the time of the explosion. Best estimates of the pour rates for the individual experiments were used in the melt
FIGURE 9: PLOT OF ESTIMATED EXPLOSION EFFICIENCY VERSUS WATER QUANTITY PRESENT BEFORE THE EXPLOSION.
FIGURE 10: PLOT OF ESTIMATED EXPLOSION EFFICIENCY VERSUS MELT QUANTITY PRESENT BEFORE THE EXPLOSION.
quantity estimation procedure, but they could not be verified. Even if the actual pour rates were known, it still would be impossible to determine exactly how much of the melt which was present in the tank actually participated in the explosions, since only small portions of the debris were recovered. Because the estimated efficiencies are also inversely proportional to the estimated melt quantity, a substantial shift in any given data point shown in Fig. 10 could occur if the pour rates were revised. This makes the data point shown for experiment No. 48 at 13.6 kg of melt and 0.43 percent efficiency especially important. The amount of melt in that test could not have been larger; all of the available melt was assumed to be in the tank. If all of the melt in the tank did not participate in the explosion, the estimated efficiency would be even larger than shown. Based on the data of Fig. 10 with the qualifications just given, it was concluded that there was no significant effect on efficiency of melt quantity over the range studied. It should be mentioned that the single experiment performed with 27 kilograms of melt did not produce an explosion.

The pour rates achieved in these experiments varied from less than 1 kg/s to about 32 kg/s. The slowest pour rates generally were not conducive to spontaneous explosions. Slow pour rates should produce either no explosions or low efficiency explosions (based on the amount of melt present) since the melt which contacts the water first has time to freeze while the remainder of the melt is being poured. This hypothesis seemed to be supported by the limited data base.

Several experiments in which the volume of water available for interaction was reduced by inserting smaller coaxial cylinders in the bottom of the interaction vessel produced no significant change in the explosion efficiency,
but the volume of water available to interact with the melt was still relatively large in those tests.

Most of the experiments were performed with highly subcooled water but two warm water tests and three boiling (saturated) water tests were performed. An experiment in which a high vapor fraction was artificially created by air injection was also performed. Neither the water temperature nor the high vapor fraction seemed to affect the efficiency of the explosions observed in those tests. The incidence of spontaneous explosions might have been reduced, but the data base is limited here also.

CONCLUSIONS

Although the early laboratory-scale experiments with stainless steel did not produce explosions for the configuration and conditions tried, it is well known that mixing molten steel with water can produce steam explosions. The more recent laboratory experiments with the core melt simulants indicate that oxide melts might be even more conducive to steam explosions than metals. Therefore, it appears the triggering of steam explosions may be quite likely for molten LWR core materials under many hypothetical fuel melt accident conditions. On the other hand, the field-scale experiments indicated that multiple explosions occurred frequently which drastically spreads the energy release in time. The incoherency noted for the individual explosions will also spread the energy release in time. Finally, the estimated efficiencies for the observed explosions were all at least an order of magnitude less than the maximum theoretical value. Thus, the achievement of maximum theoretical efficiencies in extremely large, coherent explosions appears to be unlikely.
REFERENCES


Discussion on Paper FCI4/P17

T G Theocharous
Would it be correct to say that your "trigger" has the effect of producing a premixture, rather than initiating the explosion itself?

L D Buxton
In the laboratory experiments that is correct. The trigger initiates a coarse fragmentation with only a mild pressurization. The main pressure producing events occur at later times by the explosion of the smaller droplets produced in the first interaction.

H M Kottowski
How is the efficiency calculated and how did you estimate the mechanical work from the large vessel experiment?

L D Buxton
The total mechanical work was determined by summing estimates of:
(a) The potential energy change of the water slug and other heavy materials which were blown into the air
(b) The amount of work expended in crushing the aluminium honeycomb placed under the reaction vessel
(c) The plastic work expended in permanently deforming the reaction vessel. The explosion efficiency was then taken to be the ratio of the mechanical work performed and the thermal content of the melt (3100J/g) assumed to be in the tank at the time of the explosion.

S J Board
Much of the work done in a Hicks/Menzies expansion occurs at very large volumes and it is not possible for this work to be developed within the relatively limited volume of your tank. Therefore would it be more appropriate to compare your yields with a limited volume Hicks/Menzies expansion?

L D Buxton
I agree that a full Hicks/Menzies yield is probably not possible in our configuration. Our quoted efficiencies are based on the thermal content of the fuel and would need to be multiplied by a factor or 2 or three if comparison is to be made to the Hicks/Menzies yield. Obviously, the explosions are not full yield.
OUT-OF-PILE STUDIES OF POWER BURST ENERGETICS

by

T. G. Theofanous and D. M. VanZandt

ABSTRACT

Mechanical energy release histories from thermal interactions in the so-called heavily driven mode of contact have been measured for the Freon-11/oil system. The conversion efficiency increases with oil temperature with an indication of a threshold at an oil temperature corresponding to that yielding spontaneous nucleation upon contact. Such a threshold is more clearly indicated in the behavior of the peak mechanical power release. The significance of this finding is related to the initiation and propagation steps of large scale thermal explosions.

I. INTRODUCTION

The intensity of a local thermal interaction at a particular set of conditions, may be viewed as an important indicator of the likelihood to initiate and sustain large-scale, propagating, thermal explosions from similar initial conditions. It would appear useful, therefore, to appropriately characterize this intensity and measure it directly. In addition, such studies are needed to better understand the thermal interaction behavior of nonexplosive systems, which nevertheless when appropriately premixed and constrained may yield significant interaction efficiencies.

Our basic approach is to initiate the interaction from a well controlled, premixed state (masses, temperatures, degree of premixing) and allow the system to expand against a controllable constraint (i.e., mass and backpressure of a frictionless piston). From the piston motion and the pressure transients both ahead and behind the piston we can then extract the P-V behavior and hence the interaction history. In particular through controlled constraints we can impose and or modify the time scale of the expansion. This additional degree of freedom would be useful in the determination of the interaction microprocesses and especially in the study of the recently identified pressure cut-off [1] in explosive behavior.
II. EXPERIMENTAL FACILITIES AND PROCEDURES

A schematic of the experimental apparatus is shown in Fig. 1. An isometric of the basic experimental stand is given in Fig. 2. An aluminum piston moves freely inside the precision bore 10 cm in diameter, 120 cm long stainless steel cylinder. The cylinder is mounted on a steel frame and it is attached at its lower open end to one of the faces of a die-shoe. The interaction chamber, 20 cm long, and filled with one of the interaction liquids (the hot one) is fitted in a recess machined on the opposite face of the die-shoe and connect (seal) the interaction chamber to the cylinder. Two clamps (not shown) "fall" automatically into place upon closure to secure a sealed system. The other interaction liquid (the cold one) is contained in a number of tubes attached to the bottom of the piston. The tubes are made of 0.018 mm thick aluminum foil which is sealed lengthwise and against two end caps by means of a small quantity epoxy. These tubes burst catastrophically at an internal overpressure of 20 psi. The aluminum piston is hollow, and for the set of experiments reported here it was loaded to a total weight of 7 kg using lead shot.

During an experimental run the interaction chamber containing the hot fluid is put into place, while the aluminum foil tubes have been attached to the piston which is at its lowermost position at this time. The die-shoe is slammed closed, the tubes enter the hot liquid and "explode" upon heating and thus the interaction is initiated from a "pre-mixed" state.

The piston travel history is determined by magnetic induction (eight coils along the tube length and a ring of magnets around the piston). The pressures both in the interaction area and in the compressing air volume above the piston are simultaneously recorded. A typical record is given in Fig. 3. The initial pressure pulse from the transducer placed at the base of the tube indicates the initiation of the expansion (thermal interaction).

The work of the expanding interaction is converted to kinetic energy of the piston and compression of the air contained in the space above the piston. Hence, the pressure and piston position measurements provide a redundancy useful in checking the amount of frictional losses and leakage flow around the piston seal. An average piston velocity between any two coils, \( i \) and \( i+1 \), may be calculated from intercoil distance \( \Delta x_{i,i+1} \) and time of travel \( \Delta t_{i,i+1} \).

\[
\frac{v_x}{\Delta t_{i,i+1}} = \frac{\Delta x_{i,i+1}}{\Delta t_{i,i+1}}
\]

Also a piston velocity at coil \( i \) may be calculated from the pressure transients up to time \( t_i \) required to reach coil \( i \).
\[ v_{p,i} = \frac{A_p}{m_p} \int_0^{t_i} (p_v - p_a) \, dt - gt_i. \]

Here, \( A_p \) and \( m_p \) is the piston area and mass respectively, \( p_v \) is the driving Freon pressure in the interaction chamber, \( p_a \) is the air backpressure, and \( g \) is the acceleration of gravity. From this equation an average piston velocity over the time interval \( \Delta t_i, i+1 \) may be calculated:

\[ \overline{v_p} = \frac{v_{p,i} + v_{p,i+1}}{2}. \]

An agreement between \( v_X \) and \( v_p \) is an indication of consistency in data and negligible frictional losses. This consistency was established first by several "simulation" interactions utilizing pulses of compressed air. The results are presented in Fig. 4. It is seen that especially during the accelerating portion of the expansion the results are quite adequate. Further the adequacy of the piston ring seal to prevent significant leakage flow was tested by determining the adiabatic compression characteristics of the air initially trapped above the piston. Similar tests were carried out for all the thermal interaction runs. A composite of these results is given in Fig. 5. It is seen that only the runs yielding low velocities indicate discrepancies. This is to be expected and it is not of real consequence since the more energetic interactions are of interest here. A discrepancy is also indicated only for the first coil in all the other runs. The reason for this discrepancy is not clear at this time.

III. EXPERIMENTAL RESULTS AND DISCUSSION

For the interactions reported here \( \approx 20 \text{ g} \) of room temperature Freon-11 (one aluminum foil tube 7 cm long) and \( \approx 875 \text{ ml} \) cottonseed oil were utilized. The oil was heated at an inert atmosphere to prevent oxidation at the elevated temperatures. Only the oil temperature was varied parametrically.

The total pdv work delivered by the expanding interaction mixture was normalized to the maximum possible as suggested by Vaughan [2]

\[ W_m = m_b \left\{ \frac{T_H}{T_{\text{sat}c}} - 1 \right\} + \frac{R}{M} T_H \]

to define an interaction efficiency. Here \( m_b \) is the Freon mass, \( L_f g \) is the latent heat of vaporization, \( T_H \) and \( T_{\text{sat}c} \)
are the "fuel" and "coolant" saturation temperature respectively, R is the gas constant and M the coolant molecular weight. The results, shown in Fig. 6, indicate a rapid increase in efficiency at about the oil temperature required to yield spontaneous nucleation upon contact with the oil.

The total pdv work was divided by the corresponding time of release of this energy to define an average power of the interaction. Also a "peak power" was defined by considering the expansion up to the first coil. These results shown in Figures 7, 8a and 8b respectively further enhance the trends indicated in Fig. 6 for the efficiency. The equation of the least square line in Fig. 8b is

\[ P_{peak} = 3.366 + 0.00825 \log T_H \]

and indicates an exponential buildup of power with the oil temperature.

IV. CONCLUSIONS

Mechanical energy release histories from thermal interactions in the so-called heavily driven mode of contact have been measured for the Freon-11/oil system. The conversion efficiency increases with oil temperature with an indication of a threshold at an oil temperature corresponding to that yielding spontaneous nucleation upon contact. Such a threshold is more clearly indicated in the behavior of the peak mechanical power release. The significance of this finding may be related to the initiation and propagation steps of large scale thermal explosions and renders support to the spontaneous nucleation criterion of Fauske [3].

Acknowledgment

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References

1. Henry, R.E., "Test Plan Large Scale Molten Salt-Water Vapor Explosion Studies to be Conducted at Ispra, Italy," ANL/RAS/LWR 78-1.
Figure 1. Schematic of the experimental apparatus.

Figure 2. Isometric of the experimental apparatus.
\( \bar{V}_p \) VERSUS \( \bar{V}_v \) ONE TUBE RUNS

\( \bar{V}_v \) IN FEET/SECOND

Figure 5

\( E_i \) VERSUS OIL TEMPERATURE ONE TUBE RUNS

EFFICIENCY OF INTERACTION IN PERCENT

Spontaneous Nucleation at the Interface

OIL TEMPERATURE IN \( ^\circ F \)

Figure 6

415
Figure 8b

$P_{\text{peak}}$ VERSUS OIL TEMPERATURE
ONE TUBE RUNS

OIL TEMPERATURE IN $^\circ\text{F}$

Spontaneous Nucleation at the interface

PEAK POWER OF INTERACTION IN BTU/S
H M Kottowski
How do you define the efficiency you are referring to and are the data you get from this experiment related to a practical system?

T G Theofanous
The efficiency is defined on the basis of the maximum theoretically possible work.

This experiment has an important feature relevant to a practical system, in that the aim is to produce interactions in the so-called heavily driven mode of contact, that is, fluid mixing from an initially interdispersed state by means of vapour pressure. This situation is related to a power burst situation in a reactor system. However, the experiment is fundamentally oriented with a major emphasis on determining pressure (energy) feedback effects, which as I mentioned yesterday are crucial for sustaining propagating explosions.

R Benz
Did you change the fuel to coolant ratio? If not, do you think that it might be possible to increase the efficiency measured in these experiments by changing the fuel to coolant ratio?

T G Theofanous
The only parameter changing in the experiments reported here was the oil temperature. In the next series we will go into detailed evaluation of the effect of constraint, by changing the piston weight and the air back pressure, and then we will consider the effects of changing fuel/coolant ratio.

R W Hall
I do not understand your point of needing significant vapour generation to sustain an explosion in a large void fraction mixture. Examination of the appropriate Hugoniot for such a system shows that the C-J state—which is what you need—for stable propagation—occurs just as vapour nucleates, so large amounts of vapour generation are not needed in this system.

T G Theofanous
I put this requirement in terms of the energy that would be required for a trigger. What you describe, I think, would be the case for a very strong trigger that can collapse all vapour space and proceed to the interaction through fragmentation and energy transfer in an all liquid environment. On the other hand a much smaller trigger would be required in this case if a prompt feedback was available.

A S Bain
In a previous answer you indicated that you were interested in fundamental aspects rather than practical systems. I saw films today which showed violent explosions and if someone who is anti-nuclear looks at such an event he is liable to say that it shows what can happen in a core melt down, and that claims that a nuclear reactor cannot explode are, in his view, incorrect. Surely this group here today should be aiming their results to real reactor systems; we are not scientists working in a vacuum, but are exposed to a very hostile group of anti-nuclear people.

T G Theofanous
I must have given you the wrong impression. It is basically because of interest in the real system that I am interested in studying the fundamentals. In fact we can
not solve the problem only by making measurements on the real system, since even
if one did and found no explosions, there would always be those who would say that
one had not made the right experiments. The only way to combat this is to obtain
a thorough understanding of the fundamental processes involved in explosions. In
fact until we have done this we will not even know what experiments on the real
system should be carried out.

A S Bain
I must emphasize that I feel it is important for us to realize that someone with an
anti-nuclear attitude is unlikely to separate experiments directly applicable to
reactor situations from those which are not.
Paper for presentation to

OECD–CSNI

Fourth CSNI Specialist Meeting on
Fuel–Coolant Interaction in Nuclear Reactor Safety
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FUEL–COOLANT INTERACTION STUDIES WITH
WATER AND THERMITE GENERATED
MOLTEN URANIUM DIOXIDE

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420
Fuel Coolant Interaction Studies with Water and Thermite Generated
Molten Uranium Dioxide
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1 Introduction

An experimental programme using uranium burning thermite charges to produce molten uranium dioxide is in progress at AEE Winfrith. This paper reports progress with one section of the work, which is nearing completion, in which the interaction of molten UO₂ fuel with a coolant of water in a closed vessel has been studied. The object of this work has been mainly to provide information relevant to the assessment of the consequences of melting fuel in water reactors, but it is also useful as an aid in the interpretation of the results of a similar programme involving sodium as the coolant, which is in progress.

The mode of contact of fuel and coolant appropriate to the work reported here, was one in which the fuel was released from a container under the surface of a pool of the coolant, as a pressurised, two phase mixture of liquid and vapour, which expanded into the surrounding coolant and into which it dispersed. In a closed vessel this represented a convenient geometry, for the expansion of the fuel was sensitive to the initial coolant pressure and this gave a means of varying the effective, local fuel to coolant ratio. Use was made of this effect in the investigation of the possible modes of thermal exchange between the fuel and coolant.

Later stages of the overall programme will use new facilities to investigate the interaction of larger quantities of fuel (up to 20 kg) in a number of modes of contact.

2 Experimental detail

2.1 Reaction vessel

Contact between the molten UO₂ fuel and the coolant of water, took place in a closed, cylindrical, steel pressure vessel 400mm in diameter and of unitary aspect ratio, with a total volume of 52 litres. The vessel, which is shown in Figure 1, was supported with its axis vertical, so that the flat, steel plates which formed its base and roof were located horizontally. Two laminated glass windows 200mm in diameter and positioned diametrically opposite each other in the wall of the vessel,
enabled the use of high speed cine photography to record the release of the molten charge products and their subsequent mixing with the surrounding water. The vessel was equipped with four Meclec MQ20 piezoelectric pressure transducers, three of which were located in the roof and the fourth in the centre of the base.

The thermite charge container was located centrally within the vessel and supported rigidly on a tubular mount suspended from the centre of the roof.

2.2 Thermite Charge and Charge Container

The thermite material used in the experiments reported here, was a stoichiometric mixture of powdered uranium metal and molybdenum trioxide which when ignited, rapidly produced molten uranium dioxide and molybdenum through the exothermic reaction:-

$$3\text{ U} + 2\text{ MoO}_3 \rightarrow 3\text{ UO}_2 + 2\text{ Mo} + 1.88 \text{ kJ/gram}$$

In a series of experiments, details of which are to be published separately, a number of such uranium thermite charges were ignited in closed transparent containments and pyrometric measurements made of the temperatures developed within the products. A photographically based, two colour pyrometric technique was employed which made use of an over-run tungsten filament as a temperature standard. The measurements indicated the temperature of the charge products to be within the range of 3400 to 3700°K.

The releasing thermite charge container appropriate to the work reported here, and which is shown in Figure 2, was a stainless steel cylinder with an internal volume of ~150 ml which had a capacity of some 0.55 kg of vibrocompacted thermite material. The upper end of the container was closed by a "services end cap" in which supports were mounted for an electrically operated fuse wire to ignite the charge and a pressure transducer to record the charge pressure subsequently developed. The lower end of the container was closed by a "releasing end cap", held in position by a tie bar fixed coaxially within the container and maintained under a tension of ~ 4.54 kN by a spring loaded mechanism within the end cap. In use, with the charge container located vertically in the centre of the reaction vessel, the mode of operation was such that the tie bar was heated by the burning thermite charge and was consequently softened in the region of a specially shaped and pre-
weakened section. In this condition the tie bar suffered mechanical failure as a consequence of the tension maintained within it, and the lower end cap was thus released and ejected from the end of the container by the spring mechanism. The charge pressure, typically 1.0 MPa, then caused the thermite products to be blown downwards out of the container and into the surrounding water.

2.3 Control and Instrumentation

The event sequence, culminating in the ignition and release of the thermite charge, was initiated remotely from the reaction vessel and was controlled by a gated event sequence timer. Pressure transient signals were transmitted by the transducers located in the vessel roof and base and in the charge container and were recorded on analogue magnetic tape, from which they were later recovered and digitized for processing. High speed cine photography, with a framing rate of 4000 pps, was used to record details of the evolution of the charge products following their release within the reaction vessel.

2.4 Experimental programme

In the series of experiments reported here, single 0.5 kg uranium thermite charges provided molten uranium dioxide which was released centrally within the closed reaction vessel, under the surface of water at ambient temperature (approximately 5 to 15°C). The water almost completely filled the reaction vessel, the remaining volume being occupied by a cover gas of argon. To investigate the extent to which the expansion of the fuel into the coolant, the associated mixing and any subsequent interaction could be influenced by the relative volume and initial pressure of the cover gas, these initial conditions were varied systematically.

In a first set of experiments the cover gas volume was preset to 3.6 litres and in a second, to 1.2 litres. In each case initial pressures were increased in stages from 0.1 MPa (absolute, i.e. ambient) to a maximum of 1.0 MPa.

The experiments carried out and the corresponding initial conditions are summarised in Table 1.

3 Results and Analysis

In every release into water of thermite generated, molten UO₂ carried out in this programme of experiments, a common feature was the production
of hydrogen from the chemical reaction of a small residue of unburnt uranium remaining in the charge products. This was represented in the vessel pressure records by a rapidly established step increase of pressure immediately following the release of the charge. It was thought that the presence of the hydrogen had no significant effect on the subsequent events in the reaction vessel, except that of effectively increasing the initial pressure of the cover gas.

The rate and degree of expansion and dispersal of the UO₂ into the surrounding photographic records, to be influenced by the initial pressure and volume of the cover gas. The expansion was increasingly restricted by the use of higher initial pressures and smaller volumes. A number of distinct types of behaviour were observed which corresponded to particular initial conditions in the reaction vessel, each of which was characterised by a particular type of pressure transient and form of the solidified UO₂ debris. Each of these types of behaviour is discussed below.

i **Type 1 Release**

With a relatively large cover gas volume of 3.6 litres and a low initial pressure of 0.1 MPa (absolute), the expansion of the UO₂ into the water was relatively free, leading to effectively small, local fuel to coolant ratios and to the absence of subsequent containment pressurisation by coolant vapour. This type of simple release was characterised by a damped oscillatory pressure transient associated with an oscillatory expansion of the two phase charge bubble and a corresponding oscillatory compression of the cover gas. A typical cover gas pressure transient of this kind is shown in Figure 3. The solidified UO₂ debris recovered after a Type 1 release was typically of a coarse granular form with only some 10% of the mass of the material represented by particles of a size less than 188 μm or greater than 8 mm.

ii **Type 2 Release**

When the cover gas volume was reduced to 1.2 litres at an initial pressure of 0.1 MPa, or was maintained at 3.6 litres but at an initial pressure of 0.4 MPa, the expansion and fragmentation of the charge material was much reduced. Large globules of molten UO₂
remained intact, falling to the base of the reaction vessel, where, still in a molten condition, they gave locally high fuel to coolant ratios causing localised boiling and associated containment pressurisation. This type of release was characterised by a cover gas pressure transient exhibiting a delayed peak of \(\sim 0.2\) MPa and approximately 80ms in width, occurring some 150ms after the release of the charge. In the high speed film records of several examples of this type of release, an upwelling of hot material from the base of the reaction vessel, could be identified which coincided with the peak of the containment pressurisation. Typical examples of cover gas pressure transients corresponding to Type 2 releases are shown in Figures 4 and 5. The solidified \(\text{UO}_2\) debris recovered was characterised by a form markedly different to that of a Type 1 release. Commonly 30–50% of the material was present in particles greater than 8mm in size, and the largest particles were of the order of 30–40mm in their largest dimension. The debris exhibited an open structure with evidence of numerous coolant vapour voids. Less than \(\sim 2\%\) of the debris mass was in the form of particles of less than 150 \(\mu m\) in size.

iii Type 3 Release

In nearly half of the experiments employing an initial cover gas volume of 3.6 litres at an initial pressure of 0.4 MPa and in one other at 1.2 litres and 0.4 MPa, a third and quite different type of behaviour (Type 3) was observed. As in Type 2 behaviour the initial conditions in the vessel restricted the expansion of the fuel which consequently was confined to a small volume of coolant, providing locally high fuel to coolant ratios. From the high speed film records of such releases, it was observed that as the end cap was ejected from the charge container, it was accompanied to the base of the reaction vessel by an overlying region of high fuel concentration. The impact of the end cap on the base of the vessel, at a velocity of \(\sim 8ms^{-1}\), provided sufficient mechanical shock to trigger a molten fuel-coolant interaction in this coarsely mixed region of fuel and coolant.

Apart from the record of the high speed films, Type 3 releases were characterised by a large pressure transient in the cover gas and
coolant, with an initial rise which coincided with the impact of the end cap on the base of the vessel. A typical cover gas pressure transient of this kind is shown in Figure 6. The first pressure peak was followed by a number of secondary, decaying peaks corresponding to an oscillation of the volumes of the cover gas and of the progressively condensing coolant vapour generated by the MFCI. The frequency of this oscillation was determined by the geometry of the reaction vessel and equilibrium pressure and volume of the cover gas, as was the rise time (≈ 4 ms) of the MFCI pressure transient in the cover gas. The corresponding transient in the coolant, recorded by the transducer in the base of the vessel, exhibited a rise time thought to be determined by the dynamics of the MFCI, and which was much faster (≈ 0.5 ms) as may be seen in Figure 7 which shows a comparison of the cover gas and base pressure transients.

The debris recovered from Type 3 releases was quite different to that from types 2 or 1, with evidence of much finer fragmentation. The fraction of the total mass of debris present in particles larger than 8 mm was reduced to the range 9 to 15%, while that less than 150 μm was in the range 5-30%.

The mechanical yield of the MFCI was determined by calculation of the adiabatic work done on the cover gas in compression to the maximum pressure observed, an allowance being made for the compression of the hydrogen which was also present at this time. In the case of the interaction corresponding to Figures 6 and 7 (A57) the yield was 3.14 kJ. If the fraction of the debris less than 150 μm (29%) represented the material involved in the MFCI, which would be consistent with estimates drawn from the high speed film, this yield would represent 1.3% of the total thermal energy available to this fraction of the fuel (the total energy is taken as 1.64 kJ/gram for fuel at a temperature of 3550°K). In the most energetic interaction observed (A80) the yield was 4.19 kJ from 24% of the material, corresponding to an efficiency of 1.8%.

iv Type 4 Release
With a cover gas volume of 1.2 litres and an initial pressure of 0.4 MPa or with an initial pressure in excess of this value and a
cover volume of 3.6 litres, rapidly generated interactions were replaced by another type of behaviour: Type 4. This was characterised by a further restriction of fuel expansion into the coolant and, as with Type 3, by containment pressurisation apparently initiated by the impact of the end cap on the base of the reaction vessel. However, the rise time of the cover gas pressure transient was very slow, typically $\approx 22\text{ms}$, as was the subsequent decay of pressure which was of the order of $200\text{ms}$. A typical example of such a transient is shown in figure 8. Pressure transients measured in the coolant at the base of the vessel displayed similarly slow behaviour.

Mechanical energy yields were calculated from the peak adiabatic compression of the cover gas, as before, and were of the order of $0.5\text{kJ}$. The fuel debris recovered was also characteristic of this type of release, there being typically less than 1.5% of the mass of the material as particles of less than $150\mu\text{m}$ and 45 to 60% greater than $8\text{mm}$.

In several of the experiments with initial conditions favouring Type 4 releases, delayed pressure transients, associated with the delayed coolant boiling, characteristic of Type 2 releases, were also observed. For initial cover gas pressures of $1.0\text{MPa}$ and a volume of 3.6 or 1.2 litres this contribution was very marked, and in the case of two experiments with those conditions, A70 and A77, only Type 2 behaviour was apparent. The cover gas pressure transient corresponding to experiment A70 is shown in Figure 9.

**Effect of Pressure on Type of Release**

The initial conditions and corresponding types of release are summarised for each experiment in Table 1, and Figure 10 illustrates the distribution of the type of release with the corresponding initial conditions of the cover gas. There was a considerable variation in the type of release observed for any particular set of initial conditions. This may have been due in part to the varying effect of the increment of initial pressure caused by the production of hydrogen, and in Figure 11 the types of release have been plotted against initial pressures in which this effect has been included. While an overlap is still apparent between the
conditions favouring different types of release, there is a general
trend such that at net initial pressures below 0.5 MPa a simple
Type 1 release was found, between 0.6 and 0.96 MPa, 56% of such
examples exhibited Type 2 behaviour, 28% Type 3 and 16% Type 4;
whereas above 0.96 MPa all were of Type 4 until pressures of
~ 1.45 MPa, when Type 4 behaviour was suppressed in favour of
Type 2. Similarly, upper and lower thresholds appear to apply to
the initial pressure above and below which true molten fuel-coolant
interactions did not occur.

Although each experimental release has been allocated to a
particular type, many exhibited characteristics of two types.
Additionally, variations were observed in Type 3 behaviour, which
with an increasing initial cover gas pressure tended to display
pressure transients with some features similar to those of Type 4.
Such a transient is shown in Figure 12 (A78). Despite a rate of
initial pressure rise characteristic of the Type 3 MFCI, the peak
cover gas pressure was not reached until the second oscillation
and the subsequent decay was extended.

The coincidence of pressure generation and end cap impact in Type 4
releases and the general form of the pressure transient suggests
that some fragmentation process does occur in this effect. However,
this must be relatively coarse in view of the small fraction of
fine debris recovered and the relatively slow rise time. The more
ergetic of such releases have markedly smaller fractions of the
largest debris.

The demonstration that molten UO₂/water thermal interactions can
follow the same sequence of mixing phase, trigger process and rapid
interaction as observed for other materials, is the most important
result of this work at this stage. However this is not an
unexpected result, for coolant film boiling would be expected to
stabilise the initial mixing phase. The results have also
indicated that UO₂/water interactions may achieve significant yields
of mechanical energy.

The programme of experiments is continuing with a more detailed
examination of MFCI triggering and the effect of the degree of
coolant subcooling.
Hydrodynamic modelling of fuel-coolant interactions

A preliminary attempt to model the fuel-coolant interactions seen in Type 3 releases has been undertaken in an effort to associate the magnitude of the pressures observed with the quantities of fuel and coolant involved and the timescale of heat transfer. This procedure used the two dimensional hydrodynamic code SEURBNUK (1) to model the expansion of the bubble of coolant vapour and fuel into the surrounding coolant. The geometrical model used to represent the reaction vessel, fuel bubble, end cap and cover gas is shown in Figure 13. The end cap rested on the centre of the base of the vessel, beneath the fuel bubble the precise initial volume and position of which were fixed by requirements of the code. The remaining volume of the vessel was filled with water except for the cover gas, the volume of which could only be approximated to the experimental values of 3.6 and 1.2 litres by 3.9 and 1.4 litres respectively. The SEURBNUK code enabled the expansion of the fuel bubble to be modelled hydrodynamically given a source term for the coolant vapour pressure generated within the bubble, which was determined by the rate of heat transfer from the fuel to the coolant. Heat transfer was assumed to take place on a timescale $\tau$, from a mass $M_f$ of fuel to a mass $M_w$ of water within the influence of the fuel bubble and associated with the MFCL, such that the rate of heat transfer to unit mass of coolant was given by eqn (1):

$$ Q = \frac{M_f}{M_w} \frac{C_p}{\tau} (T_f - T_w) \quad (1) $$

where $C_p$ was the specific heat of the fuel and $T_f$ and $T_w$ the fuel and water temperatures. Within a timestep, $\Delta t$, the internal energy, $U$, of unit mass of coolant within the final bubble increased from an initial value $U_0$ to that given by eqn 2:

$$ U = U_0 + \frac{Q \Delta t - P \Delta V}{M_w} \quad (2) $$

where $P$ was the pressure of the fuel bubble and $\Delta V$ its change of volume. The fuel bubble pressure was thus related by eqn 2 to the internal energy of the coolant and to the bubble volume, which was a parameter supplied by the code. The masses of fuel and coolant, $M_f$ and $M_w$ involved in the interactions and the timescale, $\tau$, were difficult
to quantify so that modelling an expansion and comparing the result to experiment, led essentially, only to values of a heat transfer characteristic $\phi$, such that:

$$\phi = \frac{M_f}{M_w \tau}$$

(3)

However, the mass of fuel was estimated as 200 g, from the proportion of fine particles recovered from the fuel debris. Similarly, the mass of coolant vaporised must, reasonably, have been within an order of magnitude of 1 to 10 g, given the compression of the cover gas experimentally observed, so that a somewhat arbitrary value of $M_w$ of 2 g was chosen.

Interactions were modelled for each of two cover gas volumes of 3.9 and 1.4 litres, both at an initial pressure of 0.4 MPa; corresponding as closely as was possible to the conditions of experiments A57 and A60. In each case a value of $\phi$ of 1000 s$^{-1}$ was found to give a satisfactory agreement with experiment, which for the ratio of the masses of fuel and coolant indicated above, corresponds to a value of $\tau$ of 0.1 s, which is much greater than the interval of interest. This effect is undoubtedly artificial and would appear to indicate that a much smaller value of $M_f/M_w$ would have been appropriate. Plausibly, if $M_f/M_w$ were in the range of 1 to 10, then for the given value of $\phi$, $\tau$ would more realistically fall within the region of 1 to 10 ms.

Cover gas pressure transients corresponding to modelled MFCL bubble expansions with cover gas volumes of 1.4 and 3.9 litres are shown in Figures 14 and 15 respectively, together with experimental points from A60 and A57. In each case the magnitude and width of the first pressure peak in the model agree quite well with the experimental values.

However, in the case of Figure 14, A60, the experimental peak pressures decay, whereas in the model they increase, for in the model no account has been taken of cooling of the fuel. Subsequent calculations have been carried out assuming a heat loss proportional to the surface area of the bubble, but difficulty was experienced in that this particular code is generally unsuitable to model more than 1 cycle of expansion and contraction.

The development of the analysis of the UO$_2$/water thermal interactions is continuing and further calculations are being performed both with
heat transfer from the fuel to the water limited to the initial contact and with account taken of heat loss from the fuel.

5 Conclusion

A series of experiments has been undertaken in each of which contact took place, in a closed vessel, between water and 0.5 kg of thermite generated molten uranium dioxide. Several types of behaviour were observed corresponding to different initial conditions in the cover gas in the reaction vessel, and these were:

Type 1: For net initial pressures less than ~0.5 MPa the expansion of the UO₂ into the water was relatively free, leading to small fuel to coolant ratio and the absence of containment pressurisation by coolant vapour.

Type 2: For net initial pressures between ~0.6 and ~0.96 MPa, the expansion of the UO₂ was limited and fragmentation reduced. Large concentrations of molten UO₂ settled on the base of the reaction vessel, causing localised coolant boiling and containment pressurisation of ~0.2 MPa.

Type 3: With conditions similar to those favouring Type 2 behaviour, the inhibition of the expansion of the UO₂ gave locally large fuel to coolant ratios. In some experiments sufficient mechanical shock was generated, by components of the charge container striking the base of the vessel, to trigger an MFCI in nearby charge material. The most energetic event gave a mechanical yield of 4.2 kJ from ~24% of the charge material, corresponding to ~2% of the total thermal energy available to this fraction.

Type 4: For net initial pressures between ~0.96 MPa and ~1.45 MPa the character of the interaction changed, becoming slower and with a more prolonged containment pressurisation. At pressures in excess of 1.45 MPa this behaviour was apparently suppressed in favour of that of Type 2.

The experiments have demonstrated that in suitable conditions molten UO₂/water interactions take place and that they follow the same sequence of mixing phase, triggering and rapid interaction observed for other materials.

A preliminary analysis of the UO₂/water interactions has been performed by modelling with the 2D hydrodynamic code, SEURBUJK, and has enabled an estimate of an MFCI heat transfer characteristic.
Acknowledgement

The authors gratefully acknowledge the assistance of Dr P C Coddington in his application of the SEURBUK code to the problem of modelling UO2/water interactions: and the assistance of Mr R C Burnett in the analysis of the UO2 debris.

References

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FIG. 1. URANIUM DIOXIDE/WATER REACTION VESSEL
FIG. 5. COVER GAS PRESSURE TRANSIENT—DELAYED COOLANT BOILING (TYPE 2) RUN A053
FIG. 6. COVER GAS PRESSURE TRANSIENT-MOLTEN FUEL COOLANT INTERACTION (TYPE 3) RUN AO57
FIG. 9. COVER GAS PRESSURE TRANSIENT-REVERSION TO TYPE 2 AT HIGH INITIAL COVER GAS PRESSURE RUN A070
FIG. 10. DISTRIBUTION OF REACTION TYPE WITH CORRESPONDING INITIAL COVER GAS CONDITION
FIG. 11. DISTRIBUTION OF REACTION TYPE WITH CORRESPONDING INITIAL COVER GAS CONDITION INCLUDING HYDROGEN CONTRIBUTION
FIG. 13. INITIAL GEOMETRY FOR SEURBNUK CODE TO MODEL MFC1 IN UO₂ / WATER REACTION VESSEL

1. FUEL BUBBLE
2. END CAP
3. COVER GAS
FIG. 15. EXPERIMENTAL NFI PRESSURE TRANSIENT FROM RUN AO57 AND CORRESPONDING SEURBNUK CALCULATION

Time (msec) vs. Pressure (MPa)
Discussion on Paper PCI4/P19

M Jacobs
Did you have any evidence of pressure increase due to coolant entrainment into the hot expanding thermite bubble during the initial expansion?

M J Bird
Not really, although we have not looked closely for this. There was certainly no evidence of this in our early results although more recently the observation of uniform and sustained cover gas pressure oscillations may be evidence of coolant entrainment in the expanding fuel bubble.

P Coddington
I have analysed these experiments and also some of the earlier ones and looked specifically at the bubble expansion and could find no evidence, certainly in the earlier experiments, of any coolant entrainment.
Observations of Tin/Water Thermal Explosions in a Long-Tube Geometry;  
Their Interpretation and Consequences for the Detonation Model

- by -

R W Hall, S J Board and M Baines

Paper FCI 4/20 presented at 4th CSNI Specialist Meeting on  
FCI in Nuclear Reactor Safety, Bournemouth, April 1979.

Central Electricity Generating Board  
Berkeley Nuclear Laboratories  
Berkeley  
Glouestershire  
GL13 9PB

March 1979
1. INTRODUCTION

This paper presents details of experiments designed to test the detonation model of thermal explosions (Board et al, 1975); on this theory large-scale explosions should propagate steadily at supersonic velocities through a fuel coolant mixture, giving a yield which has been shown to depend on details of the fragmentation and heat transfer behind the shock front (Hall and Board, 1977).

Observations of propagating explosions have been reported previously by various workers, (Briggs, 1976; Board and Hall, 1973, 1976; Reynolds et al, 1976). In the present work, a long-tube geometry is used since in 1D, propagation measurements are particularly easy to interpret. Also, in 2- and 3D geometries radial flow can tend to extinguish shock waves and if a single-phase region of coolant is present, pressure pulses can propagate ahead of the two-phase shock in the intermixed region.

The six experiments described below all use molten tin and water mixtures. In the first four detailed pressure measurements were the main objective; the last two are attempts at flow visualization to aid the interpretation of these. We discuss below the results obtained and the implications for the detonation model. A detailed interpretation in terms of fragmentation and heat transfer processes behind the shock is attempted. We finally turn briefly to the implications of the work for reactor materials.

2. EXPERIMENTAL DETAILS

(a) The Vessel and Furnace

The general layout of the apparatus is shown in Figure 1. The main vessel is an 85 - 100 cm length of 2.5 cm bore tube open at both ends. This is co-axial with an outer 5 cm bore jacket, closed at its lower end and with a controlled outflow at its upper. The vessel, which is initially filled with water at 85 - 95°C, is mounted vertically below a small furnace, from which tin at 600-750°C is introduced into the top of the inner tube. The two tubes make up a co-axial manometer: water displaced by the inflowing tin (which does not explode spontaneously in hot water) is ejected by the unequal density head in the inner tube through the outflow at the upper end of the outer tube. (This displaced flow was collected and measured in one case.) By suitably throttling the exit flow to match the furnace flow rate it is possible to produce a fairly uniform intermixed distribution of metal through the length of the inner tube, without displacing the inner tube water level too far. When smaller quantities (75 ml, see Table 1) of tin were used, gravitational flow from the furnace was sufficient, but a small overpressure on the furnace (5 - 7 psi) was used to assist ejection of the larger (180 ml) amounts.
In the first four experiments the inner tube was made of thick (3 mm) steel and the outer was of 5 mm plastic; in the flow-visualization experiments, 3 mm wall borosilicate glass was used for both components. The steel tube had a volume of about 480 ml, and the glass ones 350 ml and 400 ml.

(b) **Triggering**

Two methods of triggering the quasi-stable initial distribution have been used. In the first experiments a small detonator (No. 6 - approximately 0.1 gm of PETN) was used. This was placed in the outer vessel, some 2½ diameters (7 cm) below the lower end of the inner tube, and fired electrically when metal was detected in this region, (by its bridging across two closely spaced meshes).

In later experiments the lowest part of the outer vessel was closed off by a thin polythene diaphragm and the closed space below filled with cold water (20°C). Tin falling from the inner tube melted through the polythene and exploded spontaneously within a few milliseconds in the cold water below.

(c) **Instrumentation**

The instrumentation in the steel-tube experiments consisted of four pressure transducers (Kistler type 603B) mounted at 25 cm intervals in the side wall of the inner-tube. In the flow-visualization experiments two transducers only were used, one was mounted in the bottom of the sealed outer tube, and the other near the top of the apparatus. In the first of these two experiments the transducer was mounted in a small reservoir at the top of the tubes, but in the second experiment it was mounted some 10 cm below the top of a metal extension to the inner tube. Information from all these transducers was recorded on a U-V chart recorder and an Ampex FR1300A f.m. tape recorder, with a maximum frequency response of 40 KHz. A check for tape recorder over-load (which produces transient signals very like shock fronts!) was provided by recording each signal on two channels, one with a factor of three attenuation.

In the flow-visualization experiments two high speed cameras were used (a full frame Hadland Hyspeed and half-frame Red Lake Hycam) at framing rates of (5 - 10) x 10³ pps. One of these took a general view for intermixing and overall propagation studies of a 50 cm section of the tube, whilst the other was arranged for a close-up study of a 20 cm long region at about 2/3 of the height of the tube. Timing information (timing light and shutter pulse signals) was recorded to enable later synchronisation with the pressure traces.

Finally, a view of the full apparatus in the six experiments was obtained from a video-tape recorder (50 f.p.s).
3. RESULTS

(a) Pressure Records

Pressure records from the six experiments are given in Figure 2 (a - f); these have been plotted from the tape-recordings by a small computer-based data logger. Slightly better high frequency information is available from the original recordings. The following instrumental effects should be noted:-

(i) the top transducer (No. 4) in experiment 4 was not functioning,
(ii) the signal of the top transducer in the first flow-visualization experiment (experiment 7) is useful for timing purposes only because of its poor mounting and location,
(iii) more importantly, the base line level of many of the records becomes suspect after 5 - 10 ms, because of temperature effects.

All the results show shock propagation from the bottom to the top of the tube. Propagation velocities range from $6 \times 10^3$ to $3 \times 10^4$ cm/s, with the lower values tending to occur near the top of the tube. (The rapidly travelling negative pressure feature in the detonator-triggered experiment 2 is believed to be a wave induced in the steel walls of the tube by the detonator.) These pressures are typically 50 - 80 bars with rise times under 50 µs. The initial pressure 'spike' (evident in most records) drops in under 200 µs to plateau pressures of 30 - 40 bars which are maintained for some 10 ms. In the spontaneously triggered explosions the wave front sharpens as it moves up the column, and in one event there is also an increase in amplitude (experiment No. 4).

(b) High-speed films and Video Tape Records

(i) Intermixing Phase

Film of the intermixing phase of the flow visualization experiments (Figure 3) shows no evidence of vapour, surprisingly for such hot water (90°C). From the failure to show on the film, we estimate the vapour blanket thickness must be well under 1 mm. The low void fraction is confirmed in experiment 8; here the displaced water was collected and measured at 175 ml; at least 120 ml of metal had entered the apparatus at the time of the explosion. The difference, 50 ml, is a rough estimate of the vapour volume (giving $\alpha = 0.2$).

The tin, on entering the column breaks up on a length scale of 3 - 5 mm (comparable with the Weber break up scale $\sqrt{\frac{\sigma}{g \Delta \rho}}$ where $\sigma$ is the surface tension). Much of it subsequently reclfumps in regions comparable to the width of the tube, but from the behaviour during the fall and the subsequent explosion phase, we suggest that these regions still retain a large amount of water interspersed
within them. Experiments with aluminium at Winfrith THERMIR facility (Briggs, 1976) provide further evidence for this, (see also Baines, 1979).

(ii) **Explosion Phase**

In both the general and detailed views of the explosion phase (Figure 3) the explosion front shows as a grey fuzziness of individual lumps of tin. This is followed 1 - 2 cm (100 - 300 μs) later by a general expansion of the tin. The average velocity of the front in the lower half of the tube is about 90 m/s, comparable with typical values seen in the metal-tube apparatus. Tracking of features behind the front is difficult, but suggests flow velocities of 20 m/s. The tin clumps appear to reach these velocities in times ∼ 400 μs (Figure 4, and below).

In these flow-visualization experiments the inner tube (and in experiment 8 the outer also) is observed to shatter during the explosion - in the field of view of the close-up camera this breaking appears to occur about 15 cm behind the front.

(c) **Form of the Debris**

The post-explosion tin-debris can be divided into that found external to the apparatus and that remaining within it. In a number of cases substantial quantities of debris much finer than ∼ 30 μm were found, but this is always distributed externally to the apparatus, usually above the height of the furnace. It appears in quantity if an explosion occurs whilst tin is still flowing from the furnace, and we believe it is produced by the action of the escaping high velocity steam/water mixture on the tin outside the vessel.

Debris remaining within the tube has a rather coarser form - little is less than ∼ 100 μm. It is found collected together in cokey, honeycomb-like lumps, of high uniformity; these lumps fill the tube and are a few tube diameters in length (Figure 5). They have a void fraction of about 50% and the whole structure has a rather foam-like appearance. It seems likely that each of these lumps is formed from a separate clump of the initial tin/water mixture during the early part of the expansion phase, and there is indeed some evidence of this from the films.

4. **ENERGETICS OF THE EXPLOSIONS**

It is interesting to attempt to estimate the efficiency of the explosions, though the present design of apparatus does not allow this with much certainty. The peak pressure is comparable with that expected from the equilibrium Hugoniot for the initial mixture, or even slightly greater (see below). The commonly used method of evaluating the yield from $\frac{(F/d)^2}{2M}$ gives values of 150 - 250 J, but this is a significant underestimate when the mass accelerated is the fuel/water mixture itself, and this is decreasing with time as the tube empties. The possibility of choking at the tube exit further complicates the picture. In any case the pressure history is uncertain after a few milliseconds.
From the film the mixture within the tube reaches the velocity of $\sim 20$ m/sec (KE = 200 J) whilst the pressure is at 20 bars, so that further acceleration is to be expected beyond the end of the tube. However, this cannot be estimated without knowledge of the thermal conditions of the mixture. In experiment 7, considerable work was done on the surroundings, the furnace being projected upwards against friction, and the tube and the pressure mount down into the base of the containment box. Values estimated from these effects are consistent with a yield of a few hundred joules.

5. IMPLICATIONS OF THE RESULTS

We now discuss the implications of these observations for the detonation model. We take for granted the simultaneity (to within $\sim 100$ $\mu$s) of the pressure and visual fronts (our present apparatus is not suitable for demonstrating this since the pressure transducers are not within the field of view), since this has been demonstrated elsewhere (Board and Hall, 1976; Fry and Robinson, 1979) and it is in any case extremely plausible on physical grounds.

(a) Evidence for self-sustaining shock-fronts

All the results show clearly propagating pressure waves travelling from near the bottom to the top of the apparatus. The majority of these pulses have quite large amplitudes and short rise times, so we suggest they are shock-fronts in which the vapour void is collapsed.

Confirmation that pressure pulses are indeed significantly supersonic with respect to the two-phase group velocity is provided by a feature in experiment 4 (record 2d). A low amplitude disturbance, marked X on the record, is seen by the lowest transducer and a little later, somewhat attenuated, by the adjacent transducer. We estimate from this that the Mach number of the large-amplitude pulse which follows is $2 - 3$. Visually also, there is no evidence for any significant process occurring ahead of the shock; the size-scale of disturbances in the tin/water interface remains $\sim 3 - 5$ mm, so that there is no evidence for the "pre-fragmentation" suggested by Henry and Fauske (1975).

Across the shock the normal 1-D flow relationships should hold, so

$$\frac{P_2 - P_1}{V_1 - V_2} = j^2; \quad \text{since } P_2 >> P_1.$$

this may be approximated to $V_1 P_2 \sim D^2 \alpha$, where $j$ is the mass flux $D/V_1$, $V$ is the specific volume, $D$ the detonation velocity, and $\alpha$ the void fraction ahead of the shock. If we ignore slip behind the front, then these equations applied to say the middle regions of experiment 5, give $\alpha \sim 0.1$; if, on the other hand, we assume more reasonably that the tin is unaffected by the shock so that the equations apply to the water/vapour phases only, then $\alpha \sim 0.2$. This value appears consistent with the flow velocity seen in experiment 7. These last measurements also show that the void fraction must increase appreciably in the upper reaches of the tube, the front slowing whilst the flow velocity behind it increases slightly. This effect is presumably due to an increased vapour
blanket thickness with the hotter water and hotter tin at the top of the tube.

(b) Escalation of the explosion from spontaneous triggers

Various workers (e.g. Williams, 1976) have suggested, by analogy with chemical explosions, that the energy requirements for triggering thermal-detonations may be large. Nevertheless, computations (Fishlock, private communication and 1979) and simple theoretical considerations (Hall and Board, 1977) suggest that escalation of the explosion into a detonation will occur from quite small triggers, provided there is a fragmentation mechanism which is at least partially effective at low shock strengths.

Our present experiments show that such a process certainly occurs in metal/water explosions. In the upper parts of the tube the pressure records from the spontaneously induced events are indistinguishable in form from the detonator-triggered experiment number 2.

The rapidity of escalation in these spontaneously triggered explosions gives useful information on the reaction-zone length behind the shock. It is expected that the explosion will travel a few times this distance before approaching steady-state. Experiments 5, 7 and 8 (which have a 50:50 tin/water ratio) show no evidence for escalation through the tube, suggesting that the reaction-zone lengths must be very short (less than \( \sim 5 \) cm); experiment 4 with a more dilute tin/water ratio shows a slow escalation (Note that the explosion probably triggers between transducers 1 and 2), but even here, a zone length of under 15 cm is suggested. The consistency of these values with other estimates of reaction-zone lengths and with various suggested fragmentation mechanisms is discussed below.

(c) Location of the C-J plane

The Chapman-Jouget plane, the plane at which the flow reaches the velocity of sound in the frame of the front, cannot be observed directly and its distance behind the shock can only be inferred.

Apart from the reaction-zone length estimate above, a second estimate of the position of the C-J plane can be deduced from the form of individual pressure traces by using the vapour-detonation model described in our recent paper (Hall and Board, 1977); on this model the C-J plane occurs where the pressure is about half that of the shock peak. Most of the pressure traces do indeed show a sharp fall in pressure by about this factor over 100 - 250 \( \mu s \) (distance of 1.5 - 3 cm). [Note that this model was developed for the case of negligible slip behind the C-J plane, but is also valid for the case of very weak momentum coupling between the phases; measurements suggest there is little movement of the tin during the pressure spike (see next Section) so that the simple relationship is likely to be a reasonable approximation. Similar ratios between shock and C-J pressures are in fact given by a wide range of simple models, e.g. those with a perfect gas equation of state.]
Some confidence in this interpretation is given by noting that if the drop in pressure is indeed due mainly to vapour generation (see next Section) then \( \frac{\Delta V}{V} \approx 0.1 - 0.2 \), and the velocity of sound \( \sim V \sqrt{\frac{P}{\Delta V}} \) lies in the range \( 6 - 9 \times 10^3 \text{ cm/s} \); these values are indeed comparable with the flow velocities observed at this point (i.e. 0.8 D).

Finally, we note an observation from experiment 7, which places an upper bound on C-J position. Within the field of view of the close-up camera, the tube is observed to break close behind the front. This break follows within 15 cm of the front but does not affect its propagation, and so may be deduced to be lying beyond the C-J plane.

In summary, the evidence is for reaction-zone lengths much less than 15 cm long; this value also agrees with those suggested elsewhere from observation of propagation failure (Hall and Board, 1977).

(d) Comparison of observed and predicted pressures and energy yields

It is interesting to compare the observed data with the simple thermal equilibrium predictions to illustrate effects of disequilibrium. The C-J pressures and propagation velocities expected from a fully efficient equilibrium explosion of the nominal experimental mixture ratios and temperatures are shown in Table 2.

At these initial metal temperatures the mixture temperature is well sub-critical so that the C-J plane is located at the knee of the Hugoniot curves at a point where vapour is just being formed (cf., \( \frac{1}{4} \) initial vapour volume in dis-equilibrium case), for a wide range of initial conditions. These pressures are comparable with the observed plateau pressures only for experiment 5, but the high values predicted for experiment 7 and 8 would also fall to comparable values if the amount of tin assumed in the vessel were slightly reduced (see Table 1). The pressures predicted for the experiments with dilute tin/water ratios (Numbers 2 and 4) are significantly lower than observed, suggesting that large scale mixing of tin and water has not taken place.

The maximum energy yields (for isentropic expansion of the mixtures down to 1 bar) are also given, and are seen to be very much larger than the average yield from the experiment (\( \sim 500 \text{ J} \)) as estimated above. However, such an expansion would have taken place largely at volumes much greater than that of the apparatus, and a much more realistic estimate is \( \sim P V \), where \( V \) is the volume of the tube and \( P \) is the C-J pressure, which should be nearly constant for this degree of expansion of an equilibrium mixture. However, even this prediction is still over four times that observed. This suggests that only very limited mixing could have occurred before the C-J plane.
6. DETAILED INTERPRETATION OF THE RECORDS

(a) Preliminary Considerations

We turn now to the interpretation of the detailed mechanics of the explosion. The form of the pressure trace in a 1-D geometry is controlled principally by the rate of heat transfer and the rate of decay of slip, and both of these in turn depend on the fragmentation rate. Some estimate of slip can be made directly from the films by observing the motion of the metal regions immediately behind the shock. Such regions are observed to accelerate to near their final velocity in about two frames (400 μs) behind the visible shock front; for comparison a single half centimetre diameter drop of tin in a flow of 20 m/sec would be expected to take about 1.4 m/sec to approach full velocity, (Baines et al, 1978). It would therefore appear that either the conditions in a dense dispersion lead to very much faster acceleration rates, or more likely the characteristic size of the tin drop is rather smaller than appears on the film. There is some evidence to support the latter view from recovered unfragmented material from similar experiments. Much of the tin appears to be in thin (∼ 1 mm) sheets, strongly convoluted.

In the absence of heat transfer, the decay of slip in subsonic flow leads to an increase in pressure. In fact, after ∼ 300 μs the pressure has fallen sharply (by × 2) and so significant expansion (∼ 10%) must have taken place. Liquid phase expansion cannot have contributed significantly to this volume change so the required expansion is almost certainly due to rapid vapour production, which is consistent with the fuzzy grey appearance seen on the films as the first evidence of the shock. At this stage the enthalpy of the vapour for 10% expansion is ∼ 3J per cc, implying a vapour generation rate during the first 200 μs of 15 kW per cc.

The tin surface area needed to produce this vapour generation in constant pressure conditions, may be roughly estimated from the laser heated foil experiments of Board et al (1974), which cover the relevant transient timescale and pressure range. These suggest heat fluxes ∼ 3 kW/cm² in the nucleate boiling region, 1 kW/cm² in the film boiling region. It was found in these experiments that a maximum of 10% of the heat flux produced vapour during the transient growth of a vapour blanket and this fraction fell to zero when the film thickness reached an equilibrium value of 10 microns in subcooled conditions. The vapour generation rate would therefore imply a tin surface area equivalent to 100 - 300 micron particles; the equilibrium thickness a value of 150 microns. (The fraction of flux producing vapour might be expected to be affected by a rapid pressure transient but it was found that the equilibrium blanket thickness was remarkably insensitive to changes, for instance, in pressure, subcooling, flow etc.)
Thus, the heat transfer evidence suggests that there has been significant fragmentation within 200 μs of the shock front.

(b) The search for a fragmentation mechanism

In previous work we have suggested three possible candidates for the fragmentation process, (Baines et al, 1978) - hydrodynamic fragmentation, the effects of vapour blanket collapse, and the effects of local boiling at the liquid-liquid interface between fuel and coolant. We consider the possible role of each of these in turn, in the light of the numbers deduced above.

(i) Hydrodynamic fragmentation

We consider first the timescale of fragmentation, due to the velocity differentials occurring behind the front; these are order 20 m/sec and could be higher just behind the front. Our experimental data for single drop breakup in liquid-liquid systems (Baines et al, 1978; Baines, 1979) shows complete breakup to occur over a period of dimensionless time

$$T = ut \sqrt{\frac{\rho_c}{\rho_f}} \sim 4$$

where $u$ is the applied differential velocity, $d$ the particle size, (note both are initial values). This gives a breakup period of about 0.7 - 3 milliseconds, and a reaction-zone length therefore, of $\sim 15$ cm, based on drop sizes from the film; but if the effective size for the drop is taken to be that suggested by the drop acceleration time this estimate would be reduced by a factor of $\sim 4$ which would then be in fair agreement with the best estimates of reaction-zone length. Theopanous and Patel (1977), have also studied liquid-liquid breakup, in this case using falling drops in a liquid shock tube, and have found substantially shorter dimensionless breakup times ($T \sim 0.5$) than those of Baines et al. Breakup in 150 μs would be implied for the apparent drops size from their results, which is in satisfactory agreement with our heat transfer requirements. It is also notable that the acceleration rates recorded in their experiments for an apparent half centimetre drop and 20 m/sec velocity ($4 \times 10^6$ cm/s$^2$) are very similar to those deduced from the present experiment ($5 \times 10^6$ cm/s$^2$, see Figure 4). It therefore seems possible that similar breakup behaviour could be expected.

(The suggestion above of a convoluted form for the drops might indeed be an explanation for the differences between the Theopanous and Baines breakup data.)

Finally, we may compare the form of the debris with that produced in the recent work on hydrodynamic fragmentation of low melting point alloy dense dispersions (Baines, 1979). Although the size scales of the debris are comparable for similar flow velocities, the low melting point fragments do not have the characteristic honeycomb form of the tin. Both the tin debris and the film suggest that droplets of water dispersed within the tin regions may cause the mass

459
to foam up as the pressure is relieved.

(ii) Vapour blanket collapse

Of the energy PAV expended by the shock front in collapsing the void, only half is converted into motion along the direction of propagation (this is the energy source of hydrodynamic fragmentation). The rest is converted into the kinetic energy of vapour blanket collapse. This amounts to some 300 J or 0.75 J per cc. Such energy could produce $\sim 10^4$ cm$^2$ of surface area per cc, against surface tension if other loss processes were not significant. Although the energy available in the blanket collapse is clearly sufficient for causing fragmentation, the mechanism for achieving it and the rate at which it can be achieved, is not yet clear.

Some workers, e.g. Jakeman and Potter, (1972), Calderola & Kastenberg (1974), have suggested that the collapsing interface forms high velocity jets, which penetrate the outer fluid, but this is unlikely to fragment much of the fuel volume. Larger scale effects do however seem possible; in an irregular coarsely mixed system, non-uniformities in blanket thickness will lead to the development of a random velocity field of a length scale dictated by the scale of the initial regularities and the velocity comparable with the collapse velocity ($\sim$ a few times $10^3$ cm/s). This turbulent velocity field would distort the interface since its kinetic energy density exceeds the surface tension pressure at wavelengths longer than a few microns. Substantial breakup would however take times comparable with the flow time, $\frac{d}{u}$, probably a few hundred $\mu$s; the size scale of velocity fluctuations in the system will drop on this timescale as eddies interact and breakup. Viscous losses will dominate when the size scale is sufficiently small i.e. much less than a micron. We see that this process has points of similarity with the usual hydrodynamic fragmentation process, discussed earlier, and in particular both mechanisms produce breakup on a timescale comparable to $\frac{d}{u}$, the time for the flow to move a drop diameter.

(iii) Boiling Fragmentation

The form of the debris in these experiments is rather similar to that found by Baines and Board (1978), in studies of the interaction of large water drops on molten surfaces. In their experiments the effect of vapour blanket collapse and of bulk velocity differentials were essentially absent and so they attributed the intermixing to energy from vigorous boiling processes. In the conditions of the present experiment, the interface temperature is expected to be much greater than the thermodynamic critical temperature, so that vapour generation at fresh interfaces should take place virtually instantaneously.
It is not, therefore, clear how nucleate or other energetic boiling processes could occur. The ability of some such mechanism to explain spontaneous triggering of the explosion, is however, easier to appreciate since under conditions of film break down in which such spontaneous triggers occur, large scale nucleate boiling and considerable turbulence production would be expected on a freshly exposed surface.

(iv) Summary of the fragmentation problem

No completely satisfactory resolution of the search for the dominant fragmentation mechanism has been reached. It is clear that for the breakup mechanism seen in the work of Baines to be fast enough, the tin drops must be rather convoluted on a scale $\sim 1$ mm. This appears plausible from the form of unfragmented debris from other experiments. The results obtained by Theophanous are consistent both with the observed acceleration of the drops and the required fragmentation rate. Jetting from vapour blanket collapse is unlikely to fragment much of the tin whilst larger scale deformation by vapour blanket collapse energy must occur on a time comparable with that for hydrodynamic fragmentation and this therefore implies similar initial drop sizes.

The role for boiling fragmentation in a fully developed explosion, is not clear because the contact temperature should be super-critical. It seems likely, however, that this is the mechanism responsible for the spontaneous triggering of the explosion.

IMPLICATIONS OF THE RESULTS FOR REACTOR MATERIALS

These observations confirm earlier suggestions that the comparative inefficiency of metal/water explosions is due to the rapid coherent vapour production which takes place on hot surfaces. This vapour blanketeting will cause the pressure in the system to fall rapidly, largely removing the velocity differentials set up behind the front and probably inhibiting further mixing and heat transfer. Present knowledge suggests that for the sodium/UO$_2$ system it is probably difficult to set up the initial coarsely intermixed conditions but if this does occur, the application of a high pressure shock might be expected to collapse any vapour (probably nucleate boiling bubbles) and also produce differential velocities for hydrodynamic fragmentations. The heat transfer process would be very different from the metal/water case, since at high pressures even nucleate boiling would be suppressed in favour of single-phase transient conduction. The liquid-phase expansion is much greater in sodium
than water and it has been shown that this alone is adequate to drive an
explosion based on hydrodynamic fragmentation, (Berthoud and Scott, 1978).
Since expansion of the liquid will reduce the pressure, vaporisation of the
sodium may then occur, though it seems unlikely that film boiling will curtail
further vapour generation as it does in the water case because the interface
temperature is too low to prevent repeated contact. Efficiency will therefore
be high unless condensation in the surrounding subcooled sodium is fast enough
to produce a zero net vapour generation rate before the energy transfer is
complete. For UO$_2$/water fuel coolant interactions the possibility of stable
film boiling allowing intermixing is not seriously in dispute, but the vapour
blanket growth mechanisms working for inefficiency will probably be very similar
to those seen in metal/water explosions.

CONCLUSIONS

Six experiments studying metal/water explosions in 1-D geometries have been
described. These show evidence for self-sustaining shocks which produce a major
energy release from the system, and for the escalation of these from spontaneous
triggers. They do not, however, show evidence for full efficiency. It is suggested
that these explosions are "vapour detonations" in which fragmentation and vapour
blanketting take place a few hundred $\mu$s behind the shock. The possible fragmentation
mechanisms sustaining these explosions have been considered and it is concluded
that hydrodynamic fragmentation alone could explain the rapidity of the
observed fragmentation, on the data of Theophanous (or on that of Baines, but only
if the drops are assumed initially convoluted). The main part of blanket collapse
fragmentation will proceed at a similar rate to hydrodynamic fragmentation.
Boiling fragmentation may be operating in the triggering phase but its contribution
at later times is probably small unless the interface temperature is much lower than
the instantaneous contact temperature calculation.

Finally, we suggest that the rapid vapour blanket growth which limits the
efficiency of the present explosion may not occur in a sodium/UO$_2$ event, though
the initial conditions may not be realisable in this case. For a water/UO$_2$
system, vapour blanketting and low efficiency seems more likely.

ACKNOWLEDGEMENT

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REFERENCES

Note: 'F.C.I. Meeting' means one of the series of specialist meetings on f.c.i. sponsored by CSNI.


463
### TABLE 1

**Summary of Experiments**

<table>
<thead>
<tr>
<th>Experiment (Note A)</th>
<th>Types</th>
<th>Trigger</th>
<th>Tin</th>
<th>Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (Note B)</td>
<td>strong-tube</td>
<td>detonator</td>
<td>75 ml at 750°C</td>
<td>4 x 603B; VTR</td>
</tr>
<tr>
<td>3</td>
<td>&quot;</td>
<td>&quot;</td>
<td>NONE</td>
<td>4 x 603B; VTR</td>
</tr>
<tr>
<td>4</td>
<td>&quot;</td>
<td>spontaneous</td>
<td>75 ml at 660°C</td>
<td>3 x 603B; VTR</td>
</tr>
<tr>
<td>5</td>
<td>&quot;</td>
<td>&quot; (c)</td>
<td>180 ml at 720°C</td>
<td>4 x 603B; VTR</td>
</tr>
<tr>
<td>7</td>
<td>glass</td>
<td>&quot; (c)</td>
<td>180 ml at 720°C</td>
<td>HQ20, 603B; two high speed cameras at 5000 pps; VTR</td>
</tr>
<tr>
<td>8</td>
<td>&quot;</td>
<td>&quot; (c)</td>
<td>180 ml at 620°C</td>
<td>2 x 603B; high speed cameras at 5000 and 10,000 pps; VTR</td>
</tr>
</tbody>
</table>

**Notes**

A. Experiments 1 and 6 did not give useful data.

B. Experiment 2 was reported in outline by Board and Hall, (1976).

C. Probably not all this tin was in the water at the time of explosion

**Key**

VTR - Video Tape Recorder;
603B - Kistler type 603B pressure transducer
HQ20 - Meclec type HQ20 pressure transducer
### TABLE 2

Predicted C-J Values and Maximum Work Yield

<table>
<thead>
<tr>
<th>Experiment</th>
<th>P Bars</th>
<th>$V_1^a$ cc/gm</th>
<th>$V_2^a$ cc/gm</th>
<th>$D^a$ cm/s</th>
<th>Maximum Work Yield$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5</td>
<td>0.58</td>
<td>0.5</td>
<td>$4.5 \times 10^3$</td>
<td>37 KJ</td>
</tr>
<tr>
<td>4</td>
<td>4.5</td>
<td>0.58</td>
<td>0.5</td>
<td>$4.2 \times 10^3$</td>
<td>30 KJ</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>0.37</td>
<td>0.345</td>
<td>$1.1 \times 10^4$</td>
<td>90 KJ</td>
</tr>
<tr>
<td>7$^b$</td>
<td>165</td>
<td>0.26</td>
<td>0.25</td>
<td>$3.3 \times 10^4$</td>
<td>95 KJ</td>
</tr>
<tr>
<td>8$^b$</td>
<td>60</td>
<td>0.29</td>
<td>0.27</td>
<td>$1.6 \times 10^4$</td>
<td>75 KJ</td>
</tr>
</tbody>
</table>

**Notes:**

a. A void fraction of 0.2 is assumed.

b. A slight change in tin-mass would reduce these values to near those of experiment 5. See Note C Table 1.

c. These are isentropic work yields down to 1-bar final pressure.
FIG. 1a. Schematic Diagram of Apparatus, Experiments 2 - 5.
FIG. 1b. Flow Visualisation Apparatus. Expts. 7, 8.
FIG. 4. Motion of Tin Drop in Flow behind Front
(D = 65–70 m/s)
FIG. 5. Post - Explosion Debris, Experiment 7.
T G Theofanous
Do you think if you were to use a very large trigger you could get higher efficiencies in your experiment?

R W Hall
Yes. We cannot rule out this possibility for the denser tin/water mixtures. The present explosions are probably vapour-driven and an energetic trigger might get you into an explosion driven in the liquid-phase expansion only.
A COMPARISON OF THE SODIUM–UO₂ RESULTS
WITH THE SPONTANEOUS NUCLEATION THEORY

BY

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ABSTRACT

The available molten uranium dioxide-sodium interaction test results are compared to the predicted behavior for a sodium entrapment, homogeneous nucleation mechanism. This mechanism is found to be in accord with the reported pressures, delay times, impulses, and mechanical work for the limited scale experiments in which significant interactions are observed. For large scale experiments, this mechanism would not yield any significant energy release, which is also in agreement with the available experimental results.

I. INTRODUCTION

Historically, essential elements in the development of a detailed understanding of sodium-fuel thermal interactions have been the experiments performed with reactor materials. These tests, which include both in-reactor and out-of-reactor experiments, have been conducted with various amounts of molten fuel and over an extensive range of sodium temperatures. Since these reactor material experiments are relied upon heavily in evaluating proposed thermal interaction models, it is crucial that, where possible, these analyses be compared with the experimental results.

While many theoretical models\textsuperscript{1-7} have been presented in the literature, most of these can only be interpreted in terms of bounding calculations. However, one approach which does allow detailed evaluation, of the behavior for a UO\textsubscript{2}-sodium interaction is the interface temperature spontaneous nucleation model originally proposed by Fauske.\textsuperscript{5} In this model, two types of explosive interactions can occur, (1) a small-scale, or superheat explosion can result when the hot liquid temperature is greater than the spontaneous nucleation limit but the contact interface temperature is less than this value, and (2) a large-scale explosion that can result when the contact interface temperature exceeds spontaneous nucleation. Of these two cases, the former describes the UO\textsubscript{2}-sodium system and in this condition the system is comparatively well defined so that detailed comparisons can be made for the pressures and impulses measured as well as the mechanical energy released in a given event.

II. THE INTERFACE TEMPERATURE, SPONTANEOUS NUCLEATION CRITERIA

In 1972, Fauske\textsuperscript{5} proposed that the necessary conditions for a large-scale vapor explosion are (a) liquid-liquid system, and (b) the temperature upon contact between the hot and cold liquids must exceed the spontaneous nucleation temperature of the volatile liquid. It was suggested\textsuperscript{8} that this criterion assures dynamic film boiling and hence the requirement of premixing as well as subsequent rapid escalation of surface area which promotes heat transfer consistent with observed explosion pressure rise times. Onset of the latter process requires a trigger, which for a given liquid-liquid system may be self-induced or externally applied. The interface temperature for two semi-infinite liquid masses with constant thermal properties upon intimate contact is given by
\[
\frac{T_i - T_c}{T_h - T_i} = \left[ \frac{k_h \rho_h c_h}{k_c \rho_c c_c} \right]^{1/2}
\]

(1)

where \(T, k, \rho, \) and \(c\) are the temperature, thermal conductivity, density, and specific heat and subscripts \(h\) and \(c\) represent hot and cold liquids, respectively.

Spontaneous nucleation is the formation of critical size vapor cavities as a result of density fluctuations in the liquid independent of any pre-existing gas or vapor sites.\(^3\) The volumetric nucleation rate can be expressed by,

\[
J = \frac{Wf(\theta)}{k_1 T}
\]

(2)

where \(f(\theta)\) is a functional relationship involving the contact angle \(\theta\) and is included in Eqn. 2 to account for the possibility of spontaneous nucleation at the liquid-liquid interface rather than in the bulk of the volatile fluid (homogeneous nucleation). As shown in Ref. 9, the spontaneous nucleation threshold is dependent on both contact mode and contact time, and these effects can be represented by specifying the contact angle \(\theta\). In case of perfect wetting (\(\theta = 0\) which corresponds to \(f(\theta) = 1\)), the limit of superheat (homogeneous nucleation) is attained. This limit is well-defined for a given fluid, while the spontaneous nucleation temperature is dependent upon both the liquid-liquid system and transient in question and may be anywhere from the homogeneous nucleation limit to the saturation temperature corresponding to the ambient pressure. With the experimentally determined sodium pressure-temperature measurements reported in Ref. 10 and the surface tension measurements summarized in Ref. 11, the spontaneous nucleation temperature of sodium can be calculated as a function of \(\theta\), and this is shown in Fig. 1. For the high temperatures involved in a molten \(\text{UO}_2-\text{Na}\) system, \(\theta\) is believed to have a value between 0 and 90° (measured wetting angles less than 60° for temperatures greater than 500°C\(^{12}\)), resulting in a spontaneous nucleation temperature that can be closely approximated by the homogeneous nucleation value. Therefore, the small-scale and large-scale vapor explosion criteria for a sodium system becomes

\[
T_i < T_{HN} < T_h \quad \text{small-scale explosions are possible}
\]

\[
T_i > T_{HN} \quad \text{large-scale explosions are possible}
\]

For sodium-molten uranium dioxide, the contact interface temperature is several hundred degrees centigrade less than the homogeneous nucleation temperature. Therefore, the interface temperature criterion predicts that large-scale vapor explosions will not occur with this liquid-liquid pair. However, even though the interface temperature is well below the homogeneous nucleation limit, the hot liquid temperature is much greater than this value. In this case the potential exists for
the entrapment of a small quantity of sodium within the fuel which would result in superheating the sodium to the nucleation limit and explosive vaporization. While such events represent no significant energetics in the content of hypothetical core disruptive accidents, they can appear to be energetic in the limited scale experiments that have been performed.

If this entrapment mechanism described in Ref. 13 is a viable explanation for the observed events, then it should be consistent in the prediction of the experimental measurements, i.e., maximum pressure, delay time, impulse, etc. And conversely, if these observations are all consistent with such an explanation, it is implicit that such events do not represent a violation of the interface temperature criterion for large-scale events, but instead provide a natural extension of the nucleation arguments to another class of explosive vaporization.

To date there have been many small-scale and large-scale experimental studies, with both simulant fluids and real reactor materials, which provide considerable insight into the physical requirements for an explosion. But before discussing these observations, it is necessary to clearly define and distinguish between, small-scale and large-scale events. This will be done in terms of the basic definition, necessary conditions, energy release, and expected experimental observations for the two systems.

III. EXPERIMENTS DEMONSTRATING SMALL-SCALE EXPLOSIONS

A vapor explosion is an event in which high pressure vapor is produced at a rate which exceeds the ability of the surrounding media to acoustically accommodate the volume increase. Experimental results have demonstrated that to have such explosive events it is necessary to have (1) two liquids at greatly different temperatures and (2) these liquids must be brought into intimate contact. One mechanism for accomplishing these conditions is with the experimental apparatus of Blander and coworkers14 shown in Fig. 2. In this apparatus, a small droplet of volatile liquid is allowed to rise through a capillary tube into a column of host liquid, usually sulphuric acid or silicon oil. The column is wrapped with a heating wire to provide an increasing temperature along the length of the column, and this temperature profile can be measured with a traversing thermocouple. A droplet of volatile liquid rises within the host fluid in a liquid-liquid state, and at a certain elevation, the droplet explodes with an audible ping. By knowing the temperature profile within the column prior to the event, and by using a sufficiently small droplet so that it is essentially in thermal equilibrium with the local host liquid, the temperature required for this explosive vaporization can be determined. This temperature can be compared to the homogeneous nucleation value as shown for two different volatile liquids at the bottom of Fig. 2, and the agreement shows a remarkable comparison with the experimental data.

In these events, which are the classical nucleation experiments that have been run by several investigators (by both increasing temperature and decreasing pressure), the energy is stored in the more
volatile liquid over a long time period, i.e., the rise time of the droplet in the column. This energy transfer and storage time is long compared to the time scale of explosive vapor release. This storage of energy has been observed in systems other than the classical column experiments as seen in the limited scale tests reported by Fauske and shown in Figs. 3 and 4. In Fig. 3, Freon-11 with a normal boiling point of 24°C, was injected into water at 70°C and 1 atm, as shown, it is easily entrained and remains in the water for more than sufficient time to achieve thermal equilibration. Consequently, the Freon-11 exists in a metastable liquid state of 70°C and 1 atm until it sinks to the bottom of the glass beaker and encounters a preferred, preexisting site on the glass surface. In Fig. 4, progressive views are shown of a pentane droplet impacting upon a hot silicon oil surface. In this experiment, the silicon oil temperature is 165.5°C as compared to the homogeneous nucleation temperature of the pentane of 147.8°C. The droplet impacts upon the surface, and experiences a delay of 77 msec before explosive vaporization occurs. During this 77 msec, the energy is stored in the pentane droplet, or portions thereof, in a fashion similar to that of the rising column experiments discussed earlier. Figure 4 also shows that the work potential resulting from this explosive vaporization has been exhausted 1 msec after the event, which is a very short time interval compared to that required to store the energy. These experiments give a clear demonstration of a small-scale explosive interaction, i.e., the energy in these events was stored on a time scale that was much greater than the time required for vapor nucleation, growth, and release of the stored energy.

A large-scale event is one in which the time for energy transfer is comparable to, or shorter than, the time required for vapor growth and overall expansion of the system. Simply stated, in a small-scale interaction the energy is transferred before the event and in a large-scale interaction the energy is transferred during the event. Consequently, the designation of small- and large-scale explosions does not relate to size of the quantities involved but to the rate of energy transfer between the hot and cold liquid, and consequently to the work potential delivered by the interaction. While small-scale events may, under certain circumstances, provide a safety hazard to operating personnel, i.e., splashing of hot oil or a shower of sparks from moist wood in a fire, they do not provide any significant work potential within a reactor environment for hypothetical molten core conditions. However, large-scale events, if they can exist for given reaction materials and environmental conditions, can produce significant motions of core materials and can, in the extreme case, perhaps even test the integrity of the primary system boundary.

IV. EXPERIMENTAL CONDITIONS FOR LARGE- AND SMALL-SCALE EVENTS

Small-scale events require the entrapment of a small quantity of cold liquid within the hot liquid as opposed to large-scale events which require the intimate dispersion of one liquid within the other. Some experimental examples of small-scale events were shown in Figs. 2, 3, and 4 and the type of experiments shown particularly in Figs. 3 and 4 represent similar configurations to the initial out-of-pile systems.
which investigated sodium and UO$_2$ behavior. In Refs. 15 and 16, molten uranium dioxide was dropped into a subcooled sodium bath and the quenching process resulted in extensive fragmentation of the UO$_2$ and small pressure spikes were also observed. In the overall sense, this experimental configuration is the entrapment of hot material within a cold bath, but this configuration does not rule out the entrapment of a small quantity of liquid sodium within the uranium dioxide. Molten uranium dioxide freezes upon contact with liquid sodium, and as discussed in Ref. 17, this freezing also results in significant thermal stresses and cracking of the solid uranium dioxide surface. If liquid sodium wets the UO$_2$ surface, and this has certainly been the observation of all in-pile and out-of-pile experiments to date, this cracking of the UO$_2$ surface occurs in the presence of a wetting fluid. Since the cracks must be initiated from essentially zero radius, Laplace's equation relating surface tension, cavity radius, vapor pressure and system pressure, predicts that the surface tension forces at the crack inception would be enormous for a wetting system, and consequently, the liquid sodium would be pulled into the crack as it is formed. This would result in the entrapment of sodium on a small scale, as depicted in Fig. 5, and could produce the pressure spikes, on a very short time scale, observed in these two references. The detailed evaluation of this configuration is more difficult to analyze since the amount of superheated sodium available at the time of nucleation is not known. This parameter can be evaluated in terms of the measured delay times when sodium is injected into molten UO$_2$.

In Ref. 18, sodium was injected into a molten uranium dioxide bath, and in every instance where the experimental apparatus performed as desired, energetic events were observed, and these are tabulated in Table I. As schematically illustrated in Fig. 6, the tungsten crucible which held the molten uranium dioxide was supported by a force transducer and the peak force listed in Table I represents the maximum measurement recorded by this instrument. As shown in Fig. 6, if inertial bubble growth is assumed (which is the case for a highly superheated, low Prandtl number liquid), this peak force measurement can be used to interpret the peak pressure existing within the pool by dividing the peak force by the internal area of the crucible, 2 x 10$^{-4}$ m$^2$. The resulting peak pressure calculations are listed in Table I, and it should be noted that these are not representations of the maximum pressure which may have existed during the actual event, but are rather representative of pressures averaged over the crucible internal surface area and the response time of the force transducer. If these events result from entrapment of sodium within uranium dioxide, which certainly was the configuration of greatest interest in these experiments, the maximum measured pressure can give some insight into the spontaneous nucleation temperatures for a UO$_2$-sodium system, i.e., the maximum pressure measured is representative of the vapor pressure and consequently the maximum superheat within the system. Table I includes the sodium saturation temperatures which correspond to the peak pressures as interpreted from the experimental equation of state data for sodium.$^{10}$ The maximum superheats are quite high, and considering the crude assumptions involved, with the exception of the two low pressure events in Run #8, the values are remarkably reproducible. There are several reasons why the measured forces can be less than those corresponding to

483
the maximum superheat (response time of the transducer, poor hydro-
dynamic coupling (vapor or gas) between the interaction zone and the
 crucible, etc.), but the measurements in this system should not exceed
the predicted values.

These measurements, which represent lower limits of the maximum
possible temperature, can be compared to the calculated homogeneous
nucleation value. Table II lists the homogeneous nucleation rates as a
function of temperature for sodium at atmospheric pressure, and sponta-
aneously generated critical size vapor embryos are produced at a
significant rate when the liquid temperature is approximately 2140°K.
As anticipated, this value does lie above the values deduced from
Armstrong’s experiments, which is consistent with the small-scale
interpretation. In addition, these experiments measured efficient
events with delay times as short as 9 msec, which demonstrates that
wetting occurs on a time scale less than this interval.

In recent out-of-pile, transient overpower, fuel sweepout experi-
ments, Spencer and coworkers injected 9.4 g of thermite generated
molten uranium dioxide into annular sodium channels in which the liquid
velocity was approximately 7.6 m/sec. The instrumentation for the test
section included inlet and outlet flowmeters, strain gauge pressure
transducers, and voltage taps along the length of the test section to
monitor the location of the liquid vapor interfaces. Figure 7 shows
pressure measurements immediately upstream and downstream of the injec-
tor location and the inlet flowmeter recording for the experimental
test. A gradual pressurization of the interaction zone and correspond-
ing decrease of flowrate through the test section occurred over the
first 10 msec of the injection period. At this point, a rapid pressuri-
zation event occurred which caused both pressure transducers to be over-
ranged (as indicated by the rapid decrease in pressure and the perman-
ently strained condition of the diaphragms after the test) and the inlet
flow to rapidly decelerate to a slightly negative value and then recover.
The pressure difference required for the measured velocity change (∆P =
10.45 psi) is 8.4 MPa, and the corresponding sodium saturation temperature is
2073°K,10 which is in reasonable agreement with the values deduced from
the experiments of Ref. 10 as well as the values listed in Table II.

Bojarsky et al.20 have also reported the results of out-of-reactor,
transient overpower studies in which the fuel is melted by direct elec-
trical current. In these experiments pressures of up to 7.0 MPa with
half widths of 0.1-0.2 msec were recorded. These pressure pulses were
interpreted in Ref. 20 as bubble collapse pressures, which is one pos-
sible explanation. However, these pulses have much the same behavior
as those observed in Ref. 19, and in both cases the experimentally
measured inlet flow rates exhibit sharp decreases immediately after the
pulses. This would indicate that the pressure is the result of an
expansion (vaporization) rather than a vapor collapse. In any case,
the measured pressures are well within those obtained from the other
experiments and those predicted by the entrapment-homogeneous nuclea-
tion mechanism. These can also be compared to the reported in-reactor
experiments.

484
Many in-reactor experiments\textsuperscript{21-28} have been conducted to investigate the potential for significant fuel-coolant interactions in various postulated accident sequences. Most of these experiments are of an integral nature and are not amenable to the resolution of such detailed phenomena. Some experiments\textsuperscript{21,25,28} present a comparatively simple geometry which enables some interpretation of the measured events. In these short period burst tests, the initial pressure has been shown\textsuperscript{21,25,28} to be essentially equal to the fuel vapor pressure at the failure condition. However, many of these tests have produced "delayed pulses" which have occurred at intervals as long as 2.4 sec after peak power. These pressures, which are sometimes difficult to interpret in these confined geometries because of the possibility of pressure doubling at rigid boundaries,\textsuperscript{28} are generally in the range, prior to doubling, of 5-10 MPa which is bounded by the out-of-pile experimental measurements and the pressures predicted by entrapment. Figure 8 illustrates the measured pressure spikes and the volume (piston) displacement in the 9-pin configuration of Test S-4, as reported in Ref. 21. The first pulse is undoubtedly fuel vapor pressure and the latter pulses may also be the fuel vapor pressure resulting from additional pin failures. These later pulses could also be due to sodium entrapment, superheating, and vaporization, which is certainly the case for the delayed pulse 16, and the magnitude of all the measured pulses falls within that predicted by entrapment of sodium droplets within the UO\textsubscript{2}.

The single pin test PBE-12S\textsuperscript{28} is another capsule experiment, similar to 84, in which multiple pressure pulses were observed after pin failure but while the piston was still moving. These latter pulses were interpreted as being produced by a source other than fuel vapor pressure. Figure 9 compares the recorded pressures for the two bottom pressure transducers and the single upper transducer with the value predicted by an entrapment mechanism. Given the uncertainties in the interpretation of the lower transducers (pressure doubling at a rigid boundary) the measured behavior is bounded by the sodium saturation pressure corresponding to homogeneous nucleation at low system pressures. Consequently, like the experiments discussed above, the measured pressures from this test are in accord with an entrapment mechanism.

Another set of experimental results which gives support to these nucleation temperatures, and consequently the predicted pressures, is the sodium film boiling study by Farahat.\textsuperscript{29} In this investigation, a high temperature tantalum sphere was submerged in a sodium bath and the boiling curve was deduced from the quenching history. For sodium subcooling less than 33\textdegree K, stable film boiling could be achieved and the quenching process was quiescent. However, for larger subcoolings, transition boiling occurred immediately upon entry into the sodium bath even for the maximum sphere temperature (2590\textdegree K). Some transition experiments were quite violent, producing pressure spikes as large as 0.58 MPa and expelling considerable sodium from the bath. When the subcooling exceeded 130\textdegree K, the quenching process was again comparatively quiet. These results are listed in Table IV along with the calculated contact interface temperatures, and for the most violent region, the temperatures are very close to the calculated homogeneous nucleation temperature illustrated in Table III. Since these experimental data are for a liquid-solid system, entrapment is possible, but spontaneous
nucleation upon contact has been shown to be one controlling mechanism for liquid-solid film boiling, which appears to be the case for these subcooled sodium conditions.

V. ENERGY TRANSFER CHARACTERISTICS

Since the energy in a small-scale event is stored over a long time interval compared to the event itself, the energy release is essentially isentropic, see Fig. 10, i.e., there is no significant amount of energy transferred during the event. The temperature entropy diagram shows only stable equilibrium states as opposed to the metastable equilibrium state of superheated liquid. However, when nucleation occurs, and the liquid surrounding the cavity is pressurized by the inertial growth, the instantaneous state of the liquid is essentially that denoted by point B in Fig. 10 where \( T_B \) is the spontaneous nucleation temperature of the liquid-liquid pair. The storage of energy from points A to B takes place during the delay time which can be quite short. For the sodium-UO\(_2\) experiments reported in Ref. 9, the shortest delay time was estimated to be from 9 to 15 msec. The quantity of sodium that can be superheated to the homogeneous nucleation limit during this time can be estimated by assuming the energy transfer is conduction limited within the fuel. For simplicity in evaluating the energy transfer, the interface temperature is assumed to remain at the instantaneous contact value, the interface is assumed to be planar, and the latent heat of fusion for uranium dioxide is neglected, which compensates for assuming the interface temperature remains constant. These approximations result in the following energy balance

\[
2k_F 4\pi R^2 (T_F - T_1) \sqrt{\frac{\theta}{\pi\alpha_F}} = \rho_c \frac{4}{3} \pi R^3 c_c (T_{HN} - T_o)
\]  

(4)

The droplet radius that can be superheated to \( T_{HN} \) in time interval \( \theta \) is approximately

\[
R = \frac{6 k_F (T_F - T_1) \sqrt{\theta}}{\rho_c c_c (T_{HN} - T_o)}
\]  

(5)

For the experiments of Ref. 18, the initial fuel temperature of approximately 3100°C and a sodium temperature of 400°C produce an interface temperature of 1340°C. This results in droplet radii of 1.7 mm and 2.1 mm for delay times of 0.009 and 0.015 sec, respectively. For such times the thermal boundary layer in the fuel is approximately 0.15 mm which is an order of magnitude less than the droplet radius of curvature, thus the planar interface assumption is a valid approximation.

The energy is stored in the sodium droplet over the delay time and released by bubble growth after nucleation. If the energy addition is negligible during this growth period, which is order of magnitude 100 \( \mu \)sec, then the expansion (bubble growth) would be essentially isentropic, i.e., path B-C in Fig. 10. The work produced per unit mass of working fluid can be evaluated from the first law of thermodynamics.
\[ w = q - \Delta u \]  

(6)

Assuming that the liquid is saturated at state A, the energy addition between saturated liquid states A and B is

\[ q = c_L (T_B - T_A) \]  

(7)

and the entropy increase is

\[ s_B - s_A = c_L \ln \frac{T_B}{T_A} \]  

(8)

The mixture quality at state C is

\[ x = \frac{s_B - s_f}{s_{fg}} \]  

(9)

and the change in internal energy between states A and C

\[ u_C - u_A = x u_{fg} \]  

(10)

Therefore, the work done per unit mass during the isentropic expansion from B to C is

\[ w = c_L (T_B - T_A) - x u_{fg} \]  

(11)

Figure 11 illustrates the droplet size that can be superheated in a given delay time and the mechanical work that can be derived from the expansion of such a superheated droplet. In a limited scale experiment, energy levels of this magnitude would appear quite energetic. However, these interactions would be insignificant on the scale of a reactor subassembly.

For a sodium system with a homogeneous nucleation temperature of 2140°C, the isentropic expansion to one atmosphere results in mechanical work of 485 J/g. A sodium particle 2 mm in radius would have a volume of 33.5 mm³ and a mass of 0.02 g which yields 10 J of mechanical work. The estimates of mechanical work provided in Ref. 18 from the experimental measurements vary widely and range from 0.17 to 155 J which brackets this value and those illustrated in Fig. 11. For the CAMEL loop single-pin experiment, which experienced a delay of 0.010 sec, a sodium particle of radius 1.7 mm would achieve the nucleation temperature during the measured delay. This droplet size is larger than the test section annular gap (1.6 mm), and consequently this volume of liquid sodium could only exist in a nonspherical geometry. However, since the spherical form has the smallest surface area per unit mass, it will also have the longest response time. Assuming no condensation on the test section walls, this droplet, which has a mass of 0.013 g, would yield approximately 2.5 J of work in an isentropic expansion from saturated liquid at 2140°C down to the inlet plenum pressure of 0.82
The measured inlet flow is brought to rest by the pressurization event, and if it is assumed that the entire sodium coolant up to the injector is simultaneously stopped, which is an overestimate of the instantaneous mass brought to rest, the energy required would be approximately 1 J. This is well within the available work produced from the expanding superheated droplet.

Figure 8 lists the change in kinetic energy of the piston and sodium which resulted from the interaction pressures in the S-4 test. These energy levels, which can be equated to mechanical work, and are typical of the S series test results, are well within those that would be anticipated from the measured delay times. A similar interpretation is given in Fig. 9 for the pressure events recorded in test PBE-12S. Here again the measured mechanical work is in agreement with the expansion work derived from a sodium droplet superheated during a time interval of several milliseconds. (The time of pin failure in PBE-12S is ambiguous because of the slow, early movement of the piston prior to any measured pressure events.) Consequently, the limited scale in-reactor experiments, which provide measurements of mechanical work in possible sodium vaporization events are in accord with the prediction of an entrapment and superheating mechanism.

In comparison to these small scale explosions, a large-scale event is one in which the energy transfer process occurs over a time interval that is comparable to or less than the time scale for the expansion. Consequently, the work potential is not characterized by an isentropic expansion. A more realistic thermodynamic description of a large scale explosion may be the path ABDE shown in Fig. 10, in which the energy transfer process ABD has a time scale less than the mixture expansion of BDE. Therefore, the energy released per unit mass of cold liquid interacted is much greater (∼2500 J/g) in a large-scale event and the energy transfer time is so short that many separate coolant masses can experience this energy release in the time scale of the expansion, i.e., system coherence.

VI. PRESSURE-TIME CHARACTERISTICS

Small-scale events, which can be initiated from a single spontaneous site, are merely an isentropic relaxation of previously stored energy, as illustrated in Fig. 10. For the experimental apparatus used in the sodium injection studies by Armstrong et al.,¹⁰ the initial nucleation and bubble growth would quickly pressurize the entire UO₂ pool. This can be approximated by the inertial growth time to a volume required for compression of the pool to the sodium saturation pressure corresponding to homogeneous nucleation, which requires a time interval of about 25 μsec. After this interval, which is shown in Fig. 6b, the bottom portion of the pool is pressurized to the sodium pressure and the expansion is limited by the rate at which the upper UO₂ slug can be expelled from the system. For these experiments, the amount of UO₂ lost from the system ranged from 13.9 to 42.3 g which would be represented by a slug length L of 0.7 to 2.1 cm. Isentropic slug expansion calculations, as illustrated in Fig. 6c, were performed for UO₂ slug lengths of 1 and 2 cm. The UO₂ slug acceleration is given by
\[ a = \frac{P_v - P_{atm}}{\rho_L} \]  

(12)

the velocity is

\[ v = a \, dt \]  

(13)

and the slug displacement is calculated from

\[ y = v \, dt \]  

(14)

These were numerically evaluated for an isentropic, two-phase expansion of the sodium from point B in Fig. 10 until the UO₂ slug was expelled from the crucible. The calculated depressurizations for the two different conditions are shown in Fig. 12 and it is seen that the pressure events have both a short rise time and a rapid decay and there is little difference between the two different slug lengths. In addition the calculated system impulse is essentially the same for the two different assumptions. It is also in close agreement with the reported value of 0.4 N.M for the event with the shortest time delay, which is the one with the greatest experimental resolution of the initial conditions.

In the CAMEL loop experiments the long sodium column lengths above and below the interaction zone mean that the vapor expansion on a millisecond time scale is limited by the acoustic compression of the coolant. Given this limitation, the expansion of the 1.7 mm radius superheated sodium droplet can be calculated. The coolant velocities ahead of and behind the interaction zone at the time of the event were 3.8 and 11.2 m/sec, respectively. Assuming that the local test section pressure is 1.0 MPa and a vapor pressure equal to the saturation value at homogeneous nucleation (11.5 MPa), the compression velocity generated by such an instantaneous pressure change would be given by

\[ u = \frac{\Delta P}{\rho_L C_L} \]  

(15)

and is equal to 5.3 m/sec. This produces an upstream velocity of 1.5 m/sec and a downstream velocity of 16.5 m/sec, which together give a differential velocity of 18.0 m/sec. If this velocity is assumed constant and the small preexisting void space and the condensing potential of the surrounding coolant and structure are ignored, the expansion of the sodium droplet would be approximated by

\[ \Delta V = \text{Aut} \]  

(16)

For an isentropic expansion a droplet of the calculated size would depressurize to the test section pressure in approximately 2 msec, and this is the approximate interval that the transducers are overranged. Consequently, the observed pressure history is consistent with an entrainment-superheat mechanism.

489
In a subsequent CAMEL test, Spencer and co-workers injected approximately 25 g of molten fuel into a seven-pin configuration. A pressure spike with a peak pressure of 15.1 MPa and a width of 0.23 msec was observed about 3 msec after the start of the injection. Using the above approximate analysis for acoustic growth, the maximum pressure would be 11.5 MPa, the superheated droplet diameter would be 1.6 mm, and the pressure spike would decay in 0.15 msec. These values closely correspond to the experimental observations, and they also show an interesting and important trend for these types of interactions, i.e., as the cross-sectional area of the flow channel increases, the duration of the pressure spike is also decreased. Consequently, given this explanation, the energetics of small geometry experiments can be misleading, and with cross-sectional areas typical of reactor subassemblies, the decrease in the duration of the pressure spike would make coherence of these superheat events virtually impossible.

The pressure events discussed above are to be contrasted to those observed in large-scale experiments with simulat materials. These large-scale explosions measure pressure decay times of typically 10 msec for cross-sectional areas of the order of 100 cm², and they only occur when stable film boiling is established on contact which prevents the entrapment and long term storage of energy typical of small-scale events.

VII. LARGE-SCALE EXPERIMENTS

According to the interface temperature, spontaneous nucleation criterion, which is summarized in Fig. 13, systems which do not satisfy the criterion will not experience large-scale explosive events. However, those systems which do have interface temperatures greater than the spontaneous nucleation value, and do not have other limiting parameters, such as elevated system pressure or contact temperatures well above the thermodynamic critical value, will experience large-scale explosions essentially every time. In addition, these systems will experience the same behavior independent of whether the liquid-liquid contact configuration is hot into cold or cold into hot. When the interface temperature exceeds the thermodynamic critical temperature, free contacting mode systems experience a cut-off in explosive behavior. This specific result is system dependent and can be overridden by an external trigger such as an exploding wire, cold wall, etc. However, the lower limit is only established by the liquid-liquid pair and is not influenced by an external trigger.

The difference between the criteria for small-scale and large-scale events is shown in Fig. 12 in terms of the hot liquid temperature. It should be emphasized that this criteria only supplies necessary and not sufficient conditions for a large-scale explosion. For example, in a system like molten aluminum and water, the contact interface temperature exceeds homogeneous nucleation temperature of water and the necessary condition for escalating liquid-liquid contacts must therefore be established (i.e., sufficient trigger). On the other hand, for a system of molten UO₂ and sodium (see Fig. 12), the contact interface temperature is significantly below the homogeneous nucleation point of sodium (closer to the normal boiling point). Therefore, large-
scale explosive events should not be observed for this liquid-liquid pair. Several experiments have been conducted in out-of-reactor tests\textsuperscript{36-61} in various laboratories and countries for molten UO\textsubscript{2} quantities up to several kilograms. While the various experiments have reported a spectrum of observations on the resultant energetics, those with significant pressure rises have had rather long rise times. The interactions appear to be strongly influenced by the geometry of the system, and while they may be of importance in a particular accident sequence for a given design, they are not explosive interactions. The conclusion from all of these UO\textsubscript{2}-sodium experiments conducted to date has been that no large-scale vapor explosion occurred, which is in agreement with the interface temperature, spontaneous nucleation criterion.

VIII. CONCLUSIONS

For molten uranium dioxide and sodium, the contact interface temperature is several hundred degrees Centigrade below the homogeneous nucleation value for sodium, but the bulk temperature of the fuel is far above this temperature. Consequently, the nucleation criterion would predict entrapment of sodium within the fuel since stable film boiling could not be established. A survey of the measured pressures for UO\textsubscript{2} and sodium events shows agreement with those predicted by the entrapment mechanism and the measured delay times indicate that wetting occurs on at least a millisecond time scale. The reported impulses and the derived mechanical work from the limited scale tests are also consistent with an entrapment-superheat mechanism within the reported delay intervals. In addition, large-scale UO\textsubscript{2}-sodium experiments have not observed any large-scale explosive interactions. Therefore, the available experimental measurements for UO\textsubscript{2} and sodium are completely consistent with the entrapment mechanism. These results represent a natural extension of the spontaneous nucleation concept which is the mechanism utilized extensively in the past for the measurement of the maximum liquid superheat, and as such they are in complete accord with the interface temperature-spontaneous nucleation criterion for large-scale vapor explosions.
REFERENCES


38. Amblard, M., "Preliminary Results on a Contact Between 4 kg of Molten UO2 and Liquid Sodium," Proc. Third Specialist Mtg. on Sodium/Fuel Interaction in Fast Reactors, Tokyo, Japan, PNC N251 76-12, 2, March 1976, pp. 545-559.


NOMENCLATURE

a  acceleration
b  specific heat
c  sonic velocity
d  volumetric nucleation rate
e  thermal conductivity
f  Boltzmann's constant
L  length
p  pressure
q  energy addition
r  radius
s  entropy
t  time
t  temperature
u  internal energy
v  velocity
V  volume
w  work
W  work required to form a vapor cavity
x  quality
y  distance

Greek

g  thermal diffusivity
G  difference

Subscripts

c  cold
fg  vapor-liquid
F  fuel
h  hot
HN  homogeneous nucleation
i  interface
L  liquid
0  initial value
v  vapor
<table>
<thead>
<tr>
<th>Run</th>
<th>Time from Start of Explosion (msec)</th>
<th>Peak Force (N)</th>
<th>Peak Pressure (MPa)</th>
<th>Saturation Temperature Corresponding to Peak Pressure (^°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>280</td>
<td>1,780</td>
<td>9.0</td>
<td>2045</td>
</tr>
<tr>
<td>8 A</td>
<td>35</td>
<td>203</td>
<td>1.0</td>
<td>1491</td>
</tr>
<tr>
<td>8 B</td>
<td>43</td>
<td>99</td>
<td>0.5</td>
<td>1364</td>
</tr>
<tr>
<td>9 A</td>
<td>9</td>
<td>1,776</td>
<td>9.0</td>
<td>2045</td>
</tr>
<tr>
<td>9 B</td>
<td>46.2</td>
<td>2,123</td>
<td>10.7</td>
<td>2100</td>
</tr>
<tr>
<td>12</td>
<td>378</td>
<td>948</td>
<td>4.8</td>
<td>1838</td>
</tr>
<tr>
<td>T *K</td>
<td>P_v MPa</td>
<td>N/M</td>
<td>A</td>
<td>J sites/cm^3 sec</td>
</tr>
<tr>
<td>------</td>
<td>---------</td>
<td>-----</td>
<td>----</td>
<td>-----------------</td>
</tr>
<tr>
<td>2100</td>
<td>10.34</td>
<td>0.028</td>
<td>55</td>
<td>1.14 x 10^{-18}</td>
</tr>
<tr>
<td>2110</td>
<td>10.62</td>
<td>0.027</td>
<td>51</td>
<td>1.30 x 10^{-11}</td>
</tr>
<tr>
<td>2120</td>
<td>10.90</td>
<td>0.026</td>
<td>48</td>
<td>168 x 10^{-5}</td>
</tr>
<tr>
<td>2130</td>
<td>11.19</td>
<td>0.025</td>
<td>45</td>
<td>3.81</td>
</tr>
<tr>
<td>2140</td>
<td>11.49</td>
<td>0.024</td>
<td>42</td>
<td>1.82 x 10^{5}</td>
</tr>
<tr>
<td>2150</td>
<td>11.79</td>
<td>0.024</td>
<td>41</td>
<td>1.97 x 10^{9}</td>
</tr>
<tr>
<td>2160</td>
<td>12.09</td>
<td>0.023</td>
<td>38</td>
<td>5.94 x 10^{12}</td>
</tr>
<tr>
<td>2170</td>
<td>12.40</td>
<td>0.022</td>
<td>36</td>
<td>6.33 x 10^{15}</td>
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<tr>
<td>2180</td>
<td>12.71</td>
<td>0.021</td>
<td>34</td>
<td>2.54 x 10^{18}</td>
</tr>
<tr>
<td>2190</td>
<td>13.03</td>
<td>0.020</td>
<td>32</td>
<td>4.57 x 10^{20}</td>
</tr>
<tr>
<td>2200</td>
<td>13.36</td>
<td>0.020</td>
<td>30</td>
<td>2.82 x 10^{22}</td>
</tr>
</tbody>
</table>

TABLE II.

Homogeneous Nucleation of Sodium

P = 0.1 MPa
<table>
<thead>
<tr>
<th>Sodium Temperature °K</th>
<th>Sphere Temperature °K</th>
<th>Interface Temperature °K</th>
<th>Pressure Pulse MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1123</td>
<td>2000</td>
<td>1741</td>
<td>0.03</td>
</tr>
<tr>
<td>1113</td>
<td>2590</td>
<td>2153</td>
<td>0.17</td>
</tr>
<tr>
<td>1111</td>
<td>2590</td>
<td>2153</td>
<td>0.29</td>
</tr>
<tr>
<td>1086</td>
<td>2590</td>
<td>2145</td>
<td>0.29</td>
</tr>
<tr>
<td>1023</td>
<td>2590</td>
<td>2126</td>
<td>0.58</td>
</tr>
<tr>
<td>973</td>
<td>2478</td>
<td>2033</td>
<td>0.03</td>
</tr>
<tr>
<td>873</td>
<td>2590</td>
<td>2082</td>
<td>0.03</td>
</tr>
<tr>
<td>773</td>
<td>2590</td>
<td>2053</td>
<td>0.02</td>
</tr>
<tr>
<td>673</td>
<td>2590</td>
<td>2023</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Fig. 1. Sodium Spontaneous Nucleation Temperature

Fig. 2. Liquid Superheat Apparatus

Fig. 3. Freon-11 and Hot Water
Fig. 4. Pentane and Hot Silicone Oil
Fig. 5. Localized Entrapment of Sodium

Fig. 6. Entrapment of Sodium in a UO₂ Pool
Fig. 7. CAMEL Loop Single-Pin Results

### Linear Motion Transducer Data

**Piston Velocity**

<table>
<thead>
<tr>
<th>INTERVAL</th>
<th>cm/sec</th>
<th>ΔK.E., J</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>96</td>
<td>0.16</td>
</tr>
<tr>
<td>B</td>
<td>460</td>
<td>3.5</td>
</tr>
<tr>
<td>C</td>
<td>613</td>
<td>2.9</td>
</tr>
<tr>
<td>D</td>
<td>807</td>
<td>4.8</td>
</tr>
<tr>
<td>E</td>
<td>400</td>
<td></td>
</tr>
</tbody>
</table>

**Displacement, cm**

**Pressure-Pulse Data**

- Delayed Pulse 2420 msec after peak power
- Pulse amplitudes in MPa

**Time after peak power, msec**

30, 35, 40, 45, 50, 55

Fig. 8. Results for Test S-4
Fig. 9. Results for Test PBE-12S

Fig. 10. Thermodynamic Paths for Small- and Large-Scale Events

Fig. 11. Superheated Droplet Diameter Versus Delay Time

Fig. 12. Pressure Versus Time for Bubble Growth
Fig. 13. Small-Scale and Large-Scale Vapor Explosion Criteria
Discussion on Paper FCI4/P21

W J Camp
We cannot necessarily rule out your analysis of 12-S. However, we believe that all our evidence points to UO₂ being the discontinuous phase. It is very hard to postulate enough UO₂ in a single particle to entrap the quantity of sodium to which you refer. In PEE-98 the "triggered FCI" has a measured pressure of 32 MPa. Have you attempted to calculate this result? (We calculate a 3.7 MPa pressure at the transducer from deceleration of the slug using the HONDO wave propagation code.)

R W Henry
In the CAMEL loop experiments, UO₂ is also initially the discontinuous phase, but the pulse X-ray movies show that local accumulation of molten UO₂ can rapidly occur. In addition, the analysis presented in this paper considers only the spherical droplet. In the PEE test, it is possible for the fuel to fall in more than one location and thus trap quantities of sodium between the molten fuel layers. This increases the amount of sodium available and decreases thermal response time of the entrapped sodium since it is in a nonspherical geometry. With respect to PEE-98, Fig. 4 in Paper FCI4/P25 shows the measured pressure to be 28 MPa and with a maximum piston velocity of approximately 15 m/s, the sodium impact pressure resulting from such a velocity is very close to the measured value. Consequently, the key is to determine whether such pressures are a figment of the experimental configuration itself or an "FCI". The experimental configuration and the instrumentation do not allow this determination.

S J Board
The implication of your calculations is that if the energy yield of an event exceeds that given by Fig. 11 it cannot be a superheat event. I am sure that a number of in-pile tests, e.g. TREAT, produced energy yields well on the wrong side of your curve. Also the Argonne experiment dropped UO₂ into sodium and produced, if I remember correctly about 10J with dwell times very much shorter than your minimum of 15 ms. Therefore, they could not have been single drop superheat events.

R W Henry
The available TREAT experiments, S-series, E-series, and H-series are in good agreement with Fig. 11 in those events which are not related to fuel vapour pressure (the pulse produced by bursting the pin). The energy release estimates for the UO₂-Na out-of-pile experiments vary by two orders of magnitude depending upon the method of evaluation. The calculations given in the paper lie within the estimates and the impulses calculated in the paper are in excellent agreement with the measured impulse.
SESSION V

FCI Studies Directly Related to Reactor Conditions

Chairman: L Caldarola
Secretary: R C Burnett
Paper presented at the 4th Specialist Meeting
on Fuel Coolant Interactions

OECD - CSNI - Bournemouth U-K

2-5 April 1979

\[ \text{U}_2\text{O}_3 - \text{Na INTERACTIONS}
\]

THE CORECT II EXPERIMENT

by

M. AMBLARD*
G. BERTHOUD*

*CEA-CENG, DTCE/STT/STML
UO₂-Na INTERACTIONS
THE CORECT II EXPERIMENT

by

M. AMBLARD
G. BERTHOUD

- ABSTRACT -

The results of CORECT II experiments - which is of the shock tube type - are presented. The influence of the interaction zone constraint is emphasized and fragmentation results are related to the observed effects.
0. INTRODUCTION

All over the world, many experiments involving molten UO$_2$ and sodium have been carried out. A fine fragmentation of the fuel is usually obtained but the conversion of thermal energy in mechanical work is never observed. This may be due to 2 things: either the interaction does not happen or the loop is not able to allow the observation for this mechanical energy.

A way of appreciating this energy is to use a geometry of the shock tube type. A loop, trying to approach this kind of contact mode, was built in Grenoble: it is the CORECT II experiment.

1. DESCRIPTION OF THE LOOP

With this device, we bring into contact about five kilos of molten uranium dioxyde and a sodium column of about 100 litres. The geometry of this column was chosen to simulate the height of sodium above the interaction zone in a reactor (figure 1).

The fuel is melted in an induction oven (high frequency).

The instrumentation includes:

- Measurements of transient pressure around the interaction zone, ($P_1$ and $P_2$) in the sodium column and in the cover gas,
- Flowmeters in the sodium column, ($D_9 - D_{10} - D_{11}$) (height = 5 m; diameter: 14 cm)
- Many thermocouples (T)

By using directly the pressure and flow measurements, we can derive ($fPdV$) the mechanical work resulting from the expansion of the interaction zone with realistic constraints.
After the test, the sodium is evaporated so we can gather the fuel debris and study its granulometry.

2. EXPERIMENTAL PROGRAM

Up to now, 20 tests have been run. In these experiments, we varied:

- the sodium temperature in the column,
- the molten fuel mass,
- the conditions of contact by changing the geometry of the interaction chamber.

2.1. Experimental results

Test 12 B was singled out from the first fourteen tests, since it seemed the most typical.

Initial conditions

<table>
<thead>
<tr>
<th>Tests n°</th>
<th>UO₂ Mass (kg)</th>
<th>TNA (°C)</th>
<th>Residual Gas Pressure (mb)</th>
<th>Interaction Chamber Volume (l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 B</td>
<td>4,155</td>
<td>600</td>
<td>10</td>
<td>13,37</td>
</tr>
<tr>
<td>15</td>
<td>-</td>
<td>620</td>
<td>30</td>
<td>13,37</td>
</tr>
<tr>
<td>16</td>
<td>6,758 kg</td>
<td>644</td>
<td>10</td>
<td>13,37</td>
</tr>
<tr>
<td>17</td>
<td>2 kg</td>
<td>726</td>
<td>135</td>
<td>11,17</td>
</tr>
<tr>
<td>18</td>
<td>4,925 kg</td>
<td>685°C</td>
<td>12</td>
<td>7,76</td>
</tr>
</tbody>
</table>

The different contact modes investigated are the following: (figure 2).
Mode I: low constraint in the interaction zone. The sodium can expand freely after vaporizing without expulsing the sodium column.

Mode II: moderate constraint in the interaction zone

Mode III: high constraint in the interaction zone

Mode IV: very high constraint in the interaction zone

Mode I was used for experiments 1 to 14, and the whole mass of UO₂ (liquid plus external solid crust) contained in the HF fusion oven was transferred in the interaction chamber.

Mode I was also used for experiment 16, but only the liquid UO₂ was transferred.

Mode II was used for experiment 17.

Mode III was used for experiment 18.

Mode IV was used for experiment 19.

Mode I was used for experiment 15 but without UO₂ in order to study the "water-hammer" effect.

2.1.1. Test 128

Figure 3 shows the fall of the sodium (D₁₁). The sodium is expelled at a maximum speed of 1.99 m/s, whilst the fall-speed was 1.53 m/s. A very low energy gain, due to a thermal effect on the column, is thus obtained (Δ \(\frac{1}{2} mV^2\) = 65 J).

The recorded pressure-peak (figure 4) shows spikes during the rise that can be attributed to local thermal effects.
2.1.2. Test 15 : "water-hammer" test (figures 5, 6 and 7)

The energy gain during the first expulsion is negative (fall-speed : 1.50 m/s; expulsion : 1.31 m/s).

The flow shows spikes during the fall, (figure 6) as in the experiments with UO₂.

The pressure peak (43 bars) is perfectly symmetrical showing no oscillation, unlike test 12 b.

This pressure peak value (43 bars) does not appear to be representative of the "water-hammer" effect for all the tests, since it is closely related to the residual gas volume whose measurement was relatively vague.

2.1.3. Test 16 (figures 8 - 12)

The sodium is expelled at 2.22 m/s with a fall of 1.53 m/s; a slight energy gain is thus obtained ($\frac{1}{2} mV^2 = 100$ J), and in particular figure 8 shows discontinuity in oscillation durations :

- 1st pressure peak : 35 bars with high spikes during the rise (figure 9)
- 2nd peak : very high discontinuities whose values are superior to the overall pressure evolution

This test, which may be considered purer than test 12 b, highlights strongly heat transfers between UO₂ and sodium by local pressure measurements reaching 120 bars but with virtually no energy effects.
2.1.4. Test 17

This test, the only one with mode II, gave the strongest sodium ejection: 14 m/s i.e. \( \Delta \frac{1}{2} mV^2 = 8 \text{ KJ} \), with a measured mechanical energy \( \int PdV \) of 3.7 KJ.

During the \( \text{U}_2 \text{O}_2 \) transfer some water entered the interaction chamber. A minimum of 11.17 litres of dry steam at 135 mb and at a maximum temperature of 726°C; this corresponds to 0.3 g of water; which, reacting with sodium, may explain the energy obtained.

2.1.5. Test 18 (figures 12, 13, 14)

Carried out with mode III, this experiment gave:

- a high expulsion of the sodium (7.6 m/s)
- a 2 phase pressure peak of 69 bars and 40 ms duration, in the interaction chamber.

Another important point is that sodium vapour reached the pressurization chamber whose pressure rose from 1.3 to 2.5 bars. The vapour expansion can be seen on the magnetoscope due to its radiative effect.

No \( \text{U}_2 \text{O}_2 \) debris was found in the pressurization chamber after the experiment. For the first expulsion, the measured mechanical energy was 18 KJ.

2.1.6. Granulometric study

The particle mass distributions as a function of their diameter for tests 12 B, 16, 17 and 18 are shown in figure 15, as well as the two limits defining the area dealt with in the out-of-pile experiment PNC-ANL and in the in-pile experiment TREAT and SPERT (I) and (II).
The following observation can be made: the higher the heat transfer, the finer the fragmentation, as the following table shows.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>&lt; 100 μ</th>
<th>&lt; 250 μ</th>
<th>&lt; 1 mm</th>
<th>average diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 B</td>
<td>2 %</td>
<td>11 %</td>
<td>22 %</td>
<td>2.2 mm</td>
</tr>
<tr>
<td>16</td>
<td>7 %</td>
<td>12 %</td>
<td>26 %</td>
<td>1.8 mm</td>
</tr>
<tr>
<td>18</td>
<td>10 %</td>
<td>38 %</td>
<td>55 %</td>
<td>1 mm</td>
</tr>
</tbody>
</table>

However, the curves are still included in the area defined by Mizuta (1) and limited by curves I and II in figure 15.

2.2. Analysis

The integration of the sodium mass falling into the chamber should enable the partial pressures of the residual gas and of the sodium vapour formed to be calculated.

Test 15 (without hot UO₂) shows that the chamber is almost filled (integrated value: 12.5 l; available volume: 12.5 l). For test 18, this method gives the following results:

- available volume in the chamber: 7.14 l
- volume introduced when the column stops: 6.6 l
- residual volume: 0.54 l

With isothermal compression, 0.16 bars of gas pressure is obtained. The 69 bars measured thus represent the vapour pressure of the sodium formed. Using the following optimistic hypotheses:

- the vapour formed is saturated with a vapour fraction of 1
- the heat transfer is stopped after the 1st pressure maximum
The minimum mass of vaporised sodium is obtained (i.e. 7.67 g for \( T = 1950^\circ C \) with a specific mass of 0.0142 g/cm\(^3\)).

In order to vaporise this sodium with an initial temperature of 685°C a thermal energy of 35 KJ was necessary. This represents the minimum thermal energy transferred to the sodium.

For tests 12 c and 16, the pressure peaks (duration ~ 10 k.ms) can be attributed to residual gas compression.

The calculation of the gas residual volume (initial volume minus the introduced volume) is not precise to allow a direct interpretation from experimental results.

3. CONCLUSION

The observed effects in the CORECT II experiment appear to be strongly influenced by interaction zone constraint. Thermal effects, seemingly due to quite different phenomena, are also observed. In test 16, for example, very short but very high pressure peaks are observed, whilst in test 18 sustained pressure peaks are obtained. It is at the present time difficult to foresee what kind of phenomena will arise. The reproducibility of the tests carried out must therefore be studied before any other changes in the parameters can be undertaken.

--- REFERENCE ---

(1) H. MIZUTA,
Fragmentation of \( \text{UO}_2 \) after molten \( \text{UO}_2 - \text{Na} \) interaction,
Fig. I: CORECT II

A : Melting chamber
B : Interaction chamber
C : Valve A.B
D : Sodium column
E : Pressurization chamber
F : Tube d’amenée Na
G : Valve D.F
K : Thermal shield  Ø 300

Ø 1200/1216
590
370
sodium levels
Ø int. 146.3
Ø ext. 168.3
562
245
1140
Ø 50/85
Ø int. 129
Fig. 2

Mode I

$V_0 + V_1 = 13.371$ - Vol $\text{UO}_2$

Mode II

$V_2 = 5.61$

$V_4 = 5.571$ - Vol $\text{UO}_2$

Mode III

$V_1 = 1.41$ - Vol $\text{UO}_2$

$V_2 = 5.61$

$V_3 = 0.761$

Mode IV

$V_1 = 1.41$ - Vol $\text{UO}_2$

$V_2 = 5.61$

$V_3 = 0.071$

CEA/CENG

DTCE/STT

STML
Fig. 4
Fig. 5
CORECT II
N.16

PIC NO 2

Fig. 11

P 2

Secondes
Milli-S
Micro-S
Periode

0
814
800
100US
bar

-50.00
-45.00
-40.00
-35.00
-30.00
-25.00
-20.00
-15.00
-10.00
-5.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00

33600 33800 34000 34200 34400

10 ms
CORECT II
N. 18

Fig. 13

CEA/CENG
DTCE/STT
STML
Fig. 15: UO₂ particle size distribution

<table>
<thead>
<tr>
<th>Mean diameter</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 mm</td>
<td>6.0</td>
</tr>
<tr>
<td>0.65 mm</td>
<td>7.9</td>
</tr>
<tr>
<td>2.2 mm</td>
<td>6.29</td>
</tr>
<tr>
<td>1.8 mm</td>
<td>7.83</td>
</tr>
</tbody>
</table>

% mass distribution vs. particle diameter (mm)
Discussion on Paper FCI4/P22

R S Peckover
Could you tell us what indications you have in the type III mode for CORECT 2 that the top surface of the UO₂ is still in a molten state?

M Amblard
The crucible to melt the UO₂ has a 15cm diameter hole for bottom pouring. When the UO₂ is liquid it is released to make contact with the sodium. The approximate delay time for contact is 5 seconds.
Simulation of the CORECT II Experiment No. 18
with the MURTI Computer Programme

by H. Jacobs

Institut für Neutronenphysik und Reaktortechnik
Kernforschungszentrum Karlsruhe

Address: H. Jacobs
Kernforschungszentrum Karlsruhe - INR
Postfach 3640
D-7500 Karlsruhe 1

Revised July 1979
1. Introduction

The fuel coolant interaction (FCI) experiment CORECT II No. 18 /1/ is very interesting because it used actual reactor materials, i.e. uranium dioxide and sodium, and because, in contrast with most other experiments of this type, it produced a relatively high amount of work. Furthermore, it is a well characterized experiment in that some of the important initial conditions are known or at least fixed within a reasonably narrow range. Also, the work done by the interaction has been measured, even as a function of time, by recording the pressure as well as the expansion history. In this paper an attempt to interpret this experiment on the basis of model calculations performed with the MURTI code /2,3/ is described. These calculations give information on a possible sequence of events during the experiment, they make the importance of various experimental conditions evident, and they provide guidance in applying the experimental information to situations with different boundary conditions. The last point can also be expressed in a different way: The successful duplication of the experimental results with the code allows the calculation of the consequences of FCIs with this code with much more confidence under similar conditions. This investigation is in fact a first step towards an experimental verification of the code.

The FCI model, which was programmed as the MURTI code, is especially suited for such a study because it allows the inclusion of many effects that may be necessary to be accounted for in a meaningful description of an experiment or an accident situation, such as vapour blanketing, continuous fragmentation, inhomogeneous mixing zones, cushion gas in them, or heat losses from them. Not all of these options actually have been used for the sake of keeping the number of parameters small. Also, in contrast to most other models, the treatment of the sodium allows for temperature gradients in the sodium and a completely free sequence of states, instead of assuming a liquid phase followed by a vapour phase.

After a short description of the experiment, emphasising those aspects which are important for the analysis, some details of the modelling are discussed, especially those in which the original model had to be adjusted to the experiment. The chapter on the results begins with a presentation of the nominal case which gave the best agreement with the experiment and a discussion of the picture of the interaction that evolves from the calculation. After that, the choice of the parameters and the consequences of alternate choices are discussed. Finally, before the conclusions from this study are listed, special emphasis is devoted to two cases which show a tendency of sodium to act essentially as a heat dissipator under conditions which may be encountered in safety analysis.

2. Experimental conditions

Figure 1 shows the interaction pot and part of the sodium fill tube through which also the expansion took place. The fuel mass of 4925 g entered the interaction pot from the top and was collected in the fuel
catcher. After that, the interaction pot was closed and evacuated and then the loading sodium column was released so that it filled the feed tube and the interaction pot. First contact of fuel and sodium led to pressures in the range of 5 to 20 bar. These stopped the falling sodium column when 6.6 l of sodium had entered the system 'tube plus pot'. So, about 4.2 l had entered the pot and about 1 l was above the rim of the fuel catcher, i.e. directly available for interaction. At the same time the free volume amounted to 7.76 l - 6.6 l = 1.16 l which are to be reduced by the volume of the fuel. If we assume that it had a temperature of 3100 K (we only know that it was molten when it drained from the crucible into the catcher), it occupied about 0.56 l. So, the free volume amounted to about 0.6 l. The initial temperatures of the sodium and the structure material were 987 K and 958 K respectively.

About 30 msec after first contact of fuel and sodium, the pressure started to increase quickly, reaching 70 to 80 bar after about 10 msec. After a broad maximum which could be the superposition of two peaks of shorter duration, the pressure decayed in a roughly exponential manner with 20 msec width at half maximum. (In Figure 3b this pressure-time history is shown in a rather rough way by a curve drawn with the help of a hand-made stencil. This curve only reflects the general behaviour of the pressure.) The interaction pressure caused the ejection of the sodium with a maximum measured speed of 790 cm/sec in a wide tube which correspond to 6750 cm/sec in the feed tube. Nevertheless, the volume ejected during the initial 40 msec amounted to about 4 l only. So, during the essential part of the interaction, the feed tube remained completely filled and the constraint consisted of the sodium in this tube of radius \( r_1 = 2.5 \) cm and length \( l_1 = 114 \) cm (including valve and upper connecting piece) and that in the wide vertical tube of \( r_2 = 7.315 \) cm and \( l_2 = 500 \) cm. The pressure in the upper sodium reservoir (pressurizer) during the time under discussion remained constant at 1.3 bar.

3. Modelling of the experiment

3.1 Inhomogeneous interaction region

A special feature of this experiment is the fact that the sodium is flowing relatively slowly on the fuel and no external force like an external pressure or an initial momentum forces the two materials together. So, one must expect that the interaction develops slowly.
and especially in the beginning is highly incoherent, i.e. in different places within the interaction pot the interaction presumably is in different stages of development. The model programmed in the MURTI code is able to describe such situations by dividing the interaction region into subregions with individual interactions. But such a procedure contains many free parameters. Therefore, this feature was not used in this first study of the experiment. Consequently, in the model calculations, only representative masses of fuel and sodium are considered and they are used to describe the mean behaviour of the interacting masses. In that sense, the interaction region is modelled as homogeneous.

3.2 Initial free volume

A second important feature of the experiment is the free volume which is available in the interaction pot when fuel and sodium first contact each other. With the model in its original form, such a void space could only be modelled by a gas cushion. But since the amount of non-condensable gas present actually has been very small (the interaction pot had been evacuated to 12 mbar), this model assumption seemed not to be adequate. In preliminary calculations /4/ the void space had been modelled by eliminating any single-phase pressures by adjusting after each time step the volume of the first sodium cell (the one at the fuel/sodium interface) in such a way that it stayed close to the saturation line as long as it was on its all-liquid side. Since the volume needed for that was smaller than the available volume, the calculations proved that the free volume was able to remove single-phase pressures. But this method completely neglected the presence of the free volume not occupied by the thermally expanding liquid sodium and the effect which the vapour in the free volume had on the heat transfer process. Therefore, in this study another method was adopted.

In the following one should remember that the sodium in this model is treated as a heat-conducting and compressible liquid and that the representative masses of fuel and sodium for the purpose of the model calculation are rearranged in a one-dimensional scheme as illustrated by Figure 2 and that the state of the sodium is space dependent. (In this figure the fuel and structure material which will be discussed in the next paragraph are shown by thin lines to indicate that they are not taken into account in the hydrodynamic calculations.) Also, liquid and vapour are assumed to be homogeneously mixed in each cell. It is therefore very important in which location within the sodium the initial void space is assumed. Actually, it was introduced at the fuel/sodium interface, i.e. in the first sodium cell, by expanding this cell artificially by an additional velocity which decreased linearly from its initial value \( v_0 > 0 \) to zero within 4 msec. This means that the usual 'left hand' boundary condition for the
sodium motion (equation B. 70 in /2/)

\[(v)_{k+1/2}^0 = 0\]

is used only when \(k\Delta t > 4\) msec. (The superscript denotes location, the subscript the time.) Before that it is replaced by

\[(v)_{k+1/2}^0 = -\frac{V_0}{A}(1-k\Delta t/4\msec).

This procedure is considered to be conservative, because in this way the initial free volume or that part of it that is taken in account reduces the fuel to sodium heat transfer as much as possible and a correspondingly large fuel surface must be assumed if a given pressure level is to be reproduced.

3.3 Heat dissipation and heat losses

In the very beginning of this study it became clear that heat losses from the interaction region were very important for this experiment. Heat losses can be modelled in MURTI by adding some heat-conducting but otherwise inert material at the end of the sodium opposite to the fuel. The thermophysical properties of this so-called structure material, i.e. density, specific heat, and thermal conductivity, as well as its mass and its cross-section which equals its contact surface with the sodium can be chosen independently. Of course, as a consequence of the arrangement of the materials, any heat that is transferred to the structure material must have been passed through the whole body of the interacting sodium. In the model this is done by heat conduction only and in its original formulation it assumed that sodium vapour reduced the local thermal conductivity wherever it appeared in the sodium (see discussion in /3/). Thus, e.g. the two-phase layer at the fuel/sodium interface tended to insulate itself as well against the hot fuel as against the bulk of the sodium, which in many cases remained much cooler. But with this assumption, it was impossible to reproduce the fast temperature changes which can be inferred from the observed fast vapour pressure changes. Therefore, the model was changed by assuming a thermal conductivity of liquid sodium, 0.57 W/(cm*K), for all the sodium except that in the first cell, so that the presence of vapour in other locations only decreases the temperature gradient by increasing the distances.

In the first sodium cell, two things are done: For the calculation of the heat transfer from fuel to sodium, the original model assuming a considerably reduced mean thermal conductivity of the two-phase mixture (its definition is given in the Appendix) is used. In the calculation of the heat transfer to the second cell (i.e. the bulk of the sodium) the insulating effect of the sodium vapour is reduced by multiplying the first term in the dominator of equation B. 44 in /2/, which is

\[\frac{\delta Z}{\lambda}, \text{ by } \left(\frac{\delta Z_0}{\delta Z}\right)^2.\]
These assumptions lead to almost uniform temperatures within the sodium, with the consequence that vapour formation in the bulk of the sodium has a much higher probability than in the original model. The interpretation of the modified heat conduction model could be that the vapour does not reduce the local thermal conductivity within the sodium or equally well that vapour or even liquid sodium are moving around quickly, thus providing a fast heat exchange within the interaction region (heat pipe effect). One should note that none of the models that assume a uniform interacting sodium from the beginning, could have detected the necessity of such an assumption.

3.4 Constraint

In the light of the 10 msec pressure-rise time it is obvious that the inertial constraint approximation is to be used throughout. As outlined in chapter 2, the interaction region expands by pushing sodium out from the interaction pot through a tube of 20 cm² cross-section. For the model calculations this has been taken as the reference flow cross-section. Therefore, with respect to acceleration, the effective length of the loading sodium column is

\[ l_0 = l_1 + a \ l_2 = 169.9 \text{ cm} \]

with \( a = (r_1/r_2)^2 = 0.1168 \)

Furthermore, under the experimental conditions, we have to take into account the pressure increase at the cross-section increase (Bernoulli's law)

\[ \delta P = \frac{\rho_0}{2} (1 - a^2) \ u^2 \]

and the frictional pressure loss of the whole system

\[ \delta P = - \rho_0 \ a \ u \ |u|. \]

The coefficient \( a \) has been derived from the constant negative velocity during the descent of the sodium column. During this period the acceleration term vanishes and the pressure difference just equals the sum of the \( u^2 \) terms. We thus have:

\[ \delta P = \rho_0 u^2 \left( \frac{1 - a^2}{2} + a \right) \]

With \( \delta P = 1.69 \text{ bar} \) (1.3 bar in the pressurizer plus 0.39 bar gravitational pressure head), \( \rho_0 = 0.781 \text{ g/cm}^3 \), and \( u = -1096 \text{ cm/sec} \) (-1.28 m/sec in the wide tube) we find \( a = 1.31 \). Since for the ejection case, the Bernoulli term has to be subtracted, we finally get:

\[ \frac{dv}{dt} = \frac{1}{l_0} \left[ \frac{1}{\rho_0} (P - P_\infty) - 0.82 \ u^2 \right] \]

538
3.5 Thermophysical data

For the fuel a specific heat of 0.548 J/(g·K) and a thermal conductivity of 0.030 W/(cm·K) were assumed. The corresponding values for the structure material (steel) are: 0.75 J/(g·K) and 0.42 W/(cm·K). The latent heat of melting of the fuel is 282 J/g. The temperature dependent thermophysical data of the sodium still assumed a critical temperature of 2850 K (see /3/) but this can be tolerated because the actual sodium temperatures remained below 2100 K, i.e. in a region where only minor changes are necessary to adjust the data to the new determination of the critical point /5/.

4. Results

4.1 Nominal case

The best fit to the experimental pressure-time history was obtained using the following assumptions: The fuel has a mass of 4918 g (in the model the volume has to be defined and the density is a function of the temperature), an initial temperature of 3100 K, and a density of 8.75 g/cm³. Its surface increases linearly from 4000 cm² to 6.0 m² within 10 msec. The interacting sodium has a volume of 1.0 l and with a density of 0.781 g/cm³ this gives a mass of 780.7 g. Its initial temperature after the measurements is 987 K. The structure material has a mass of 21 kg, a density of 7.0 g/cm³ and a (measured) initial temperature of 958 K. Its contact surface to the sodium which equals its cross-section is 2400 cm². The free volume is 319 cm³. The choice of these parameters will be discussed in a separate paragraph below.

The pressure-time history obtained with the parameters given above is shown in Figure 3a and compared to the experimental one in Figure 3b. There is good agreement between these two with respect to the pressure rise rate, the maximum value, and the width of the peak. The agreement

![Diagram a) nominal case](image1)

![Diagram b) nominal case and experiment](image2)

Fig. 3: Pressure-time histories
is less satisfactory during the pressure drop, possibly because the experimental geometry starts to change already during that period due to voiding of the sodium tube which rapidly exposes cold surfaces to the hot two-phase sodium. Also one realizes that the initial pressure oscillations are not described by the homogeneous model.

Figure 4 shows the measured and calculated velocity histories. It can be seen that the initial acceleration is higher in the experiment due to the pressure of the preceding local interactions which are not modelled. Again the maximum values and the general shape of the curves agree quite well. Of course, the exact value of the calculated maximum velocity depends on the friction coefficient, the determination of which from the experimental data is rather uncertain. So, also the maximum velocity is uncertain by about 10%.

Figure 5 shows the calculated temperature histories at the centers of those cells of fuel and sodium that contact each other. From this figure it can be seen that heat exchange starts in the very beginning but is stopped by the introduction of the void space at the interface. So, both temperatures almost return to their original values. Then, when the void space is complete and the fuel surface continues to increase, the temperatures again start to approach each other. During this period also a redistribution of the void space within the sodium takes place, which reduces the vapour mass.

Fig. 4: Velocity-time history: nominal case

Fig. 5: Temperature-time history: nominal case
fraction in the first sodium cell. After about 25 msec this leads to an increased heat transfer rate and a pressure build-up which in turn causes expansion and new vapour formation so that the heat transfer rate again is decreased. As a consequence, the fuel surface is reheated due to temperature equilibration within the fuel and we finally see a slowly decreasing bulk fuel temperature. Within the sodium, the temperature gradient is less pronounced throughout the interaction. After the re-formation of the insulating vapour layer, the heat losses to the structures, which have increased with the sodium temperature, override the heat input. Therefore the sodium temperatures start to decrease. Besides the heat losses, other modes of reducing the sensible heat, i.e. conversion into latent heat of vaporization and mechanical energy are negligible.

In the end, 3910 kJ of heat have been delivered by the fuel (its temperature then is about 2165 K) and 3295 kJ (84 %) have been lost to the structure material of which nonetheless 60 % are below the boiling point of sodium at 1.3 bar, i.e. 1183 K. The work done by the sodium amounts to 16.8 kJ. Since the pressure is still 12 bar, some additional work is to be expected and a total specific work of 4 J per gramme of fuel can be inferred. In comparison with 1378 J available per gramme above 1100 K this gives a conversion coefficient of 0.29 %.

The pressure-time history observed in this experiment is rather insensitive to the ejection history. Merely it is controlled by the varying conditions of heat input to and heat losses from the sodium. This is indicated by the high fraction of heat which is lost to the surroundings (already at the time of maximum pressure it amounts to 65 %) and the fact that the calculated pressure-time history remains essentially unchanged when further expansion of the interaction zone is artificially suppressed after it has reached the volume which in the experiment is present initially. (In that case, only the pressure decay is slowed down due to a higher heat input rate during that period.) This means that the actual confinement is almost equivalent to a fixed volume.

The confinement within the interaction pot appears to have provided the tens of milliseconds of contact between fuel and sodium, which were necessary to heat the sodium sufficiently, after the materials had been intermixed without important pressure build-up. The latter may have been possible only in the presence of the large initial free volume. Indeed, the pressure spikes produced by the (probably local) interactions following first contact of fuel and sodium are very similar to that observed in the ANL experiment M5 /6/ (see also paragraph 4.3) in which the interaction is completely unconfined. Apparently small-mass interactions in unconfined systems produce very short (a few milliseconds) pressure bursts with maximum pressures in the range of 10...20 bar. The important point is that in the CORECT II experiment no. 18 these premature interactions have occurred so late that they couldn't prevent the mixing of a larger fuel mass (see next paragraph) with a corresponding sodium mass. During the ensuing confined medium-mass interaction, the heat transfer on an average occurred in a two-phase process. The interaction, therefore, may be called 'confined boiling'.
Following the model calculations, the pressure rise is caused by a transient increase of the heat flux density which quenches itself by prompt vapour formation. (In the presence of the strong confinement, this prompt quenching is possible only due to the presence of the internal free volume.) In these calculations the heat flux density increases due to a transient thinning of the insulating two-phase layer at the fuel-sodium interface. But it may well be imagined that a similar effect could be produced by a transient increase of the fuel surface (fragmentation) as it has been done in preliminary calculations /4/ or the contact surface (intermixing) with the heat flux density remaining more or less constant until the rising sodium temperature leads to additional vapour formation. So, the model description presented here must be regarded as just one possibility. Furthermore, heat transfer through a homogeneous two-phase layer is used to model a combination of processes occurring concurrently at different locations, such as conduction through a vapour layer, intermittent liquid-liquid contact, and evaporation of sodium films. And despite the simple model geometry, the partial removal of the insulating two-phase layer in the model is a consequence of complex motions within the column of a compressible and volatile fluid modelling the interacting sodium. One contribution stems from small pressure spikes following complete re-condensation in one cell, which largely must be considered as modelling effect. Another contribution arises from a relatively small downward acceleration of the loading sodium column. Initially it is assumed at rest. But when, in the beginning, the still unheated sodium is forced to evaporate by forming the void volume, its vapour pressure is about 1 bar lower than the constant external pressure. Finally, a very important contribution comes from thermal expansion of the interacting sodium, which is illustrated by two facts: at the time of maximum pressure, the sodium has about 2000 K and its specific volume is 46% larger than at 987 K. At the same time, the volume occupied by thermal expansion of the liquid sodium is more than twice the volume gained by ejection of the loading sodium column.

4.2 Discussion of parameters

The constraint and the initial temperatures have been chosen in accordance with the available experimental information and have not been varied. With respect to the other parameters at the best upper limits are known. Three of these essentially unobservable parameters directly control the heat transfer rates and therefore have a critical influence on the pressure-time history: the amount of void volume or vapour that initially is formed at the fuel/sodium interface, the fuel surface area, and the surface area of the structure material. Obviously the heat remaining in the sodium and therefore its pressure can be increased by increasing the fuel surface area, or decreasing the amount of vapour, or decreasing the surface area of the structure material. Therefore, a rather close fit to the experimental result can be obtained with different parameter combinations and from the model calculations one cannot deduce a single set of parameters which could be interpreted as experimental evidence of the values of the unobservable parameters. However, higher values of the fuel surface area combined with larger void volumes tended to slow down the pressure decay.
Smaller void volumes could not be used because they led to single-phase pressurization. And the value assumed for the surface area of the structure material (2400 cm²) is already so large that it can only be justified by pointing out that the heat loss model is rather poor in that it assumes that the heat must always be transferred through all the interacting sodium, while in reality most of the vapour flows away, leaving fuel and heat sink in close proximity. Yet, this large value had to be used in order to bring down the pressure fast enough.

In the nominal case, the maximum possible masses of fuel and sodium were assumed to interact. But from the experiment we know that only about one third of the fuel was fragmented into fine particles (radius smaller than ~0.13 mm). These were found distributed all over the interaction pot and in the sodium tubes. In contrast to that, a similar amount of mass was found in the fuel catcher. Its particle spectrum differed significantly from the remaining fuel in that large particles (radius several millimeters) prevailed /7/. This could indicate that about one third of the fuel had interacted properly and that the mass which had remained in the fuel catcher essentially had not been involved in the interaction. In order to check these possibilities, the fuel mass was varied. In the first instance, the fuel mass considered in the nominal case was reduced to 1750 g (36 %) while all the other parameters, especially the fuel surface, were held constant. Figure 6 shows the resulting pressure-time history. Besides the low pressures it is essential to note that after 75 msec the whole fuel has cooled down to about 1327 K. Obviously, under the assumed conditions, such a small amount of fuel is not able to sustain a vapour pressure peak as high and broad as observed.

As outlined above, higher pressures can be obtained by increasing the fuel surface area or decreasing the structure material surface area. But before the maximum vapour pressure reached 70 bar, single-phase pressures occurred. To prevent this, the amount of interacting sodium was reduced to 62.5 % so that less volume was needed for its thermal expansion. But at the same time, this further reduced the vapour pressures by increasing the heat losses. If only the sodium mass, considered in the nominal case, is reduced to 62.5 %, the peak pressure drops to 29 bar and in order to reproduce the measured maximum pressure, the surface area of the structure material must be reduced to 1120 cm² – a value which looks much more reasonable than the original one. Using the reduced sodium mass and varying the surface area of the structure material, it was possible to duplicate the measured pressure-time history essentially as well as in the nominal case assuming

a) fuel mass 3273 g (66 %) and surface area 912 cm²
b) fuel mass 1750 g (36 %) and surface area 323 cm².
The calculated pressure-time histories are compared with the measured one in Figure 7. So, the calculations themselves do not exclude the possibility of only fractions of the fuel taking part in the interaction. However, the value of the surface area of the structure material which must be used in conjunction with the 36% of fuel is much smaller than the surface area available in the upper part of the interaction pot and, therefore, seems to be too small. After all, in the homogeneous model (see paragraph 3.1) the heat transfer through a two-phase region is used to model on average the behavior of a larger mass, while the actual interaction is highly incoherent in space and time. Furthermore, during the development of the pressure peak, the interacting masses are completely contained within the interaction pot so that it is hard to imagine that part of the fuel could be separated from liquid sodium. Perhaps this could happen to the fuel in the fuel catcher at times after the period which is considered in these calculations, when most of the liquid sodium has been ejected from the interaction pot and the part of it which had got into the fuel catcher has been vaporized completely. (In the end of each calculation, the fuel temperature is close to 2000 K.) In conclusion, it appears to be neither necessary nor justified to exclude a noteworthy part of the fuel from the interaction.

The total mass of structure material has simply been chosen so large that in none of the cases presented here its finiteness played a role. This should correspond to the real situation in which also the thickness of the thermal boundary layer that develops within the tens of milliseconds under discussion is small compared to the wall thicknesses of the various components. (If the temperature of the surface of the structure material is suddenly increased by \( \Delta T \), a layer of 1.14 mm is heated by more than 0.2 \( \Delta T \) within 50 msec, see equation 2.2 in [2].)
Figure 8 shows the effect of varying the initial free volume in the nominal case. This means that at the same time the void volume available in the model and the initial thickness of the insulating two-phase layer are varied while it is assumed that the degree of fragmentation and intermixing does not depend on the void volume. Under these conditions its reduction to about 300 cm³ leads to the superposition of a single-phase pressure peak on the rising flank of the vapour pressure peak. Of course, in this case the void volume must be interpreted as total free volume, whereas it is to be interpreted as that part of it that contributes to vapour blanketing, if the system remains in the two-phase state. In the two other cases, the void volumes are larger than in the nominal case and correspondingly the maximum pressures are much lower.

The time period during which the fuel surface increases ('fragmentation time') has very little effect on the result of the calculations when it is varied in the range of about 7... 20 msec. And its influence outside this range seems to emerge from interference with the way in which the presence of the void volume and its effect on the fuel to sodium heat transfer are modelled.

The parameter variations have shown that the cases reproducing the experimental pressure-time history are marginal in two respects: on one side they just avoid the single-phase state. On the other side, the maximum pressure observed in the two-phase state is about the maximum possible (no vapour pressure higher than 90 bar was observed in all the calculations) and slight changes in the assumptions can reduce it by a factor of two (e.g. reduction of the sodium mass in the nominal case). This uncertainty in the prediction of the results is due to the way in which the initial free volume is modelled. Also, in the presence of the latter, it is impossible to derive from the experiment definite information on the unobservable parameters by use of this or any other parametric model. It is even impossible to use a parameter

Fig. 8: Pressure-time histories with different void volumes
set determined here in another model because the ways in which vapour blanketing and the internal motions within the interacting sodium are modelled themselves are very important. On the other hand, the conclusions regarding the nature of the interaction are independent of the special choice of these parameters and so are the results of parameter variations when one of the parameters that give a good fit to the experiment is varied within a certain range. The absolute values may not be fully reliable, but trends are firmly indicated.

4.3 Sodium as energy dissipator

In two cases a relatively moderate variation of a single parameter has led to cases in which the sodium assumed the role of an energy dissipator without acting as working fluid. In the first of these (36% of fuel, Figure 6), it is important that the heat capacity of the heat sink is much larger than that of the fuel and that a high rate of heat transfer to the heat sink has been assumed by assuming a large surface area of the structure material. Therefore the rate of heat transfer to the structure material remains high for a long period while that from fuel to sodium decreases early because the small fuel mass is cooled down soon. In the second case (500 cm$^3$ of void volume, Figure 8), the heat transfer rate from fuel to sodium is strongly reduced due to the thick initial two-phase layer. After 75 msec the fuel has assumed a mean temperature of 2540 K while the mean temperature of the heat sink is 1110 K. This case may be taken as indicative of the behaviour of unconstrained systems. However, the pressure calculated here using a homogeneous model must be interpreted as background pressure. Besides that, local interactions as discussed above seem to be possible and their pressures could be higher (for short periods) than the one calculated here.

Despite the fact that the experiment itself has been designed to simulate the conditions within a single subassembly, the trend indicated by these two derived cases may be applicable to completely different situations, in which the following two basic assumptions are fulfilled: very large initial void volume and important heat sinks present. An example of that is the situation envisaged in the M5 experiment /6/: The simultaneous flow of molten fuel and sodium into a dry cavity below the reactor vessel. In this situation, even the condition of a low fuel to sodium mass ratio might be fulfilled. If such an interaction occurs within a very large free volume, even local interactions producing additional pressure bursts can hardly become effective, since in spherical expansion the pressure decreases proportional to the inverse square of the distance.

5. Conclusions

1. The FCI model that is programmed as the MURTI code has been able to duplicate the experimental results (pressure-time history and ejection history) due to some special features and after a few adjustments to the experimental conditions. Special consideration was devoted to modelling the initially present free volume as realistically as possible. However, this has introduced a certain
degree of indefiniteness which requires due circumspection when
drawing conclusions from the calculations. All the parameters used
are in accordance with the present day understanding of the differ-
ent phenomena.

2. In the presence of the relatively large initial void volume, only
orders of magnitude could be determined for the unobservable param-
eters. The experimental result can be reproduced equally well
using different parameter combinations, because some of them effec-
tively balance each other. But the understanding of the nature of
the interaction evolving from these calculations is independent of
the special set of parameters being used and variations of the re-
\[\text{results following from variation of a single parameter can be relied on as qualitative indication of trends, as far as the model assump-
\text{tions involved are realistic.}

3. The observed interaction can best be described as 'confined boil-
ing', since during the phase of pressure build up it is almost
perfectly confined and all the time the heat is transferred from
fuel to sodium in a two-phase process on average in space.

4. Details of the pressure-time history are determined by the inter-
play of heat transfer from fuel to sodium and heat losses to the
surroundings. The pressure rise is caused by a transient increase
of the heat transfer rate while the pressure decay is due to pre-
dominant heat losses to the surrounding structures after vapour
blanketing has been (re-) established.

5. In the calculations presented here, fragmentation was already com-
p \[\text{plete when the pressure started to rise. The coherent interaction}
mitigated by the presence of the void space (accommodation of
thermal expansion and vapour blanketing). However, the transient
rise in the rate of heat input could also be due to a transient
increase in contact area caused by fuel fragmentation or increase
of interacting masses.

6. The following predictions can be made for changed experiment con-
ditions:
\[\text{a) If the degree of fragmentation and intermixing is not decreas-
ing for decreasing void volume, a single-phase pressure peak}
appears when the initial void volume is reduced below 300 cm\(^3\).
b) If the interaction region (including the void volume) is not
allowed to expand, the pressure-time history remains essential-
ly the same with only the decay being slowed down.

7. Two derived cases in which fuel mass and void volume respectively
are varied moderately, clearly indicate the possibility that so-
dium assumes the role of an energy dissipator rather than acting
as working fluid.

8. Warning: It is impossible to use the values of the unobservable
parameters which are reported here for the sake of completeness in
combination with another model because they strongly depend on the
way in which vapour blanketing is modelled.
Acknowledgement

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Appendix

In deriving the mean thermal conductivity of the two-phase mixture it is assumed /8/ that the mixture consists of identical cubical cells in each of which the liquid portion forms a cube-shaped droplet with its sides parallel to those of the cell. This leads to the following formula (for the meaning of the symbols see the nomenclature):

\[ \lambda = \lambda_v + \Delta \lambda \left[ \frac{1}{\phi} + \left( \frac{3}{\sqrt{1/\phi}} - 1 \right) \frac{\Delta \lambda}{\lambda_v} \right] \]

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Nomenclature

\( a \)  \quad \text{factor in formula for frictional pressure losses}
\( d \)  \quad \text{differential}
\( k \)  \quad \text{subscript counting time steps}
\( l_0 \)  \quad \text{length of loading sodium column in model}
\( l_1, l_2 \)  \quad \text{lengths of tubes in experiment}
\( r_1, r_2 \)  \quad \text{radii of tubes in experiment}
\( t \)  \quad \text{time}
\( v \)  \quad \text{sodium velocity}
\( v_0 \)  \quad \text{initial value of artificial expansion velocity}
\( A \)  \quad \text{area ratio (fuel surface over flow cross-section)}
\( P \)  \quad \text{pressure}
\( P_e \)  \quad \text{external pressure}
\( \alpha \)  \quad \text{ratio of cross-sections of tubes 1 and 2 in experiment}
\( \delta \)  \quad \text{spatial difference}
\( \lambda \)  \quad \text{thermal conductivity}
\( \lambda_v \)  \quad \text{thermal conductivity of saturated vapour}
\( \Delta \lambda \)  \quad \text{thermal conductivity of saturated liquid minus thermal conductivity of saturated vapour}
\( \rho \)  \quad \text{density}
\( \rho_0 \)  \quad \text{initial sodium density}
\( \phi \)  \quad \text{volume fraction of liquid}
\( \delta Z \)  \quad \text{width of sodium cells in Eulerian coordinate system}
\( \delta Z_0 \)  \quad \text{initial sodium cell width}
\( \Delta t \)  \quad \text{time step}
Discussion on Paper FCI4/P23

J P Breton
Do you assume a constant cross section for metallic structures? This cross section varies very much during the experiment.

H Jacobs
Indeed, the heat sink is modelled as a slab, with constant cross section. I agree that this is a poor representation of the real conditions.

H Schins
Dr Henry has just talked about small scale events. Could Drs Amblard, Jacobs or Henry look at this experiment from that point of view.

H Jacobs
This is not a small scale event as there are 5000 kg of UO₂ involved.

R E Henry
This is where the categories that the Chairman recommended in Grenoble come into play. What I was discussing as small scale events and large scale events were explosive interactions, but the rise time of the pressure in this experiment is very many acoustic transmission times of the system. Whilst such thermal interactions may be important in a hypothetical accident sequence they are non-explosive. That is why we set up category 2 where the inertial restraint of the system was important as opposed to the first category where just the inertial restraint of the interaction zone was of sufficient importance to obtain the interaction.

H Schins
Perhaps my question has not been understood. I was really wondering if it was possible to give an alternative explanation. Is it possible to imagine a sodium drop entrainment configuration which would produce the same pressure and would perhaps correspond to a sodium drop of say 1 cm diameter?

H Jacobs
A superheat event would produce a sudden pressure rise and not such a gradual one as observed here, so it is difficult to bring these together.

R E Henry
A superheat event would also have nowhere near the energy reported in this experiment. One is talking in terms of several Joules in terms of a superheat event in mm or cm sized droplets, as opposed to 18 KJ in this experiment.

R Beng
Where does the second small pressure peak in the calculations come from?

H Jacobs
This is a recondensation spike (sodium evaporates for some time at this point and then recondensation occurs). Such spikes are modelling effects and occur quite frequently in two-phase hydrodynamic calculations.
FUEL-SODIUM THERMAL INTERACTIONS IN
THE CAMEL TOP SAFETY TESTS

by

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EXPERIMENTS have been performed in which a molten UO₂/metal mixture, generated by a thermit reaction, has been injected into flowing sodium in bundles of simulated LMFBR fuel pins. A flash X-ray system has been used to observe fuel motion in the channels. Sharp pressurization events were produced in each of the tests in which positive sodium flow rate continued into the region of injected molten fuel for longer than a few milliseconds past the injection onset. The measured FCI events were consistent with the sodium entrapment and superheat (small-scale interaction) model for the sodium/molten UO₂ system. No large-scale, energetic FCI's were produced.

I. INTRODUCTION

In the hypothetical transient overpower (TOP) accident in a liquid-metal cooled fast breeder reactor (LMFBR), an unterminated reactivity insertion is postulated which causes the fuel power to rise exponentially while the system coolant flow rate remains at nominal value. Fuel inside the cladding becomes molten and eventually bursts through the cladding, being injected together with fission gas and some ablated stainless steel cladding into the flowing sodium coolant. The key questions in such a scenario relate to the coherence of pin failures throughout the subassembly, the motion of the fuel in the coolant channels, the occurrence and energetics of fuel-coolant thermal interactions, and the postaccident debris configuration.

The out-of-reactor CAMEL tests being performed at Argonne National Laboratory¹,² are both phenomenological (in the sense of seeking and characterizing the occurrence of fuel-sodium thermal interactions) and at the same time are performed under conditions appropriate to the TOP accident. In these experiments, a molten mixture of UO₂ (81%) and molybdenum (19%), produced by a thermit reaction at approximately 3470°K, is injected into sodium which is flowing through a bundle of simulated LMFBR fuel pins. Tests have been performed in both single-pin and seven-pin bundle configurations, which were designed to give nominally one-dimensional and two-dimensional coolant flow behavior, respectively. Tests have also been performed with varying system hydraulics (encompassing initial sodium velocity, flow pressure drop, and inlet and outlet inertial lengths) which influence the length of time that sodium is driven into the region of injected molten fuel in the presence of the adverse pressure gradients established. The significant hydraulic parameters for the tests to be described are listed in Table 1. Figure 1 shows an illustration of the thermit injector system together with design features of the seven-pin test section. Figure 2 shows a photograph of the completed C2 single-pin test section.
A unique feature of these tests has been the introduction of a flash x-ray cine system which has provided visual observation of fuel motion. The tests have also been instrumented with permanent-magnet flowmeters for measuring bundle inlet and outlet flowrate, strain-gauge-type pressure sensors at various axial locations along the test train, and void detector circuits for monitoring channel voiding behavior. Additionally, fast-response, quartz piezoelectric transducers were used for direct measurement of interaction zone pressures in the seven-pin tests. Using the flash x-ray system together with the test section instrumentation, it has been possible to correlate flowrate and pressurization data with corresponding fuel motion in the channels.

II. SUMMARY OF TEST RESULTS

A single-pin, one-dimensional test was performed first in which the test apparatus was designed for "weak" hydraulic conditions characteristic of the TREAT MARK-II loop. A total of 12.9 g of reaction products were injected into the coolant channel over a time span of about 50 msec. At the onset of injection, the sodium velocity through the coolant channel was 3.5 m/sec, the sodium temperature was 770°K, the local channel pressure was 0.14 MPa and the total flow ΔP was 0.06 MPa. The x-ray frames showed that the fuel stream entered the channel horizontally, traversed the annulus striking the pin cladding, and wrapped around the pin perimeter. By 8 msec after the onset of injection it was accumulating at the back side of the annulus and was spreading uniformly both upward and downward. Upon injection, the channel pressurized to 0.4 MPa, greatly exceeding the inlet plenum pressure, causing reversal of the inlet flow within about 3 msec. There were no FCI's measured in this test (due to the early flow reversal), and there was no fuel sweepout. The fuel accumulated locally in the channel causing effectively a 94% area blockage and reducing the final flowrate to 0.60 m/sec, one-sixth the initial flowrate.

In the single-pin, one-dimensional test performed with "strong" system hydraulics characteristic of the IMFBR system (CAMEL C2), 9.4 g of molten thermite products were injected overall into the sodium channel over about 50 msec. At the onset of injection, the sodium velocity was 7.6 m/sec, the sodium temperature was 770°K, the local channel pressure was 0.39 MPa, and the system overall pressure drop was 0.79 MPa. According to the x-ray frames, Fig. 3, the first fuel to enter the channel spanned the coolant annulus horizontally, impinging on the simulated fuel pin cladding. As the injection proceeded, the fuel was effectively deflected in the downstream direction due to the buildup of an axial pressure gradient across the injected fuel mass. Test data, Fig. 4, shows that a pressurization event occurred at 10.0 msec which brought the inlet flow to momentary reversal in less than 1 msec. The nearby static-type pressure transducers were severely overranged by this event, causing their signals to drop out for several milliseconds. The pressurization event was accompanied by a sudden, local channel voiding which propagated in the downstream direction. The x-ray frames showed that the event caused a nearly complete upward dispersal of all the fuel injected into the channel up to that time (estimated to be 3.0 to 4.0 g). The fuel injection was slowed or even halted momentarily by the pressure rise in the channel, although it resumed again within a few milliseconds. A second pressurization event occurred at 40 msec, again overranging the nearby pressure transducers and sending the inlet flow
into momentary reversal. This event occurred as the fuel injection was nearing its completion. The x-ray frames showed no indication of any significant fuel motion accompanying this event. The fuel injected after the first pressurization event (5 to 6 g) exhibited no net axial motion. It accumulated locally in the coolant annulus forming a partial plug about 20-mm in length, centered at the injector elevation. This partial plug covered effectively 84% of the channel cross section and was responsible for reducing the system flowrate ultimately to 70% of its original level.

In the seven-pin, two-dimensional test performed with "strong" system hydraulics (CAMEL C3), 27.3 g of molten thermite products were injected into the simulated pin bundle. At the onset of injection the sodium velocity was 6.7 m/sec, the sodium temperature was 770°K, the local channel pressure was 0.34 MPa, and the system overall pressure drop was 0.81 MPa. The injection was completed over a time span of about 100 msec. As in the C2 test, the first fuel to enter the coolant channels entered horizontally, impacting the simulated fuel pins, and spread approximately uniformly upward and downward as in stagnation-type flow (Fig. 5). Two pressurization events occurred early in this test at 2.73 msec and 10.74 msec. As shown in Fig. 6, these events ranged in amplitude from about 15 to 18 MPa peak and were very sharp, less than 0.25 msec full pulse width at the base. The pressure events caused momentary reductions in flowrate which were recorded at the inlet flowmeter following a wave transit time of 2.33 msec. In contrast to C2 in which sharp, momentary reversals in flow direction were caused by the events, no flow reversals were recorded in C3. The x-ray frames taken after the first two pressurization events showed upward motion of dispersed fuel through the central channels of the bundle. A third pressurization event was recorded much later in the sequence at 49.19 msec. This low amplitude, triangular-shaped event appears considerably different from the other pressurization events, and no significant amount of fuel motion was associated with it. The last pressurization event occurred at 80.32 msec, as the fuel injection was nearing its completion. This final event was characteristically sharp and was remarkable from the standpoint of initiating substantial fuel motion and upward dispersal, as viewed in the flash x-ray frames. The final debris configuration was a 50-60 mm long partial plug located primarily in the central bundle subchannels. This plug covered effectively 60% of the channel cross section and caused ultimately a 6% reduction in the system flowrate. The total amount of fuel swept from the injector region was found to be 8.55 g, 31% of the mass injected.

The outcome of the HUMP seven-pin test was qualitatively very similar to C3. In this test 23.7 g of thermite products were injected over about 70 msec into the same seven-pin test configuration as used in C3. The "weak" hydraulic conditions in this test included 3.5 m/sec initial sodium velocity, 0.25 MPa pressure at the interaction zone, and 0.08 MPa flow pressure drop across the bundle length. Figure 7 shows the substantial reduction in flowrate caused by channel pressurization at the onset of injection. The net system flowrate remained positive, however, with the result that two sharp pressurization events were produced. The two events, which occurred at 5.66 and 11.51 msec after the onset of injection, had measured peak pressures of 2.42 and 5.80 MPa and pulse widths of 0.60 and 0.38 msec, respectively. The first event caused a 0.66 m/sec decrease in flowrate, as measured at the inlet flowmeter after a
wave transit time of 0.86 msec. The second event caused an abrupt reversal in flowrate which recovered fully in less than 3 msec. The x-ray sequence in this test, Fig. 8, also showed "bursts" of upward fuel material through the central channels, similar to C3, apparently initiated by the two events. The final plug configuration was also similar to C3 as was the overall mass of fuel swept out, 6.2 g (26% of mass injected). The plug covered effectively 68% of the channel cross section and reduced the system flowrate by 20%.

III. INJECTION CHARACTERIZATION

In these TOP-simulation tests, the molten thermite products are injected through a 12.7-cm long, initially evacuated standoff tube (Fig. 1). The flash x-ray sequences typically show that the fuel is momentarily held up at the lower, 0.025 mm diaphragm until the combination of pressure and heating causes the diaphragm to burst, initiating the injection sequence. The reaction products enter the channels as a two-phase mixture, comprised of the liquid UO₂/Mo mixture plus the argon fill gas contained originally in the void of the packed reactants. At the very onset of injection, the void fraction is probably small, due to buildup of the liquid during the brief delay prior to diaphragm rupture. Afterward, the injection void fraction may be as high as 75%. Separate effects tests performed with gas injection only (αg = 1.0) have shown that the noncondensible gas entering the coolant channel is swept directly downstream by the flowing sodium in a bubbly flow regime (αs = 0.3 in single-pin test section). It should be noted that the presence of noncondensible gas in the injected mixture is not qualitatively different from the reactor case in which the fuel is ejected through the cladding breech by expansion of retained fission gas. The liquid phase of the injected mixture contains about 19% molybdenum metal. Examination of the plug formations in the various tests has shown that the molybdenum is contained at finely-distributed sites within a continuum of UO₂. It should also be noted that the presence of a metallic constituent in the injected mixture is also not qualitatively different from the reactor case in which ablation of the cladding at the breech is expected to accompany the fuel ejection.

Separate effects tests have shown that the initial fuel ejection velocity is of the order of 10 m/sec. The initial rate of mass injection ranged from the order of 0.4 g/msec to slightly greater than 1.0 g/msec for the various tests. Calculations of the breakup time of UO₂ liquid globules or jets by stripping or shattering mechanisms in the flowing sodium have shown that little if any breakup can be expected prior to the fuel striking the cladding surfaces in the test bundle.³ It was shown that nearly all the injected reactants would traverse horizontally through the flowing sodium until impinging on the cladding surfaces, as indeed has been observed in the x-ray frames. As a result, the injected molten fuel accumulates at least momentarily in the subchannels, occupying a progressively larger fraction of the channel cross section as it spreads among the pins. The net axial motion of the fuel depends upon whether it emerges homogeneously (one-dimensional case) or nonuniformly (two-dimensional case) into the entire channel. In either event, the important point to consider is that in this time interval sodium is being driven into the underside of a region of accumulating molten fuel. This is true despite the fact that an adverse pressure gradient is
typically established upon injection, causing a deceleration of the
incoming flow. In the cases where FCI's have been measured, the inertia
of the inlet flow, in combination with other hydraulic parameters, has
been sufficiently large to maintain positive sodium flowrate throughout
the duration of the initial channel pressurization.

IV. FCI CHARACTERIZATION

The consistent observation is that in every test performed in which
the sodium inertia was great enough for the above description to apply,
sharp pressurization events were produced. Direct measurement of the
events, Figs. 6 and 7, showed that the pressures ranged up to about 18
MPa; the pulse widths were very short, ranging from 0.23 to 0.60 msec.
The events occurred as early as 2.73 msec to as late as 80.49 msec after
the onset of injection. The events appear to be randomly distributed in
time, with no identifiable initiator, and with no indication of inter-
relation or propagation. The events are interpreted to be local, small
scale fuel-coolant interactions. The measured characteristics of these
events are consistent with the sodium entrapment and superheat model for
the sodium/molten UO₂ system. This mechanism is also consistent with
the physical picture of the interaction zone; that is, sodium being
driven up into a region of an accumulating continuum of molten fuel.
This physical picture of the FCI also suggests that the interaction has
its origin near the lower extremity of the accumulated fuel. In the C2
test this certainly appeared to be the case. The first FCI event at
10.0 msec ejected upward nearly all the fuel in the channel at that
time. The details of fuel motion accompanying the events in the seven-
pin tests were not so obvious. However, it was clear in several in-
stances that the events were associated with the onset of upward fuel
motion which persisted for many milliseconds after the events themselves.
In general, the effects of the FCI events on the overall test sequences
were to initiate fuel sweepout independent of the presence or absence of
hydraulic-related sweepout forces. The events caused only momentary
flow reduction and little or no upstream voiding, in contrast to the
predictions of FCI parametric-model calculations which typically show
extended vapor blanketing and flow reversal.

Characteristics of the various measured pressurization events are
summarized in Table 2. This table lists both the peak and the average
interaction zone pressures (averaged over the total pulse width at the
base, Δt), the impulse imparted to the inlet sodium column, and the work
performed on the inlet column. The impulses were calculated from

\[ I = A_{IZ} \int P(t) \, dt \]  

(1)

where \( A_{IZ} \) is the channel cross-sectional area at the injector region and
\( P(t) \) is the measured interaction zone pressure. This was also compared
with the equivalent expression based on velocity behavior

\[ I = P A_{IZ} \Delta U_{IZ} \Sigma L_i \]  

(2)

where \( \Sigma L_i \) is the total physical length of the inlet column and \( \Delta U_{IZ} \) is
the velocity change at the interaction zone. For wave propagation
through a long column having changes in flow area and duct dimensions,
\( \Delta U_{IZ} \) was related to the measured flowrate change \( \Delta U_{meas} \) by

556
\[ \Delta U_{Iz} = \frac{1}{s_{tot} (\rho c)^{FM}} \cdot \frac{A_{Iz}}{A_{FM}} \cdot \Delta u_{meas} \] (3)

where \( s_{tot} \) is the total transmitted wave. The acoustic speed in the interaction zone, \( c_{Iz} \), was evaluated from the measured wave propagation in the test section. In evaluating \( s_{tot} \), regions whose calculated acoustic periods were short compared to the pulse width \( \Delta t \) were ignored. For the tests in which pressure was measured directly, \( \Delta U_{Iz} \) could also be estimated from the compressible relation

\[ \Delta U_{Iz} = \frac{P_{avg}}{\rho c_{Iz}} \] (4)

For nearly all the FCI events the pulse widths were shorter than the acoustic transmission time to the inlet plenum. As a result, only a fraction of the inlet sodium column was involved in the column response. In these cases, Eq. 2 was replaced by

\[ I = \rho A_{Iz} c_{Iz} \Delta t \cdot \Delta U_{Iz} \] (5)

If \( \Delta U_{Iz} \) is evaluated using Eq. 4, this formulation reduces exactly to Eq. 1. Equation 1 was used for the "best estimate" calculations in Table 1. The "maximum" estimates (quantities in parentheses) were obtained simply by assuming the measured flowrate reductions were applied uniformly to the entire inlet column lengths.

The same procedures were used for calculating the work performed by the events on the inlet sodium column. These work estimates do not include work performed on the fuel mass which in most instances was simply not tractable. For the C2 test, however, an estimate of work performed in ejecting the fuel upward can be made on the basis of the x-ray data. The observed fuel displacement between frames 100 and 101, Fig. 3, suggests an expulsion velocity of 26 m/sec. Applying this to a fuel mass of 4.0 g gives an energy change of 1.35 J. This, added to the 0.23 J imparted to the sodium column, gives a total energy of 1.58 J (0.4 J/g) which is approximately 0.13% of maximum theoretical based on the assumed 4 g mass. No fuel motion was observed accompanying the second event in this test, and no additional energy release over the 0.15 J listed would be calculated. In general, the work performed by the sharp FCI events measured in all three tests was very small.

The following summarizes some of the significant FCI findings from these CAMEL tests:

(1) Sharp pressurization events are consistently produced when sodium flow is directed into a region of accumulating molten fuel.

(2) The pressure amplitudes and submillisecond time scales of events are consistent with the sodium entrapment and superheat model.

(3) The events appear to be random and show no indication of propagation.

557
(4) Fuel motion has been observed to sometimes, but not always, accompany the events. When observed, the fuel motion has appeared nearly always in the upward direction.

(5) The events caused only momentary reduction in the sodium flow-rate with little or no upstream voiding.

(6) The energetics of the measured events were very small.

REFERENCES


<table>
<thead>
<tr>
<th>SYSTEM COHERENCY</th>
<th>TREAT MARK-II LOOP</th>
<th>LMFBR SUBASSEMBLY</th>
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<tr>
<td>MOCKUP</td>
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<tr>
<td>One-dimensional (Coherent)</td>
<td><strong>HUMP ONE-PIN</strong></td>
<td><strong>CAMEL C2 (ONE-PIN)</strong></td>
</tr>
<tr>
<td></td>
<td>$U_o = 3.5 \text{ m/sec}$</td>
<td>$U_o = 7.6 \text{ m/sec}$</td>
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<tr>
<td></td>
<td>$\Delta P = 0.062 \text{ MPa}$</td>
<td>$\Delta P = 0.79 \text{ MPa}$</td>
</tr>
<tr>
<td></td>
<td>$L^* = 0.59 \text{ m}$</td>
<td>$L^* = 1.93 \text{ m}$</td>
</tr>
<tr>
<td></td>
<td>$m_f = 12.9 \text{ g}$</td>
<td>$m_f = 9.4 \text{ g}$</td>
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<tr>
<td>Two-dimensional (Incoherent)</td>
<td><strong>HUMP SEVEN-PIN</strong></td>
<td><strong>CAMEL C3 (SEVEN-PIN)</strong></td>
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<td></td>
<td>$U_o = 3.5 \text{ m/sec}$</td>
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<td>$\Delta P = 0.08 \text{ MPa}$</td>
<td>$\Delta P = 0.81 \text{ MPa}$</td>
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<td></td>
<td>$L^* = 1.41 \text{ m}$</td>
<td>$L^* = 2.81 \text{ m}$</td>
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<tr>
<td></td>
<td>$m_f = 23.7 \text{ g}$</td>
<td>$m_f = 27.3 \text{ g}$</td>
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TABLE 2. Summary of Measured FCI Events in CAMEL TOP Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Event, msec</th>
<th>At, msec</th>
<th>( P_{\text{peak}, \text{MPa}} )</th>
<th>( P_{\text{avg}, \text{MPa}} )</th>
<th>( I, \text{N.sec}^{(1)} )</th>
<th>( W, \text{J}^{(1)} )</th>
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</thead>
<tbody>
<tr>
<td>C2 (2)</td>
<td>#1 (10.0)</td>
<td>0.4 (est)</td>
<td>--</td>
<td>9.27 (calculated)</td>
<td>0.13 (0.30)</td>
<td>0.23 (0.49)</td>
</tr>
<tr>
<td></td>
<td>#2 (40.0)</td>
<td>0.4 (est)</td>
<td>--</td>
<td>8.51 (calculated)</td>
<td>0.12 (0.28)</td>
<td>0.15 (0.31)</td>
</tr>
<tr>
<td>C3</td>
<td>#1 (2.73)</td>
<td>0.231</td>
<td>15.1</td>
<td>5.53</td>
<td>0.20 (0.21)</td>
<td>0.58 (1.15)</td>
</tr>
<tr>
<td></td>
<td>#2 (10.74)</td>
<td>0.183</td>
<td>17.9</td>
<td>8.21</td>
<td>0.24 (0.52)</td>
<td>0.42 (2.19)</td>
</tr>
<tr>
<td></td>
<td>#3 (49.19)</td>
<td>0.731</td>
<td>1.73</td>
<td>0.77</td>
<td>0.095 (0.13)</td>
<td>0.39 (0.74)</td>
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<tr>
<td></td>
<td>#4 (80.32)</td>
<td>0.365</td>
<td>12.2</td>
<td>4.29</td>
<td>0.26 (0.52)</td>
<td>1.00 (2.94)</td>
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<td>HUMP</td>
<td>#1 (5.66)</td>
<td>0.60</td>
<td>2.42</td>
<td>0.82</td>
<td>0.083 (0.21)</td>
<td>0.052 (0.063)</td>
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<tr>
<td>7-pin</td>
<td>#2 (11.51)</td>
<td>0.375</td>
<td>5.80</td>
<td>2.30</td>
<td>0.145 (0.65)</td>
<td>0.045 (0.219)</td>
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</table>

Notes:
(1) Best estimate applied to inlet sodium column; quantities in parentheses are maximum estimates.
(2) FCI pressure estimated from inlet flowmeter data.
Fig. 1. CAMEL 7-PIN TEST SECTION AND INJECTOR
Fig. 2. Thermite Injector Attached to C2 Single-pin Test Section
Fig. 4. Channel Pressure and Flowrate Data from C2
Fig. 5. Selected x-ray Frames from CAMEL
7-pin Test C3
Fig. 6. Interaction Zone Pressure and Inlet Flowrate Data for C3
Fig. 7. Interaction Zone Pressure and Inlet Flowrate for HUMP 7-pin Test.
Fig. 8. Selected x-ray Frames Illustrating Fuel Motion During HUMP 7-pin Test
Discussion on Paper FC14/FP24

S J Board
How do you estimate the energy release in the presence of voids in the test section?

R E Henry
The estimate was obtained by assuming the inlet sodium column, ie upstream of the interaction zone, uniformly responds in the manner recorded by the inlet flow meter. This estimate neglects the contribution in the downstream direction, but it also overestimates the work done on the inlet slug. Such calculations are only used for order of magnitude estimates.

W J Camp
In your experiments what was the ramp rate TOP you were thinking about? If your aim was to simulate low to moderate ramp rates (a few °/sec) the clad should be much hotter. Do you not think that this might change the results with respect to FCI and with respect to sweepout?

R E Henry
The CAMEL loop experiments do not attempt to simulate a given ramp rate. The specific question addressed was the behaviour of molten fuel after it was released into a sodium coolant channel. This was conducted in an out-of-pile facility so that fuel motion could be monitored by a pulse X-ray system, and the temperatures used in the loop are set by the limitations of the preexisting CAMEL loop. With respect to possible changes in FCI, various in-pile experiments have been conducted for different ramp rates, which result in different sodium temperatures. These experiments experience the same behaviour as observed in the CAMEL loop tests, and thus there has been no indication to date that the sodium temperature affects the FCI. With respect to sweepout, the 7-pin tests indicate that the sweepout phenomena is more dependent on the two-dimensional character of the flow than the surrounding cold surfaces which may promote freezing.
PROMPT BURST ENERGETICS (PBE) STUDIES

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Introduction

The Prompt Burst Energetics (PBE) program is part of the Advanced Reactor Safety Research Program conducted on behalf of the U.S. Nuclear Regulatory Commission by Sandia Laboratories. These studies involve an in-pile experimental program and complementary analytical investigation of the energetic response of important reactor fuel-clad-coolant systems subjected to energy deposition conditions associated with super-prompt critical excursions. The objectives of the present program include identification and characterization of the phenomena which dominate the conversion of thermal energy to work, development of models which accurately predict the energetics associated with such hypothetical accidents, and provision of the necessary input data for those models. This program includes the examination of the integral effects of fuel-clad-coolant interactions, fission gas release, and fuel and fission product vapor pressure during super-prompt critical core disruptive conditions, and thus, serves to define the initial conditions for hydrodynamic expansion of the disrupted core.

To date, eighteen single-pin PBE experiments have been completed. Three experiments have been performed with fresh UO₂ fuel in a helium filled capsule (1) twelve experiments have examined the fresh UO₂/Na system (2) and three experiments involving the fresh UC/Na system (3) were performed in collaboration with the Fast Breeder Reactor Project at KfK, Karlsruhe, West Germany. In addition to the integral, pin-geometry experiments, other smaller scale "separate effects" experiments are being performed at Sandia to provide more detailed information about individual phenomena. Work to date has addressed the effective equation of state of reactor fuels at high temperatures, including determination of fresh fuel vapor pressure (4,5) and effects of fission products on the fuel pressure source. Another in-pile experimental program is being developed to examine aspects of fuel coolant interactions (FCI) including fragmentation and heat transfer. These experiments are outlined in another paper in this Conference. (6)

An important conclusion drawn from the PBE work to date is that FCI's do occur in both the UO₂/Na and UC/Na systems under simulated LMFBR accident conditions. This paper presents a description of the PBE experiment methods, discusses the results of four sodium-in experiments and associated interpretative analysis, and substantiates the conclusions drawn from those results. An outline of future PBE experimental work is also given. A presentation of Sandia's FCI modeling work is contained in another paper. (6)

Experiment Methods

The experiments described herein were performed using an instrumented, stagnant sodium-filled autoclave irradiated in Sandia Laboratories' Annular Core Pulse Reactor (ACPR). These

*This work supported by the U.S. Nuclear Regulatory Commission.
experiments simulate, to the extent possible, the geometry of a single fuel pin and associated coolant channel. Figure 1 shows a cross section through the fueled portion of the PBE capsule. The fuel pin is surrounded by a sodium annulus bounded by a molybdenum liner (0.51 mm wall thickness) which simulates the geometry of six adjacent fuel pins and serves as a refractory liner for the Inconel pressure vessel (1.27 mm wall thickness). The spaces between the molybdenum liner and the pressure vessel are filled with sodium.

The fuel pin and coolant channel occupy the lower portion of the inner pressure vessel as shown in Figure 2. The upper boundary of the coolant channel is a tungsten alloy piston which serves as an inertial constraint on the system. From the measured piston motion (monitored with a variable reluctance type linear motion transducer) estimates can be derived of the fraction of thermal energy that is converted to work. The capsule is instrumented with eddy current type pressure transducers (rated at 34.4 and 68.9 MPa) located at the top and bottom of the coolant channel and with stainless-steel sheathed Ch-Al thermocouples (1.02 mm O.D.) located in pairs adjacent to the fuel pin at the top, midplane, and bottom of the active fuel column. Isothermal initial conditions are established by means of electrical heater tapes outside the Inconel pressure vessel. The initial conditions for the four experiments described herein were established at 773 K.

During the reactor transient, the transducer outputs, reactor power signal, and a fiducial generated when the reactor power exceeded 1 kW were recorded on FM tape. The data were digitized from the tape and processed via a dedicated computer system.

Fresh uranium dioxide fuel pins were fabricated for these experiments by Hanford Engineering Development Laboratory (HEDL) and Los Alamos Scientific Laboratory (LASL). The pins were fabricated with EBR-II length (343 mm) fuel columns and utilized FTR-type cladding and cross-sectional dimensions. The pin design incorporates a scratch gauge assembly in the upper plenum to provide a passive indication of total axial fuel expansion occurring during the experiment. The UC fuel pins, which were similar in design to the oxide pins, were provided by the Fast Breeder Reactor Project at KfK, Karlsruhe, West Germany. The fuel pin characteristics are summarized in Table 1.

Experimental Results

Results of four PBE experiments are presented here. These include two fresh oxide experiments (PBE-5S and -9S) and two fresh carbide experiments (PBE-SG1 and -SG2). The results of these experiments are typical of the two experiment series.

Data histories from the four experiments are shown in Figures 3-6. These include pressure histories measured at the top and bottom of the coolant channel and the piston displacement histories. (The time of maximum reactor power is marked in each Figure.) The pressure histories are all characterized by high amplitude, short duration pressure transients which are followed, in some experiments, by a lower amplitude sustained pressure which decays away within 35 ms. It is noted in two of the experiments described here (PBE-9S and PBE-SG2) that second pressure transients
Table 1. PBE Fuel Pin Characteristics

<table>
<thead>
<tr>
<th></th>
<th>5S</th>
<th>9S</th>
<th>SG1</th>
<th>SG2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Material</td>
<td>UO$_2$</td>
<td></td>
<td>UC</td>
<td></td>
</tr>
<tr>
<td>Enrichment ($^{235}$U)</td>
<td>14</td>
<td>50</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Fuel Mass (g)</td>
<td>64</td>
<td></td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>Planar Smear Density (%TD)</td>
<td>85</td>
<td></td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Pellet Diameter (mm)</td>
<td>4.93</td>
<td></td>
<td>4.96</td>
<td></td>
</tr>
<tr>
<td>Fuel Length (mm)</td>
<td>344</td>
<td></td>
<td>359</td>
<td></td>
</tr>
<tr>
<td>Fuel Clad Bond</td>
<td>He</td>
<td></td>
<td>He</td>
<td></td>
</tr>
<tr>
<td>Clad Material</td>
<td>316SS</td>
<td></td>
<td>1.4970SS</td>
<td></td>
</tr>
<tr>
<td>Clad Outside Diameter (mm)</td>
<td>5.83</td>
<td></td>
<td>6.00</td>
<td></td>
</tr>
<tr>
<td>Clad Thickness (mm)</td>
<td>.38</td>
<td></td>
<td>.38</td>
<td></td>
</tr>
<tr>
<td>Wire Wrap Diameter (mm)</td>
<td>1.39</td>
<td></td>
<td>1.35</td>
<td></td>
</tr>
</tbody>
</table>
are observed coincident with the stoppage of the piston and that these transients are observed only at the top of the capsules.

The important results of the experiments are summarized in Table 2. In the oxide experiments, pressure transients are observed nearly coincident with the peak of the reactor power pulse, while in the carbide experiments delays of 10-90 ms are observed. In the PBE-SG1 experiment, the response of several thermocouples (including destruction of thermocouple junctions) indicated that the pin geometry was lost approximately 70 ms before the high amplitude pressure transient. Note the very high pressure (255 MPa) observed in the most energetic of the carbide experiments (PBE-SG2).

Estimates of the thermal-to-mechanical energy conversion can be derived by comparing the maximum piston kinetic energy to the total fission energy deposited in the entire fuel pin up to that time. These values are shown in line 9 of Table 2. Note that in all cases only a small fraction (less than 0.2%) of the fission energy is converted to work. It is important to note that in the three experiments shown here, excluding PBE-5S, the piston reached the end of its travel while the channel was still pressurized (see Figures 4-6), and, thus, the potential energy conversion is much greater than indicated by piston motion. This is further emphasized by the time integrals of the pressure histories shown in lines 10 and 11 of Table 2.

Interpretive Analysis

The conclusions stated below are drawn from experimental and analytic evidence. The experimental evidence is derived from pressure, piston displacement, temperature and reactor power histories, as well as post-test radiography and examination. Analytic evidence comes from application of several types of computer codes to various aspects of the experiment. The analysis includes hydrodynamic and heat transfer modeling of the pin and channel, post-pin failure modeling, and pre-failure modeling with a pin model, EXPAND. The important results of that analysis are included here.

The EXPAND pin failure model was developed to provide information about the time and location of clad failure, thermodynamic states of fuel, clad and coolant at failure, and in-clad fuel motion prior to clad rupture. The development of this model, which incorporates those phenomena occurring during prompt burst excursions, provides a tool uniquely applicable to experiment and accident analysis. The importance of EXPAND modeling with respect to energetics (both PCI and fuel vapor) is that it provides the thermal and hydrodynamic conditions at the start of UO2-Na interaction.

Results of the EXPAND analysis of the experiments considered here are summarized in Table 3. Of particular interest are the comparisons of failure time and the pressure at failure. Note that for the oxide experiments the predicted pin failure times (Col. A) are in substantial agreement with observed pin failure evidenced by onset of the high amplitude pressure transients (Col. B). Such agreement does not exist for the carbide
Table 2. PBE-Experimental Results

<table>
<thead>
<tr>
<th></th>
<th>PBE-5S</th>
<th>PBE-9S</th>
<th>PBE-SG1</th>
<th>PBE-SG2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Time to Significant Pressurization (1) (ms)</td>
<td>2.8</td>
<td>-1.8</td>
<td>90.1</td>
<td>9.0</td>
</tr>
<tr>
<td>2) Maximum Pressure Amplitude at Top (MPa)</td>
<td>31.2</td>
<td>31.1</td>
<td>7.8</td>
<td>172.</td>
</tr>
<tr>
<td>3) Maximum Pressure Amplitude at Bottom (MPa)</td>
<td>47.3</td>
<td>53.9</td>
<td>38.</td>
<td>255.</td>
</tr>
<tr>
<td>4) Maximum Radially Averaged Energy Deposition (J/g)</td>
<td>2350.</td>
<td>3520.</td>
<td>1500.</td>
<td>2420.</td>
</tr>
<tr>
<td>5) Total Energy Deposition (kJ)</td>
<td>130.0</td>
<td>194.3</td>
<td>102.5</td>
<td>165.9</td>
</tr>
<tr>
<td>6) Maximum Measured Piston Velocity (M/s)</td>
<td>11.4</td>
<td>13.8</td>
<td>2.5</td>
<td>31.6</td>
</tr>
<tr>
<td>7) Measured Piston Kinetic Energy (J)</td>
<td>28.5</td>
<td>41.5</td>
<td>1.36</td>
<td>218</td>
</tr>
<tr>
<td>8) Total Energy Deposited at Peak Piston Momentum (kJ)</td>
<td>123.1</td>
<td>129.9</td>
<td>83.8</td>
<td>132.2</td>
</tr>
<tr>
<td>9) Measured Energy Conversion Ratio</td>
<td>$2.3\times10^{-4}$</td>
<td>$3.2\times10^{-4}$</td>
<td>$1.6\times10^{-5}$</td>
<td>$1.7\times10^{-3}$</td>
</tr>
<tr>
<td>10) Pressure Integral to Piston Stoppage (kPa's)</td>
<td>19.5</td>
<td>19.9</td>
<td>5.1</td>
<td>57.0</td>
</tr>
<tr>
<td>11) Total Pressure Integral (kPa's)</td>
<td>19.6</td>
<td>98.3</td>
<td>23.8</td>
<td>212.</td>
</tr>
</tbody>
</table>

(1) Time from Peak of Power Pulse to Significant ($\geq$ 3 MPa) Pressurization.
Table 3. Comparison of EXPAND Results with Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Total Energy Deposition (J/g)</th>
<th>Failure Time (ms)</th>
<th>Predicted Pin Pressure at Failure (MPa)</th>
<th>Observed Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBE-5S</td>
<td>2350</td>
<td>3.0, 2.8, 2.8</td>
<td>9.7</td>
<td>47.3</td>
</tr>
<tr>
<td>PBE-9S</td>
<td>3520</td>
<td>-0.7, -1.8, -1.8</td>
<td>2.5</td>
<td>53.9</td>
</tr>
<tr>
<td>PBE-SG1</td>
<td>1500</td>
<td>2.4, 90.1, 17.9</td>
<td>0.5</td>
<td>38.0</td>
</tr>
<tr>
<td>PBE-SG2</td>
<td>2420</td>
<td>0.4, 9.0, 3.9</td>
<td>0.4</td>
<td>255.0</td>
</tr>
</tbody>
</table>

A - EXPAND Calculation

B - Earliest observation of pressure greater than 3 MPa

C - Earliest Experimental Indication—Pressure, Temperature, or LMT

(1) Referenced to Peak of Reactor Power Pulse

(2) Maximum Observed at Bottom Transducer—Same time as B. These results reflect an approximate doubling of source pressures due to channel acoustics.
experiments where predicted failure times are much earlier than any experimental evidence indicates. It must be noted that the earliest indications of pin failure in the carbide experiments are not the high amplitude pressure transients but are thermocouple and linear motion transducer responses as indicated in Col. C. The comparison of predicted and observed pressures at failure is addressed below.

The EXPAND analysis is terminated at pin failure. Heat transfer analysis of the carbide experiments was performed with the TAC2D code\(^6\) in order to estimate the fuel vapor pressure at times after pin failure. The analysis assumed intact geometry and neglected any heat transfer by vapor transport. Thus these calculations overpredict fuel temperatures and, hence, vapor pressures at times after pin geometry is lost in the experiments. Using an extrapolation of low temperature vapor pressure data for uranium carbide,\(^9\) the maximum vapor pressure calculated for PBE-SG1 is less than 0.1 MPa; for PBE-SG2 a maximum pressure of 6.0 MPa is calculated. While acknowledging uncertainties that may be present in the vapor pressure data, it is highly unlikely that fuel vapor pressure could account for the observed pressure histories in the carbide experiments.

To aid in understanding the detailed structure of the pressure histories of the PBE-5S Experiment (see Figure 3), the channel acoustics were modeled\(^10\) using the CSQ(II) two-dimensional hydrodynamics code. The important result of the analysis is that the observed pressure histories can be accurately reproduced by imposing at the core midplane a step increase in pressure to 20 MPa followed by a decay of the pressure source to 0.2 MPa in approximately 4 ms. Thus the observed pressure transient may exceed the driving pressure by more than a factor of two. The oxide vapor pressure formulation used in the EXPAND analysis is believed to be a lower bound to the vapor pressure.\(^4\) The actual oxide vapor pressure may be a factor of two or more greater than calculated. Thus, the apparent lack of agreement between calculated and observed pressures shown in Figure 3 for PBE-5S may be misleading.

The rapid quenching of fuel vapor arises from prototypic mechanisms (heat transfer to clad and coolant) and non-prototypic mechanisms (heat transfer to cold vessel walls). To date no model has been able to describe the observed quenching phenomena.

The apparent coincidence between the piston stoppage and the second pressure transients in PBE-9S and PBE-SG2 (see Figures 4 and 6) prompted examination of possible sources of that signal. Mechanical effects in the transducer were investigated experimentally; however, preliminary studies indicate no transducer response to the vibrations associated with piston impact. The second pressure transients were observed only in the top sodium slug, which is separated from the lower slug after piston displacement by a low-density "bubble". Thus the phenomena of importance occurred only in the upper slug. As the piston is decelerated at the end of its travel, the sodium column moving with it is compressed and, hence, pressurized. The piston, absorber sleeve, and sodium column were modeled with HONDO,\(^12\) a transient finite deformation code, in order to estimate
the magnitude and duration of the pressure transient arising from piston deceleration. The calculated pressure transient at the location of the upper pressure transducer was 1.8 MPa for PBE-9S and 3.7 MPa for PBE-SG2, both much smaller than the observed transients of 32 MPa and 41 MPa respectively. These results, combined with the lack of fuel vapor pressure, suggest a triggered FCI as the pressure source; triggering pressures of this magnitude has been estimated for liquid UO₂-liquid Na systems by Patel and Theofanous.(13)

Conclusions

From the experiment results and related analysis outlined here, a number of conclusions have been drawn:

1. The timing and magnitude of the initial pressure transients in the fresh oxide/sodium system are consistent with fuel vapor pressure. This is based on the EXPAND and CSQ analysis of PBE-9S. Because of uncertainties in the fuel EOS, sodium pressurization may also contribute to the initial pressurization. Definitive experiments to identify the initial pressure source will be conducted during 1979.

2. The secondary pressure transients and sustained pressures in the oxide/sodium system arise from fuel-coolant interaction (FCI) induced sodium pressurization. Since it is not possible to thermally and mechanically isolate fuel from the sodium for tens of milliseconds without maintaining pin geometry, it is not possible to describe the observed pressure histories in terms of fuel vapor. Thus, sodium pressurization is the only plausible explanation. The decay of the lower amplitude sustained pressure most certainly arises from heat transfer to the vessel walls.

3. FCI-induced pressurization is the dominant pressure source in the carbide sodium system. This is based on the total lack of fuel vapor pressure using available UC EOS data. The same arguments stated in conclusion (2) apply here as well.

4. Spontaneously initiated FCI's are observed in the carbide system. No apparent triggering mechanisms were observed for the pressure transient in PBE-SG1. As indicated, there is experimental evidence that there was fuel, presumably mixed with sodium, in the channel for as long as 70 ms before the observed pressure transient.

5. FCI's triggered by low amplitude pressure transients (2–4 MPa) are observed with both oxide and carbide. In the experiments, the trigger is supplied by deceleration of the sodium slug moving with the piston. This conclusion is suggested by the apparent cause and effect relationship between piston stoppage and the onset of secondary pressure transients in PBE-9S and PBE-SG2. This is further supported by the HONDO analysis and given credence by recent work in liquid-liquid fragmentation.
Clearly complete analytic descriptions of the phenomena responsible for the observations given here do not yet exist. Sandia's PCI modeling work is the subject of another paper in this Conference. (6)

Future PBE Experimentation

In-pile PBE work has resumed in the Annular Core Research Reactor (ACRR). Fresh fueled experiments are planned to address questions raised by previous work and to reduce experimental limitations identified in previous work. The scope of the work will be expanded to address fission product effects in irradiated fuel. Experiments are scheduled to determine the partition of the initial pressure source between fuel vapor and sodium pressurization. These will involve the use of a low vapor pressure liquid metal simulant coolant. Heat losses from the experiment will be reduced by use of insulated walls for the coolant channel and by extension of the single pin geometries to seven pins. The improved capabilities of the ACRR will be utilized to provide improved temperature profiles peaked at the fuel centerline. This may lead to more efficient mixing of molten fuel and coolant before the channel is voided by fuel vapor. The new ACRR Fuel Motion Detection System will provide detailed information about fuel motion and the size and location of PCI interaction zones.

References


Figure 1. Cross section of PBE Fuel Pin Housing
Figure 2. PBE Experiment Assembly
Figure 3. PBE-5S Data Histories
(Time of Peak Power, $T_p = 28.6$ ms)
Figure 4. PBE-9S Data Histories
(Time of Peak Power, $T_p = 540.4$ ms)
Figure 5. PBE-SG1 Data Histories
(Time of Peak Power, $T_p = 30.6$ ms)
Figure 6. TBE-332 Data Histories
(Time of Peak Power, $T_p = 31.4$ ms)
585
S J Board
How would the delayed pulse coincident with piston stopping be explained on a superheat model? At best there would be only a small probability of random coincidence, in fact the pressure increase from impact would reduce the superheat and make nucleation less likely at this time than any other.

R E Henry
I have been asked a similar question by Bill Camp. The delayed pulse in the PHE-98 experiment would not be explained by a superheat model. The principal question to be answered by such experiments is whether this pressure pulse arises because of fuel to sodium energy transfer or is the pressure pulse representative of this particular test, this particular test assembly, etc. The measured pressure pulse is essentially the sodium impact pressure corresponding to the piston velocity and the question to be addressed is whether or not this particular test assembly has any specific characteristics leading to such hydrodynamic impact. It is not sufficient to merely state that this was not seen with other test assemblies.

For example what impact pressure would one get from not only just stopping the piston, but anything else following behind the sodium slug that also would have to be brought to rest? Using some figures given to me just now by Ken Reil, I have estimated a pressure of some 30 MPa, which is what is seen in the graphs.

W J Camp
I agree with the figure of 30 MPa, but this is the pressure arising from the impact of a slug of UO₂ and sodium behind the piston when the velocity is instantaneously reduced to zero. However my point is that I do not really believe that I can have such an impact. If I had such a mass of UO₂, I would have some soft vapour between it and the sodium which would slow it down. Secondly the observed pressure hangs on for a long time, whereas a UO₂ pressurization would not have a long tail like that. Finally Ken Reil made the point that experiment 58 did not show that magnitude, in fact the small pulse seen in 58 was consistent with the HONDO calculations used to model the deceleration of the slug (these calculations were actually for experiment 98, where the piston velocity was slightly higher).

R E Henry
Were the transducers checked after the experiment to show they had the same zero and sensitivity?

K O Reil
No checks have been made because the assembly has not yet been fully dismantled for PIE, though the test itself caused partial disassembly. However differences in zero would have shown up later in time as the system came into temperature equilibrium, and no biases or losses were noted in these experiments. Thermal effects only affect gains by about 10%, but they do account for the apparent negative pressure which then goes positive and returns to the base line level. This arises from thermal gradients across the diaphragm and the two temperature compensating coils, and shows up primarily as a zero shift with only minor changes of sensitivity.

A S Bain
You used fresh UO₂ in you experiments. Can you model, or speculate, on the influence of fission products, particularly gases and volatiles in fuel with a burn up of say 100,000 MWD/Te.
K O Reil
We have plans, to conduct PBE experiments within the next year with irradiated oxide fuels of somewhat lower but comparable burnups. Preirradiated fuel offers another pressure source in the system - namely fission gas - in addition to the fuel species vapour pressure and FCI. Further, the presence of fission gas may alter the course of any FCI, both as a cushion to pressurization and by interfering with heat transfer on the fuel-coolant interface. At this time I would not like to speculate further.

A S Bain
I did not follow you logic in discussing the influence of thermal conductivities of UO₂ and UC on clad failure; does not the thermal expansion due to the melting of UO₂ crack the sheath in any case?

K O Reil
There is void space in the clad to accommodate the melt expansion, and the difference in clad behaviour is primarily due to the thermal stress in the cladding both from average clad temperature and thermal gradient. We assume that the fuel slumps against the clad on melting, which gives perfect contact when it resolidifies.

A S Bain
The total energy input is important, and I would have thought that with the same energy input you would not have reached the same temperature with UC because of its higher conductivity.

K O Reil
The heating time scales of these experiments are of the order of 15 to 20 m secs, and on these scales the fuel is essentially adiabatic with the exception of the clad itself.
A Study on Pressure Generation Caused by Actual Fuel Failure in the NSRR Experiment

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Division of Reactor Safety
Japan Atomic Energy Research Institute
1. Introduction

Investigation of reactor fuel failure under accidental conditions and its consequences including fuel-coolant interactions (FCI) is one of the important areas of reactor safety research. The Nuclear Safety Research Reactor (NSRR) project was started in Japan Atomic Energy Research Institute for the in-pile experimental study on fuel behaviors under accidental conditions. The general objectives of the phase I program of this project are to investigate the threshold energy, mechanisms of fuel failure and failure consequences under fast power excursion in reactivity initiated accident (RIA).

Since the experiments were started in October, 1975, over 300 tests have been conducted to date on light water reactor fuels. Various types of fuel rods were tested under different power burst and cooling conditions. Violent ruptures of fuel rods resulting in pressure pulse generation were experienced in about 70 tests out of 300. The cases in which pressure generation were observed were the failure of intact rods under very large power excursion and the cladding rupture of waterlogged rods and of pre-pressurized rods.

Failure modes and resulting pressure pulses differ among these test cases; i.e., molten fuel is expelled and causes molten fuel-coolant interaction in the failure at very large energy depositions, while superheated water or steam trapped in the pellet-cladding gap space plays the major role for pressure generation in waterlogged rod failure and so on.

In the following sections, experiment facilities and the method of transient measurement are described briefly. Then test results on failure modes and pressure pulse generation are presented and discussed. Besides the fuel rod test results, some preliminary results of uncladded UO₂ pellet irradiation tests will be referred to.

2. Experiments

Power burst condition of RIA was simulated by irradiating the actual fuel rods in a pulse reactor. The pulse reactor used, named NSRR, is a modified TRIGA-ACPR (Annular Core Pulse Reactor) whose remarkable features are (1) the large pulsing power capability which enables to energize the moderately enriched fuel by nuclear fission
over melting temperature of UO$_2$, and (2) a large dry experiment cavity (22 cm inner diameter) in the central region of the core where an experimental capsule or a loop can be installed.

Figure 1 shows the general arrangement of the reactor facilities. The core structure is mounted on the bottom of a 9 m deep open-top water pool. A large experimental tube extends from the top of the reactor pool through the core center to the sub-pile room beneath the pool bottom. The experimental capsule containing test fuel rods is inserted through this experimental tube and fixed at the center of the core. There are two ways of access to the core region, off-set and vertical loading tubes. As no radiation shielding plug is required in the off-set tube, an experiment capsule is easily inserted or removed through this off-set tube. This provision enables to handle a lot of in-pile experiments quite efficiently.

Table 1 summarizes the major characteristics of the NSRR. A large pulsing power is realized by quick withdrawal of transient control rods by pneumatic driving system. The maximum reactor capabilities in pulse operation are the peak reactor power of 21,000 MW, total energy release of 117 MW·s with the pulse width of 4.4 ms. With this maximum pulse, we can deposit in the 10% enriched fuel approximately 450 cal/g of UO$_2$ adiabatically which amount to 180 cal/g in excess of melting enthalpy of UO$_2$. Figure 2 is a schematic of experiment capsule and internal hardware. Test rod is supported at the center of the experiment capsule. Test rod is cooled by surrounding water under ambient temperature and pressure conditions.

Major instrumentations are also indicated in Figure 2. Cladding surface temperatures were measured by very thin bare-wire Rt-Pt·Rh thermocouples attached to the cladding by spot welding. Pressure pulses in the capsule and fuel rod internal pressures were measured by strain gage type fast response transducers at the capsule bottom and at the lower end plug of the fuel respectively. Jump up velocity of water column was measured by a float type movement sensor, and the transient displacement of fuel rod by LVDT (Linear Variable Displacement Transducer). The sensors for transient measurement are summarized in Table 2.

PWR type fresh fuel rods were used as standard test sample in NSRR experiments. Figure 3 shows the schematics of the standard test rod, and the major design characteristics are summarized in Table 3.
3. Test Results

3.1 Fuel Failure Modes

Large varieties of failure patterns have been found in the NSRR experiments depending on the fuel rod characteristics and test conditions. However, the failure patterns can be categorized, from the viewpoint of pressure generation characteristics at failure, into two different modes, i.e. the failure caused by the fracture of embrittled cladding and that initiated by the internal pressure burst of the cladding. The first mode, cladding fracture, was observed in the failures at comparatively lower energy depositions of less than 340 cal/g of UO₂. The cladding break generally occurred during the rewetting period of the cladding resulted from the combined effects of embrittlement by oxidation, local thickness change of cladding by partial melting, and chemical binding between pellet and cladding. The rod was broken into two to several pieces, but not fragmented in this energy deposition range. During the failure of this mode, no mechanical forces such as pressure pulses and water column ejection were generated. The second mode, cladding rupture, occurred in three cases, i.e. failure of standard rods at very large energy depositions, that of waterlogged rods and of pressurized rods.

The failure pattern of standard rod changed when the energy deposition exceeded 340 cal/g·UO₂, which roughly corresponds to the enthalpy rise to cause gross melting of the fuel pellets. At this high energy deposition failure, cladding was ruptured at very early period of the transient before cladding temperature increased to the melting point, and molten fuel was expelled to the surrounding coolant.

Failure of waterlogged rods was a low temperature rupture of the cladding by very large internal pressure generation at the energy deposition of as low as 150 cal/g·UO₂. The waterlogged rod tests simulate the condition of a start up accident in a power reactor in which defected fuel, which had become waterlogged during shutdown, were assumed to be subjected to a sudden overpower. Fuel rods were waterlogged before the tests and subjected to a power burst in NSRR. A large internal pressure was generated in the rod by the expansion of heated water in the pellet-cladding gap space. Cladding was ruptured
at low temperatures, generally resulting in all or most of the fuel being expelled as fine solid particles.

In pre-pressurized rod failure, internal pressure of test rods was increased from 2 to 50 kg/cm² in order to simulate the pressure accumulation with burn up. High temperature rupture of the cladding occurred for the initial internal pressure of over 6 kg/cm². As the rupture was much milder than cold temperature rupture, fuel pellets were not expelled and resultant pressure pulses were rather small. As mentioned above, any failure of this second mode accompanies the generation of pressure pulses and coolant ejection. Major characteristics of different failure patterns and typical appearances of post test rod for each failure type are summarized in Table 4. In the following section pressure pulses measured in the failures of the second mode, i.e. high energy deposition failure, waterlogged rod failure and pressurized rod failure will be described.

3.2 Pressure Pulses Measured at Fuel Failure

3.2.1 High Energy Deposition Failure

Transient histories of reactor power, pressure pulses, ejected water column displacement and the cladding temperature are indicated in Figure 4 for the energy deposition of 485 cal/g-UO₂. At the final period of the power excursion, sharp pressure pulses were generated with the failure occurrence and the water column was expelled. Cladding temperature was, however, still very low at this time of failure. Then, about 30 milliseconds after the failure, broader pressure pulses followed periodically. The peak values of first pressure pulses and of water column velocity are plotted as a function of energy depositions. Pressure pulses of measurable value were detected at the energy of over 340 cal/g-UO₂. Both the peak pressure and water column velocity increased consistently for the insertion of higher energy densit to the fuel. Maximum values of peak pressures and water velocities measured in NSRR tests were 18 kg/cm² at capsule bottom and 21 m/s both at the energy deposition of 526 cal/g-UO₂. Particle size distribution of the fragmented fuel debris was measured by screening. The results are summarized in Figure 5. It is shown that the fragmentation became more profound as the energy deposition was increased.
3.2.2 Waterlogged Rod Failure

Figure 6 shows transient measurements in a waterlogged rod test. At first, rod internal pressure increase was observed coincidentally with the enthalpy rise of the pellet, then a sudden drop of the rod pressure occurred indicating a cladding rupture. With the initiation of cladding rupture, a sharp pressure pulse of around 100 kg/cm² was generated in the capsule. Then, after 20 to 30 milliseconds, smaller pressure pulses followed periodically. Cladding temperature rises till the time of rupture were around 100°C at highest, and no significant temperature rises were indicated after the cladding rupture. This temperature behavior shows that cladding rupture occurred by very large internal pressure accumulation while the cladding was still cold, and most of the fuel was driven out of the cladding instantly at rupture. These observations suggest that the first pressure pulses were originated by the release of rod internal pressure, and that the second group of pressure pulses in later period was due to the heating by ejected fuel fragments.

Maximum values of the first pressure pulses were plotted as a function of water content in the rod in Figure 7. Tests were conducted at the two different energy deposition levels, 160 and 240 cal/g of UO₂. This plot indicates that

(1) the peak pressure were not so much influenced by water content or by pellet-cladding gap width, and that

(2) larger energy depositions resulted in higher peak pressures.

Peak values of the second pressure pulses were generally smaller than those of first ones. However, as the potential thermal energy stored in the dispersed fuel fragments is much greater than the source of the first pressures, the influence to the environment by the second pressures and resultant coolant ejection would probably not be so smaller than the first pressure pulses.

Maximum values of this second pressures are plotted versus total energy deposition in Figure 8. It is interesting to see that the second pressures at 240 cal/g of UO₂ were lower than those at 160 cal/g of UO₂. One can explain this phenomena that more violent cladding ruptures in the former cases, caused more rapid ejection of coolant,
which resulted in less effective contact between fuel fragments and the coolant. Therefore, the generation of the second pressure pulses will be much influenced by the failure sequences and the environmental conditions of the fuel rod.

3.2.3 Pressures at Pressurized Rod Rupture

Pressure generation mechanism at pressurized rod rupture is much simpler than aforementioned cases. Expansion of the released rod internal gas is the only source of the pressure pulses. Typical transient measurements are indicated in Figure 9. Cladding rupture occurred about 0.8 second after power burst. A sudden decrease of rod internal pressure and the generation of a pressure pulse in the capsule indicate the occurrence of cladding rupture. Before this time, cladding temperature increased to over 1000°C, and resulted in cladding ballooning under quasi-constant internal pressure condition until burst. As the capsule pressure was measured at capsule bottom, measured peak value was approximately 1/8 of the source pressure due to the decrease in propagation process.

4. Discussions

4.1 Pressure Generation at Cladding Rupture

Some pressure pulses, large or small ones, will be generated in any type of cladding rupture. Even in high energy deposition failure of the standard rods, the initial peak of the first pressure pulses is believed to be the rupture pressure of the cladding. It is difficult to say, however, that the major part of the first pressure pulses consists of whether the pressures by cladding rupture or those caused by FCI or both. On the other hand, the maximum pressures are generally caused by the release of cladding internal pressure at rupture both in waterlogged and pre-pressurized rod failures. In this type of pressure generation, maximum value of pressure pulses will be strongly controlled by the mechanical strength of the cladding kept at time of rupture, because the pressure of released gas or liquid corresponds to the cladding rupture pressure itself. Consequently, there might be a large difference in maximum pressure depending on the cladding temperature at time of fuel
failure.

In waterlogged rod failure, quick expansion of heated water in the gap results in a large pressure accumulation so rapid, presumably within 10 milliseconds, that the cladding ruptures before DNB occurs at cladding surface. As the cladding rupture pressure of the NSRR standard rod is as large as 1000 kg/cm² at room temperature, waterlogged rod failure can generate very large source pressure pulses. The pressures at the measured point, at bottom center of the test capsule, are estimated to be approximately 1/10 of the source pressures at fuel rod surface considering the sonic wave propagation in the capsule. Therefore, rupture pressure of 1000 kg/cm² may result in a pressure pulse of around 100 kg/cm² at the measured point, which shows a good agreement with the measurement. In the pressurized rod failure, on the other hand, cladding does not rupture until it attains enough temperature to burst, as the internal pressure rise during the transient is very small. Measured pressure were, therefore, quite moderate, and the peak values were approximately 1/10 of the rod internal pressures.

4.2 Pressure Generation Caused by Fuel Dispersal

Dispersal of fragmented fuel was observed during fuel rupture in high energy deposition failures and in waterlogged rod ones. In both cases, pressure generation caused by this fuel dispersal was detected. In this section, the fuel dispersal processes and their influences on pressure generation in the above two failure cases are discussed.

The sequence of pressure generation in high energy failure is believed to be as follows. At first, fuel is melted very quickly before cladding reaches melting point. Expansion of heated gap gas, build up of vapor pressures of UO₂ and impurities, plus prompt thermal expansion of molten fuel might bring about a pressure accumulation within the intact cladding during this heat up period. Then the internal pressure rise and weakening of the cladding by temperature rise might result in the cladding rupture and the ejection of molten fuel into coolant. Rupture pressure may propagate at first, then the steam explosion by the heating of fragmented molten fuel may follow. The details of fragmentation procedure are not known yet. It is most likely, however, that the molten fuel is expelled with a considerably
high initial velocity which results in breaking up the molten fuel into finer particles. As the energy deposition was increased, decrease of fuel particle size as well as the increase of stored enthalpy in the fuel might have resulted in larger mechanical energy generation. As was described in section 3.2.1, two different groups of pressure pulses were identified. The first group is thought to correspond to the FCI at the first contact of the ejected fuel and the coolant. Then, as the time of the pressure increase of the second group coincide with the time of reentry of ejected coolant, these second pressure pulses would be the results of FCI between reentrant coolant and the remaining fuel fragments.

In the waterlogged fuel failure, fuel pellets are ejected by high internal pressure at the time of rupture. As the failure occurs at much lower energy depositions than the high energy failure, fuel is not melted. However, as the pellets are generally fragmented into very fine particles of 0.5 mm or less in average diameter, the rapid heating of the coolant by fragmented solid fuels can result in a steam explosion like that of FCI. In order to confirm the fragmentation procedure of fuel pellets in waterlogged rod, uncladded pellets were irradiated in the water capsule. Dry pellets contained in a plastic bag were not fragmented. No pressure pulses were generated in this case. Pellets immersed in water were, on the other hand, broken into very fine particles as was seen in waterlogged rod failure, and generated pressure pulses. The pressure history measured in this uncladded pellet experiment are compared with that of a waterlogged test in Figure 10. Except for the first pressure pulses at the time of rupture, observed pressure behaviors were quite similar to those as were experienced in waterlogged rod failure. This result indicates that the second pressures observed in waterlogged rod failure should be resulted from the FCI between fragmented solid fuel particles and the coolant.

5. Conclusions

Through the actual fuel failure experiments in the NSRR, the information on the pressure generation procedure has been obtained in connection with failure modes as follows:

(1) Pressure generation was observed only in the cases in which rod
failures were initiated by cladding rupture, i.e. in the failures in high energy deposition tests, waterlogged rod tests and pre-pressurized rod tests.

(2) Fragmentation at the failure of fresh intact rods occurred when the energy deposition exceeded 340 cal/g·UO₂. Molten fuel was expelled by cladding rupture resulting in the pressure generation of around 30 kg/cm² by molten fuel-coolant interaction.

(3) Waterlogged rod ruptured at relatively low energy depositions possibly by prompt accumulation of large internal pressure. Low temperature rupture of the cladding produced large and sharp pressure pulses and ejected solid fuel fragments. Interaction between the solid fuel particles and the coolant generates second pressure pulses of significant value.

(4) Rupture of pre-pressurized rod also produced pressure pulses, although the generated pressures were very moderate and not influential to the environment. As both the pressures in the fuel rod and that in the capsule were measured, the data are useful for understanding the propagation behavior of pressure pulses.

References


 Reactivity Accident Laboratory and NSRR Operation Section: Quarterly Progress Report on the NSRR Experiments (6); Combined, January 1978 - June 1978, JAERI-M 7977 (October, 1978)
Table 1: Major characteristics of NSRR

<table>
<thead>
<tr>
<th>Reactor Type:</th>
<th>Modified TRIGA-ACPR (Annular Core Pulse Reactor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Vessel:</td>
<td>$3.6^m \text{wide} \times 4.5^m \text{long} \times 9^m \text{deep}$ open pool</td>
</tr>
<tr>
<td>Fuel:</td>
<td></td>
</tr>
<tr>
<td>Fuel type</td>
<td>12 wt% U-ZrH fuel</td>
</tr>
<tr>
<td>Fuel enrichment</td>
<td>20 wt% U-235</td>
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<tr>
<td>Clad material</td>
<td>Stainless steel</td>
</tr>
<tr>
<td>Fuel diameter</td>
<td>3.56 cm</td>
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<tr>
<td>Clad diameter</td>
<td>3.76 cm O.D.</td>
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<tr>
<td>Length of fuel section</td>
<td>38 cm</td>
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<tr>
<td>Number of fuel rods</td>
<td>157</td>
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<tr>
<td>Equivalent core diameter</td>
<td>62 cm</td>
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<tr>
<td>Control Rods:</td>
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</tr>
<tr>
<td>Number</td>
<td>8 (including 2 safety rods)</td>
</tr>
<tr>
<td>Type</td>
<td>Fuel followed type</td>
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<tr>
<td>Poison material</td>
<td>Natural $B_4C$</td>
</tr>
<tr>
<td>Rod drive</td>
<td>Rack and pinion drive</td>
</tr>
<tr>
<td>Transient Rods:</td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>2 fast transient rods and 1 adjustable transient rod</td>
</tr>
<tr>
<td>Type</td>
<td>Air followed type</td>
</tr>
<tr>
<td>Poison material</td>
<td>92% enriched $B_4C$</td>
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<tr>
<td>Rod drive</td>
<td>Fast: Pneumatic</td>
</tr>
<tr>
<td></td>
<td>Adjustable: Rack and pinion &amp; pneumatic</td>
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<tr>
<td>Core Performance:</td>
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</tr>
<tr>
<td>a) Steady state operation</td>
<td></td>
</tr>
<tr>
<td>Steady state power</td>
<td>300 kW</td>
</tr>
<tr>
<td>b) Pulse operation</td>
<td></td>
</tr>
<tr>
<td>Max. peak power</td>
<td>21,100 MW</td>
</tr>
<tr>
<td>Max. burst energy</td>
<td>117 MW-sec</td>
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<tr>
<td>Max. reactivity insertion</td>
<td>$3.43% \Delta k$ ($$4.67$)</td>
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<tr>
<td>Min. period</td>
<td>1.12 msec</td>
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<tr>
<td>Pulse width</td>
<td>4.4 msec (1/2 peak power)</td>
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<tr>
<td>Neutron life time</td>
<td>30 $\mu$s</td>
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<td>Experiment Tube:</td>
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<td>Inside diameter</td>
<td>22 cm</td>
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Table 2  Sensors for transient measurement

<table>
<thead>
<tr>
<th>Measuring Item</th>
<th>Sensor Type</th>
<th>Measuring Range</th>
<th>Response Frequency</th>
<th>Remarks</th>
</tr>
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<tbody>
<tr>
<td>Cladding Surface Temperature</td>
<td>Pt-Pt.13%Rh T/C</td>
<td>Room Temp.</td>
<td>~200 Hz</td>
<td>Spot welded to the Cladding Surface</td>
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<td></td>
<td>Wire Diameter 0.1 mm</td>
<td>~1700°C</td>
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<td></td>
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<tr>
<td>Fuel Internal Pressure</td>
<td>Flash Diaphragm Type</td>
<td>0~500 kg/cm²</td>
<td>resonance freq.</td>
<td></td>
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<tr>
<td></td>
<td>Strain Gauge Transducer</td>
<td></td>
<td>170 kHz</td>
<td></td>
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<tr>
<td>Capsule Internal Pressure</td>
<td>&quot;</td>
<td>0~200 kg/cm²</td>
<td>response freq.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>110 kHz</td>
<td></td>
</tr>
<tr>
<td>Water Velocity</td>
<td>Float Type Transducer</td>
<td>0.1~20 m/s</td>
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<tr>
<td>Fuel Axial Displacement</td>
<td>LVDT</td>
<td>~±10 mm</td>
<td>~1 kHz</td>
<td></td>
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<tr>
<td>Cladding Axial Displacement</td>
<td>LVDT</td>
<td>~±10 mm</td>
<td>~1 kHz</td>
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Table 3  Major design characteristics of test rods

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Standard</th>
<th>Waterlogged</th>
<th>Pressurized</th>
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<tr>
<td>UO₂ Pellets</td>
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<td></td>
<td></td>
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<tr>
<td>Diameter</td>
<td>9.29 mm</td>
<td>9.29 mm</td>
<td>9.29 mm</td>
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<tr>
<td>Length</td>
<td>10 mm</td>
<td>10 mm</td>
<td>10 mm</td>
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<tr>
<td>Density</td>
<td>95 % T.D.</td>
<td>95 % T.D.</td>
<td>95 % T.D.</td>
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<tr>
<td>Enrichment</td>
<td>10 %</td>
<td>10 %</td>
<td>10 %</td>
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<tr>
<td>Shape</td>
<td>Chamfered</td>
<td>Chamfered</td>
<td>Chamfered</td>
</tr>
<tr>
<td>Cladding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Zircaloy-4</td>
<td>Zircaloy-4</td>
<td>Zircaloy-4</td>
</tr>
<tr>
<td>Wall Thickness</td>
<td>0.62 mm</td>
<td>0.62 mm</td>
<td>0.62 mm</td>
</tr>
<tr>
<td>Pin</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Diameter</td>
<td>10.72 mm</td>
<td>10.72 mm</td>
<td>10.72 mm</td>
</tr>
<tr>
<td>Pellet-cladding Gap</td>
<td>0.095 mm</td>
<td>0.095 mm</td>
<td>0.095 mm</td>
</tr>
<tr>
<td>Element</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall Length</td>
<td>265 mm</td>
<td>265 mm</td>
<td>265 mm</td>
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<tr>
<td>Fuelled Length</td>
<td>135 mm</td>
<td>135 mm</td>
<td>135 mm</td>
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<tr>
<td>Weight of Fuel Pellets</td>
<td>96 g</td>
<td>96 g</td>
<td>96 g</td>
</tr>
<tr>
<td>Plenum Gas Space</td>
<td>He 1 atm.</td>
<td>He 1 atm.</td>
<td>He pre-pressurized from 2 to 50 atms.</td>
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Table 4  Summary of failure modes and appearances of post test rods

<table>
<thead>
<tr>
<th>FUEL TYPE</th>
<th>FAILURE MODE</th>
<th>ENERGY DEPOSIT (CAL/G.U02)</th>
<th>APPEARANCES OF POST TEST FUEL RODS</th>
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<tbody>
<tr>
<td>STANDARD FUEL ROD</td>
<td>CLADDING FRACTURE</td>
<td>260 - 340</td>
<td></td>
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<tr>
<td></td>
<td>PELLET MELT</td>
<td>&gt;340</td>
<td></td>
</tr>
<tr>
<td>WATERLOGGED FUEL ROD</td>
<td>LOW TEMP. BURST OF</td>
<td>&gt;130</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CLADDING</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRESSURIZED FUEL ROD</td>
<td>HIGH TEMP. BURST OF</td>
<td>&gt;160</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CLADDING</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 1 General arrangement of NSRR facilities
Fig. 2 Schematic of experiment capsule and internal hardware
Fig. 3 Schematic of standard test rod
Fig. 4 Transient data during fuel rupture at 526 cal/g·UO₂
Fig. 5 Summary of particle size distribution in high energy deposition failure

Test No. 111-19
20% enriched fuel
526 cal/g·UO₂
collecting ratio 79%

Test No. 111-18
20% enriched fuel
483 cal/g·UO₂
collecting ratio 96%

Test No. 111-21
10% enriched fuel
441 cal/g·UO₂
collecting ratio 98%

Test No. 111-20B
10% enriched fuel
388 cal/g·UO₂
collecting ratio 99%

(1) 0 - 125 μm
(2) 125 - 250 μm
(3) 250 - 500 μm
(4) 500 - 1000 μm
(5) 1000 - 2000 μm
(6) 2000 - 4000 μm
(7) over 4000 μm
Fig. 6 Transient data during waterlogged rod rupture at 156 cal/g-UO₂
Fig. 7 Maximum values of first pressure pulses versus water content in the rod
Fig. 8 Maximum values of second pressure pulses versus energy deposition

- 100% waterlogged
- 70%
- 30%
- less than 10%
- 100%
- 70%

{ standard fuel }

{ wide gap fuel }

fully filled capsule water

kg/cm²

Second Capsule Pressure

Total Energy Deposition

150 200 250 cal/g·UO₂

610
Fig. 9 Transient data during pre-pressurized rod failure at the energy deposition of 229 cal/g-UO₂
Fig. 10 Pressure waves generated by fragmented UO$_2$ pellets compared with those at waterlogged rod rupture.
Discussion on Paper PCI4/26

K O Reil
Is energy deposition quoted the radial average at the axial midplane, and what is radial profile peak to average or peak to minimum?

T Fujishiro
Energy deposition values used are the radial average at the axial maximum. The radial peaking factor for 10% enriched fuel is 1.12.

R B Duffey
Would you please tell us the design and safety limits for the energy deposition in operating power reactions in Japan for reactivity insertion events.

T Fujishiro
As far as I understand the licensing requirement for the failure threshold under a Reactivity Initiated Accident is 170 cal/g UO₂, and the threshold for mechanical energy generation is 240 cal/g UO₂. The above are based on test figures of 260 cal/g UO₂ and 340 cal/g UO₂ respectively.