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THERMAL-HYDRAULIC TRANSIENTS WITH COOLANT AND CORE
MATERIALS IN LMFBR SAFETY EVALUATIONS

Quarterly Progress Report

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HIGHLIGHTS FOR MARCH - MAY, 1976

Task I - Thermal-Hydraulics of LOFA Initiating Phase

Efforts to minimize the running time for HEV-2D, and include downstream condensation effects, prior to carrying out a set of runs for CRBRP, were initiated. Calculations for an one-dimensional gas-dynamic "voiding" case for which an analytical solution could be found confirmed the accuracy of the numerical scheme.

The previously mentioned transient clad relocation data indicated that a developing two-phase friction multiplier can be significantly smaller than the fully developed (steady-state) one. A new test-section was designed and constructed to further investigate this phenomenon.

Several modifications of the experimental system for the study of plugging phenomena have been completed. The system is ready for the second series of runs to further investigate the effects of initial superhead and/or ablation.

Initiating-phase (LOFA) system's effects were investigated with reference to SAS channel choice and arrangement, clad relocation velocities, and core-wide incoherencies. Preliminary results indicate that all three aspects can play a significant role in affecting accident evolution.

The physical structure of the can-wirewrap-clad-pellet system is presently neglected in LOFA analyses. Its thermal-mechanical behavior can potentially affect (a) fuel slumping, (b) plenum fission-gas release, and (c) clad melting patterns.

Task II - Recriticality Considerations

It appears that the major portion of the fission-gas plenum pressure is not likely to be released prior to the inception of the SLUMPY-dominated portion of the LOFA initiating phase. This pressure can induce a mode of recriticality which could significantly alter the course of events. A preliminary assessment has been possible utilizing SAS-3A.

Detailed evaluation of the LOFA phenomenology led to the definition of the "Transition-to-the Transition Phase" as an important time domain with potential for mild recriticalities.

The liquid shock tube, intended for shock-induced fragmentation studies in multiphase systems is near completion. All associated instrumentation has been received.

The test section for the boiling pool dynamics studies has been completed; and all instrumentation has been received.

Scoping calculations considering the effects of steel in the thermal-to-mechanical energy conversion phase of a hydrodynamic disassembly indicate that the effect is not likely to be detrimental.

Task III - General Consulting

The principal investigator participated in the Staff's effort to provide answers for the NRDC interrogatories.

The principal investigator is participating in the current Staff effort to assess the CRBRP energetics.

TASK I. THERMAL-HYDRAULICS OF LOFA INITIATING PHASE

I.1 Voiding Dynamics (C. Miao and T. G. Theofanous)

The major emphasis in this quarter has been placed upon improving the computational effort for HEV-2D, and including downstream condensation effects. Several approaches have, and still are, being examined, such as various iteration schemes as well as matrix inversion manipulations. We are trying to take advantage of the fact that the simple-phase incompressible liquid zone will occupy the majority of the subassembly at the time of flow reversal.

Meanwhile, the checkout of the presently available code version was done by considering an one-dimensional gas-dynamic voiding problem for which an analytical solution could be found. The problem considers a forty-foot long pipe (open at both ends) full with gas at one atmosphere. The gas is heated by means of a uniform, volumetric heat source. It expands and voids the pipe. As may be seen from the sample of results presented in Figures 1-3, the comparisons are good.

I.2 Cladding Motion (W. Prather and T. G. Theofanous)

Following a number of successive improvements, the experimental set-up has reached a final form having certain important high quality features relevant to the clad relocation problem. They are: (a) The molten film forms rapidly enough so that essentially no motion is observed prior to its complete formation. The experiment can thus be run under transient conditions with the proper value of the air velocity. The point here is that when melting is not sufficiently rapid and the gas exceeds certain flooding limits, the liquid is transported as it melts thus preventing the formation of a

complete film. A significant amount of effort went into achieving a satisfactory operation in that regard. (b) Downstream freezing is very important in the experiment as, of course, it would be in the reactor. When the test section region being downstream of the initial film location remains cold after film melting, it serves as a heat sink for the transported film and results in quick freezing and plugging. The whole transient, therefore, lasts only for a fraction of a second. The new test section allows for controlled downstream heating so that the more detailed features of the relocation process, including freezing phenomena, can be observed for a longer period of time. The test section frame is shown on Figure 4(a). (c) The instrumentation techniques have been developed to the point where detailed, pressure profiles and flow transient, as well as local film thickness can be measured and recorded in synchronization with high speed movies. (d) The wetting properties of the film and its base metal were found to be very important. Such properties now are kept under control (wetting or non-wetting) for the film and downstream region as desired. (e) The transient runs must be carried under constant pressure drop conditions or controlled pressure drop transients as the case might be in the reactor. Unless special provisions are made upon film melting one normally observes a drastic pressure drop surge, which obscures the fundamental phenomena under consideration and is therefore undesirable. In our present system we can achieve conditions over the whole range of interest, i.e. air velocities as high as 400 ft/sec, with a pressure drop increase of less than 30%. Translated in gas velocities this means a variation of only 15%, and it is considered adequate for these studies. (f) Techniques were developed to control splashing of the film on the test section window. The test can be run in a

splashing-free mode, or with splashing as it might be required. (g) The final disposition of material is determined, by weighing the resolidified material, separately for the original film region, the downstream region, and by difference we can also determine the amount entrained.

We have found that the value of J_g^* , a dimensionless superficial gas velocity, is useful to characterize the outcome of the gas-film interaction. A typical comparison may be seen in the pictures of Figures 4 and 5. The top of the original film is indicated by the two horizontal lines near the center of the picture in Figure 5(a), and is at the same location for all three cases shown. It is clearly seen that as the value of J_g^* increases the amount of downstream relocation increases. In test NTS-3 nearly 70% of the film remained motionless. None drained, about 15% relocated downstream as shown in the figure and the remaining, nearly 18% was entrained. In runs NTS-2 and -5 only half remained in its original position, the other half relocated downstream, and the entrainment was negligible. In general for gas velocities yielding J_g^* less than one, the upward relocation is small, large waves develop, they splash on the window just opposite to the original film location and resolidify. These conditions are also favorable for entrainment and removal completely from the test section. On the other hand for J_g^* greater than one, significant downstream relocation is observed. Now the waves have no time to grow and therefore no splashing at all is observed. If the downstream area is wettable the film continues rising until it freezes as shown in the pattern of Figure 5. If the downstream area is non-wetting the film is entrained, in the downstream region, into the air stream. Some splashes on the window opposite this area and resolidifies, and some entrained as small droplets moves rapidly out the exit of the test section. These

droplets were moving with velocities as high as 5.5 ft/sec.

The most interesting discovery is that the two-phase multiplier under these transient conditions were found to be much lower than predicted by the steady-state correlations. This means less film/air interaction, hence, less air flow diversion (due to radial incoherencies). Hence for the two-phase region we will predict higher air flow but less momentum transfer to the liquid. The two effects appear to just balance and the net effect on clad velocities we have calculated previously (Nuclear Engineering and Design 36, 59 (1976)), accounting for the expected degree of radial (melting) incoherencies, would not be great. At present we are repeating this analysis with the correct transient two-phase multipliers that we have determined experimentally.

It has been previously accepted that molten clad wets solid fuel. Just recently R. Ostenson of ANL has reported that the expected wetting would be poor. Until this question is settled clad relocation dynamics should be considered as a film relocation process and/or as an entrainment process. An entrainment process in general would favor incomplete diffuse (thick) downstream plugs. A film relocation process, on the other hand would favor more complete and thin (for reactor conditions) downstream plugs. So would also a film process which disintegrated into a sluglet flow regime. The steel plugs observed in R-series in the upper reflector region were thin and complete. However a factor, not present in the R-series tests, that would tend to promote clad entrainment, or even affect available driving forces for clad relocation, is the venting of the high pressure plenum fission gas of irradiated pins. As mentioned elsewhere in this report, for the CRBRP LOFA, this gas will still be venting for the

duration of the clad relocation process and it should be given some consideration.

Considering everything discussed it is still our judgement that our use of a clad relocation velocity of 80 cm/sec is a reasonable upper bound on the associate reactivity feedback.

I.3 Freezing and Plugging (T. G. Theofanous)

The primary effort during this quarter has been to refine the experimental apparatus and the techniques, for experimentation and data acquisition, based on the observations and ideas derived from the studies reported in the previous quarterly. Further the apparatus has been modified to accept metals as well as molten glass. Preliminary data have been obtained and it looks like that all relevant conditions can be controlled precisely as desired.

In considering the clad freezing problem in the upper blanket, it appears now that there is no doubt that the solidification potential, expressed by the magnitude of the parameter $f = C_p \Delta T / h_{fs} \sqrt{\pi}$ (as defined in previous quarterlies), is so great that for the velocities expected to occur under LOFA conditions the rapid formation of thin plugs would be expected. If such plugs had time to form, i.e. under "slow" LOFA accidents, prior to fuel disruption, they would impede fuel removal from the core region. For the "fast" LOFA scenarios, on the other hand, there is not enough time for motion and plug formation. Molten fuel now would be mixed with molten cladding, in relatively fine dispersion, and as such would enter the cold blanket and fission-gas plenum region. Freezing and plugging phenomena now would be rather complicated and a number of phenomena would be relevant

to the outcome. In view of the uncertainties in initial conditions a number of approaches, or view points, must be examined to cover all possibilities.

(a) Consider just molten fuel at 3200°K (just above melting) entering the blanket and solidifying on the blanket UO_2 pellets, i.e. neglect all value of cladding. The solid boundary layer would build at such a rate that complete plugging would be expected in less than a second. The corresponding penetration can be obtained from a knowledge (or guess!) of the velocity. Velocities expected under such conditions would not be much greater than a few feet per second. Hence even this upper-bound calculation would indicate complete plugging.

(b) In reality, however, the role of steel cannot be neglected and it would always cause a smaller penetration distance. Consider for example the blanket steel at 1200°K receiving molten fuel. Even with fuel temperature just above the melting point (in fact substantially higher values would be expected) the contact temperature would be above the melting point of steel. The chaotic fluid motions then would tend to entrain the very thin fuel crust that would break-off as the steel melts and expands. This would lead to a bulk-solidification process of the type specified by Ostenson and Jackson. Under such conditions very short penetration distances would be expected. What is needed now is to better define the physics of the bulk penetration model, and it is hoped that the currently obtained data with our new experimental set-up will aid us in doing so. Further in considering this model the limited amount of steel in the above core region must be taken into consideration. That is why the details of melting and

entrainment are needed in order to study the bulk thermal interaction properly. According to the original Ostenson-Jackson model only the heat lost through the channel boundaries is considered. In fact molten steel will be entrained at least 1,000°C cooler than the surrounding molten fuel. It, therefore, represents a significant volume-distributed heat sink which when taken into account yields even shorter penetration distances.

Taking into account the above mentioned mechanisms we obtain $X = 6.6 \cdot 10^{-3} U$ cm, where U is fuel velocity in cm/sec and X is the penetration distance. Neglecting the steel heat up mentioned in the previous paragraph the result is $X = 18.8 \cdot 10^{-3} U$ cm. It is thus seen that even extremely high fuel velocities would lead to very small penetration distances.

I.4 Assessment of Core-Wide Incoherencies for LOFA*

Intra-subassembly incoherencies have played an important role in recent advances of our understanding of the phenomenology of wholecore accident evolution. Inter-subassembly incoherencies, on the other hand, although readily recognizable have been acknowledged only implicitly. It has been generally expected that they would play a beneficial role in reducing in a significant way, the calculated power transients. The complete lack of an explicit treatment however must be attributed to the inadequacy of current analytical tools. The latter have evolved in the direction of detailed modelling of local phenomena, and became limited to a 10-channel arrangement. Currently several laboratories are working on removing this limitation. Since such efforts are of no small magnitude and not likely to provide results in the very near future we sought an alternative approach better suited to current needs. The approach is based on the observation that the reactivity contribution of individual physical processes, as they occur in the course of a whole-core accident, take place on a time scale small compared to that of the accident itself. Taking advantage of this observation the required degree of incoherency can be achieved by appropriately reshuffling the subassembly groupings at several key times in the evolution of the accident. The 10-channel SAS3A version is quite adequate for this procedure, which will be illustrated for a particular loss-of-flow accident scenario for the CRBRP.

It is well known that for reactors with a "large" sodium voiding reactivity feedback some particular choices of SAS input parameters can produce energetic phenomena during the initiating phase. These phenomena are generally referred to as LOF-driven-TOP phenomena. Interestingly enough, core-wide

* J. Massey, L. Lois (REG), and T. G. Theofanous

incoherencies as portrayed in a 10-channel calculation are responsible for such events, which originate due to TOP conditions induced due to sodium voiding, clad and fuel relocation taking place in portions of the core while other portions are still full of sodium. Such calculated events have caused major concern, even though, in the opinion of many workers in the field, such calculated results appeared quite pessimistic in relation to what might actually be expected. Assuming the existence of such accident conditions no apparent arguments appeared feasible to reach within the framework of the original calculations. The results of the proposed method, on the other hand, indicates that at least for the CRBRP the potential for a clear cut argument in favor of significant reduction in LOF-driven-TOP severity exists.

In the calculations discussed here the most energetic case currently calculated for the CRBRP was selected to illustrate the magnitude of the incoherence effects. This involves the assumption of no axial expansion feedback, and no fission gases available for dispersal in SLUMPY. For clad motion we have considered two cases: (a) as predicted by CLAZAS and (b) accounting for intra-subassembly clad melting incoherencies. The first approach produces clad velocities up to 240 cm/sec and in our opinion represents a gross overprediction. The second approach produces clad velocities around 80 cm/sec and in our opinion it represents a more reasonable upper bound. We have demonstrated earlier that the second choice produces a significantly more benign behavior as compared to the results of the first one. Here we will show the additional reduction of initiating phase reactivity rates due to core-wide incoherencies.

The objective of this channel-subassembly reshuffling is to place the minimum number of subassemblies in a SAS channel when they are undergoing

a process which adds significant amounts of reactivity. In order to accomplish this, the assignment of subassemblies to SAS channels was varied during the accident. In the voiding sequence, those subassemblies which had high power to flow ratios and would undergo voiding first were placed in channels by themselves. Orifice zone and Power-to-Flow rates were the factors used for grouping the remaining subassemblies. In processes which occur later, such as clad motion, those subassemblies that were undergoing clad motion were left in a subassembly per channel geometry while the lower powered subassemblies were rearranged to give less coherence to their voiding reactivity. During the next sequence those subassemblies that were completely voided, (having added all their available coolant reactivity), were placed in the same channel while those undergoing clad motion were left in a subassembly per channel arrangement. Subassemblies which were about to undergo fuel slumping or FCI were arranged as close to subassembly per channel geometry as possible. At this time Power and Burnup became the important parameters for specifying subassemblies to be grouped together.

In implementing the previously described procedure care had to be taken to insure a continuity of power and net reactivity from one arrangement to another. In order to have a new arrangement start at time t with the conditions that already exist from the previous sequence the net reactivity history already calculated was used to determine the state of the new arrangement at time t . In this manner the conditions, i.e. power, void positions, fuel temperatures etc. of the individual subassemblies were approximately the same in going from one arrangement to another. This method of interfacing two different arrangements gave the necessary continuity of power, reactivity, and reactivity rates.

From early trials of reshuffling subassembly arrangements at certain times, it was found that indeed the procedure did not cause or introduce any artificial discontinuities in core parameters. Further since the channel rearrangements were introduced at their proper times the core was provided the opportunity to reach to the transient with as much incoherence as is presently possible. The major result of this procedure is that the accident time scale is expanded, reactivity and power exhibiting smoother behavior and slower rise, and hence affect the core conditions at the time of FCI.

Only a small sample of results are included in this abstract. For the purpose of this discussion the traditional 10-channel SAS model will be referred to as L-Model (for lumped model), while that of the present analysis as DP-Model (for distributed parameter model). Using this definition the key events in each accident sequence as determined by the various models are summarized in Table 1. It is seen that 25% fewer subassemblies were voided in the DP-Model at the end of the early voiding in the high powered channels (Initial Voiding Phase). Also an 18% decrease in net reactivity was noticed prior to clad motion. This difference was also noted in the power level at this time. Throughout the remainder of the accident the DP-Model showed consistently longer times for initiation of major events (caused mainly by the incoherence of the early voiding) and decreases in reactivity additions during these events. Also the introduction of the previously described assumption (page 2) on the incoherence of clad motion was used and significantly reduced the reactivity effects of this process, (down by 61%). This decrease lead to the long delay in the initiation of FCI, and gave the core a chance to void further. The reactivities at the inception of FCI were approximately the same for all cases (reactivity from slumping tended to equalize all cases

Table I
Comparison of DP and L Models

		DP Model		L Model	
I	Number subassemblies started voiding at end of initial voiding phase (@ 12.30 sec)	54		72	
II	Net reactivity prior to clad motion	.7141\$ @ 12.395 sec		.8798\$ @ 12.327	
III	Normalized power to prior clad motion	4.5187 @ 12.39		11.3800 @ 12.33	
		incoherent clad motion <u>DP-Model I</u>	coherent <u>DP-Model II</u>	incoherent clad motion <u>L-Model I</u>	coherent <u>L-Model II</u>
IV	Clad reactivity after .177 sec of motion	.085\$	.2175\$	.085\$	.3717
V	Net reactivity at start of slumping	.824\$	.9052\$	.864\$	.853\$
VI	Net reactivity at start of FCI	1.01045\$	1.00285\$	1.004\$	1.020\$
VII	Number subassemblies with a significant amount of voiding at start of FCI*2	102		72	
VIII	Average net reactivity rate leading into FCI ($\Delta\rho/\Delta t$)	~1.072\$/sec	~1.48\$/sec	~2.98\$/sec	~4.72\$/sec
IX	Average $\Delta\rho/\Delta t$ after start of FCI*1	7.946\$/sec	(run not carried past FCI)	26.44\$/sec	62.45\$/sec
X	Time @ start of clad motion	12.4320 sec.	Same	12.3266	Same
XI	Time @ start of slumping	12.763 sec.	12.5706	12.546	12.457
XII	Time @ start of FCI	12.7997 sec.	12.6120	12.5857	12.5077

*1→ Significant is considered to mean approx. half of subassembly voided.

*2→ Ramp rate caused by initiation of FCI in the first channel.

just before FCI), but the ramp rate following FCI for the DP-Model showed a significant reduction: down from 26\$/sec for the L-Model I and from 62\$/sec for the L-Model II to 8\$/sec for the DP-Model. The major cause for this reduction was the fewer subassemblies available for FCI (i.e. more of the core in the DP-Model was already voided) in the DP-Model. This reduction in the number of subassemblies which were available to undergo FCI and the subsequent reduction in ramp rates considerably reduces the work potential of the following disassembly. In conclusion it is noted that core-wide incoherencies should be pursued further as they may considerably alter the evaluation of the accident. In the particular case of LOF driven TOP events the proposed method appears to have the potential for providing some insight as to what degree these phenomena might affect the accident scenario. In general, however, if a realistic approach to accident modelling is to be sought, the distributed nature of core behavior must be vigorously pursued.

I.5 Upper Fuel-Blanket Segment Behavior (T. G. Theofanous)

We became interested in this problem with the idea that radial fuel expansion might be helpful in driving, through the wire-wrap, one pin against another and against the S/A wall thus producing an essentially solid matrix. If this were to happen, it would limit, or at least reduce, slumping of the upper fuel segment. It would also affect plenum fission gas-release and tend to limit the rates of fuel ejection from the remaining gases (see also Section II.1).

From SAS calculations, just before slumping, the fuel radius increased in the range of 0.0003-0.0007 in. Of course clad expands more but it is in the range of (or already) melting. Also fuel is quite plastic at this point. It does not appear that the case can be clearly made based on fuel expansion alone. Work is continuing.

TASK II. RECRITICALITY CONSIDERATIONS

II.1. Plenum Fission Gas Induced Recriticality (J. Massey and T. G. Theofanous)

The plenum fission gas found at pressures as high as 50 atmospheres represents a significant amount of stored energy, whose effects must be carefully assessed, both under normal and accident conditions. It has been looked at previously as a potential source for fuel pin failure propagation as well as a driving force for rapid voiding during accident conditions. From the standpoint of these studies one would look for upper bounds on discharge rates. On the other hand, there is some experimental information, from operating reactors, that fuel pin failures do not lead to rapid, catastrophic, release of the high pressure fission gas. In such calculations the impedance of the fuel/clad gap must be considered. It is our assessment that times of the order of one second would be required for venting the fission-gas plenum volume, following clad failure. Further, the nature of this venting process is such that it would not appear amenable to very precise calculation especially under accident conditions involving power transients.

From the point of view of the Loss-of-Flow accident it is clear that as the time-scale for the accident scenario is compressed the time available for uneventful venting decreases. Uneventful venting can be accomplished prior to the loss of strength of the fuel column. Should significant pressure remain instead, one would expect buckling of the fuel column, and pin disruption, in a mode that forces the upper remaining solid segment to the lower one. The resulting reactivity insertion could touch off a chain reaction among the remaining (unvented) fuel pins resulting to disassembly.

Even the so-called mild CRBR LOFA cases (axial expansion, no clad motion, fission-gas fuel dispersal) are fast compared to those of the FFTF, and the time-scale required for gas venting. It would appear, therefore, that during

the sodium-voiding induced power transient, at some point, some pins, will be "caught" into the sequence favoring the just outlined fuel compaction phenomena. In order to gain some insight into the possible phenomenology we have performed two SAS calculations. In the first (Case A) it was assumed that all pins retained sufficient fission-gas plenum pressure to cause aggravated slumping upon slumping initiation. In the second (Case B), it was assumed that the first two channels to void (channels 1 & 2) had sufficient time to vent all their gas-plenum pressure. The remaining pins retained their plenum pressures. Forced slumping was simulated by inputting an appropriate gravitational acceleration. In order to prevent the liquid fuel from draining too fast its viscosity was increased by a large factor. The two cases were run with no axial expansion feedback, clad velocity of 80 cm/sec, and no fission gas induced fuel dispersal. It is expected, however, that with forced slumping the scenario would not be very sensitive to these assumptions. The role of the fission gas plenum pressure was not considered in channels undergoing FCIs.

For Case A fuel slumps in channel 2, within 740 msec from clad melting, with a melt fraction of 50%, at a power level of 11P. The net reactivity is 80¢. Within a few milliseconds channels 1, 3, 4 & 5 successively slump and bring the reactor super prompt critical. At this point the reactivity is greatly moderated by Doppler feedback. The resulting power transient induces FCIs in channels 7, 8, 9, & 10 and the concomitant reactivity rates. By that time the power level is more than 600 X normal and increasing rapidly. Hydrodynamic disassembly conditions now exist and the calculation was terminated.

The scenario of case B developed along quite different lines. Now following the slumping of channels 3, 4, & 5 under subprompt critical conditions, FCIs in channels 7, 9, 8 and 10 result, and conditions for a moderately severe hydrodynamic disassembly develop.

It should be pointed out, that the above are preliminary results. Careful examination is continuing to check against internal inconsistencies or physically unreasonable phenomena, especially since substantial differences from the usual LOFA cases exist. It does appear, however, that for "fast" cores a thorough examination of possible deleterious effects from the fission-gases is in order. These effects have the potential to further aggravate difficulties and uncertainties already present with respect to the interplay between normal fuel slumping and fission gas dispersal as affecting likelihood, extend and magnitude of FCIs from pin failures in unvoided channels.

Even for "slow" cores this problem needs careful examination. All phenomena relevant to venting time-scales under accident conditions need study to reduce and better understand the relevant uncertainties. Finally, TREAT-type experiments with all important prototype features would seem appropriate.

II.2 Transition-to-the-Transition Phase (T. G. Theofanous)

Insofar as recriticality is concerned current work seems to be concentrating in whole-core fuel-steel pools. In most cases quasi-static approaches are employed by considering a subcritical (dispersed) pool and examining its potential for collapse under the influence of boundary losses, internal heat sinks, or pressure generation at the boundary.

Given the weak upper core structure of the CRBRP, as compared to that of the FFTF, it would appear worthwhile examining the termination potential

from relatively mild pressures (power bursts) prior to ever entering the transition phase, pool configuration. The relevant time period would encompass the post-SAS (provided initiating phase phenomena did not yield hydrodynamic disassembly), and pre-Transition Phase period. It is hence called Transition-to-the-Transition Phase, or Tr-to-Tr Phase for short. This period is dominated by fuel motion and associated reactivity and power histories. It would last till a major portion of the S/A walls have melted or till relief can be achieved by blowing out the above core structure. The time scale for melting to occur would be of the order of a few seconds. Since one would expect each subassembly exit plugged, such a time scale would yield ample opportunity for several cycles of oscillatory fuel motion within each channel. Small power bursts would therefore not be unlikely, and hence a termination via steel and/or vapor pressures prior to entering the transition phase.

Let us consider the sequence of the phenomena in order. We will assume that LOF-driven-TOP disassembly has been initiated by fission-gas fuel dispersal at some appropriate power level. At this time the fuel in about 1/3 of the core (high power) is partially molten, the clad is not too far above its melting point and the two are well interdispersed. The fuel removal from the core region ceases upon entering the cold areas both above and below the core. Now fission gases separate out and thus increase the reactivity of the system. Due to large core-wide incoherencies in this process as well as due to the mild nature of the separation process itself one would not expect large recriticalities to result. It is important now to recall that fuel melts at 3,000°K and boils a mere 400°K later. Steel on the other hand melts at 1700°K and boils 1,400°K later. At normal power levels and with no losses the fuel

heats up at a rate of 250°C/sec. With almost all the cladding well intermixed with the fuel, itself (cladding) being nearly 3 power-seconds away from boiling, and the continual addition of new steel, at its melting temperature, due to can wall melting, it appears that the burst would most likely terminate by fuel vapor pressures. That is, motion away from the center would be expected. The resulting sluggish motion could lead to another burst and so on till the moderate pressures, of the order of 150 psi, required to breach the upper core structure, just as the subassembly walls have lost their strength, are achieved by steel vapor pressures. A mild, energetically, termination is thus envisioned.

Carefully planned in-pile experiments appear necessary to investigate Tr-to-Tr Phase phenomena. Subassembly size experiments would suffice as having the proper surface-to-volume ratio. Behavior under power transients, such as fuel motion, wall attack, and pressure buildup would be desirable. Meanwhile, small scale experiments using simulant fluid, should prove helpful. Our experimental facilities, in this area, are presently being assembled. Experimentation is scheduled to start in August, 1976.

II.3 Thermal-to-Mechanical Energy Conversion (T. G. Theofanous)

Several years ago (Theofanous and Fauske ANL/RAS 72/71) it was determined that should the "then calculated" FFTF HCDA, FCI interaction zone pass through the fission gas plenum the cold steel structure would dissipate a major portion of the energy. This is due to the high interfacial area available (about 10 cm² area per cm³ entering this zone), and the large temperature driving forces. This credit is not presently claimed-for in accident analyses due to uncertainties of the interaction between the expanding high pressure

zone and the upper core structure (i.e. penetration versus flowing-off). The role of the steel, already mixed with the fuel, however, has not been taken into consideration in the CRBRP energetics as yet. In fact, it is expected that most of the cladding would be well mixed with the fuel in the core region for the duration of an LOFA. That is, clad between 20 and 30% of the fuel quantity should be available in a well mixed state. The question is, should conditions of hydrodynamic disassembly develop, what would the role of steel be in the thermal-to-mechanical energy conversion process. Further the role of steel must be examined during the disassembly phase itself.

Both processes are of similar time duration of the order of 10 msec, for typical conditions. During disassembly, the motions are not as violent, as in the subsequent expansion process, but there is better liquid/liquid contact due to the lower void fraction. Due to the short times involved we will consider conduction controlled heat transfer. For an initial fuel temperature of 5,800°K and initial steel temperature of 2,000°K the total heat flow in 10 msec is 130 msec/cm². Assuming an area of 3 cm² per 0.2 cm³ of fuel we obtain 390 J total energy transfer. This energy comes from a thermal boundary layer in the fuel of approximately equal to 0.07 mm i.e. ~18% of the clad thickness. Clearly, in the same time interval the cladding will have achieved nearly uniform temperature. With these numbers, approximately 5% of the fuel has been affected by heat transfer and cooled down. No significant pressure would result from the heated cladding. Based on these numbers it is concluded that the steel is not likely to provide a working fluid during the expansion, nor is it possible to support, at this time, large amounts of energy dissipation due to its presence. Further no substantial steel effects would be expected during disassembly. As before pressure would not develop, nor will the Doppler feedback be

substantially degraded due fuel cooldown. These results depend, of course, on the degree of dispersion assumed. It is difficult to envision an order of magnitude greater interfacial area, however.

In a completely different approach, representing the opposite extreme of the one just considered we have assumed all the fuel to achieve equilibrium (parametrically) with 30%, 60%, or 100% of the steel present. Now in some cases both fuel and steel pressures contributed to the sodium slug energy at impact, however, no order of magnitude differences were observed compared to currently utilized fuel expansion calculations.

It is desirable to better define the above mentioned processes and approaches. An experiment, now designed for implementation in the next fiscal year, will help in making such determinations. At such time the role of sodium found within the core during disassembly will be also assessed. At present all these phenomena together with potential entrainment during the expansion into the sodium pool, are useful in providing a proper perspective of the uncertainties associated with mechanical energy release calculations.

Figure 1

PRESSURE TRANSIENT AT CENTER OF REGION FOR ONE DIMENSIONAL UNIFORM HEATING

Figure 2

PRESSURE TRANSIENTS AT CENTER OF REGION FOR ONE DIMENSIONAL UNIFORM HEATING

Figure 3

VELOCITY TRANSIENT AT END OF REGION FOR ONE DIMENSIONAL HEATING

a

b

Fig. 4. Clad relocation experiment. (a) Frame of test section.
(b) Final disposition of material for a run with $J_g^* \approx 0.7$.

(a)

(b)

Fig. 5. Clad relocation experiment. Final disposition of material.
(a) $J_g^* = 1$ (b) $J_g^* = 1.2$