FUEL FAILURE PROPAGATION AND SOME ASPECTS OF DESIGN-SAFETY INTERACTION IN LMFBR

E. U. KHAN,

Babcock and Wilcox Co.,
Nuclear Power Generation Division, Lynchburg, Virginia, U.S.A.

ABSTRACT

Under normal or near normal operating conditions there are potentially four causes of fuel failure propagation in LMFBR's. These are briefly described. Models have been developed to predict the possibility of fuel failure propagation within the core. These have shown that fission gas-blanketing should not lead to failure propagation beyond one assembly. It appears that the detrimental affect of nuclear transients occurring during normal operation on fuel failure propagation can be designed out. Thus, small scale flow blockage caused by pin motion, cladding deformation of an initially defective pin, fuel swelling and fuel debris are the most serious mechanism which could lead to fuel failure and to fuel failure propagation. A reactor core with good coolant mixing and strong, well designed assembly cans may delay propagation of failure to other assemblies. Any delay in failure propagation may be as good as preventing it if there are adequate detection devices with timely operation of counteraction systems.

1. INTRODUCTION

Some fuel pin failures may be expected to occur during normal operation and at any time during the lifetime of the core. The results of such failures and the consequences of continued operation following a fuel failure are important areas of concern in the design, operation and evaluation of safety for liquid metal fast breeder reactors. Fuel failure propagation, if it occurs, can lead to disastrous situations. Initially local coolant disturbances could lead to large coolant disturbances like sodium voiding. This may cause degradation of heat transfer and a reactivity addition, causing fuel melting and slumping with further reactivity increase, leading to core disruption and vessel damage.

In order to determine if propagation of a failure will occur and the extent of propagation if it does (i.e., does a single element failure lead to the failure of a few adjacent elements, a sub-assembly or a large section of the core), it is necessary to identify all initiating mechanisms, the mode of failure transport through the coolant from the initial failure to the neighboring element and the effects of the failure of neighboring elements that can continue the failure propagation through the coolant to other fuel elements. (Fig. 1)

2. INITIATING MECHANISMS

The four potential initiating mechanisms that may occur during normal operation are discussed in the order of their importance on failure propagation.

2-1: Gas Blanketing-Degradation of heat transfer and reactivity effects due to neutron hardening are the consequences of gas blanketing.

2-2: Overpower Transient-Nuclear transients occurring during normal reactor operation are expected not to exceed 120% of full power, yet combined with other initiating mechanisms it can either initiate failure or enhance the rate of fuel failure propagation.

2-3: A Defective Fuel Rod-A fuel rod initially defective or which has failed in a previous transient can be a source of fuel failure propagation. An initial cladding breach might enlarge due to thermal cycling and/or corrosion.

2-4: Flow Blockage-Flow starvation combined with rapid heat generation during operation at power can initiate fuel failures by reactivity addition and thermal effects.

3. FUEL FAILURE CRITERIA

A fuel rod is said to have failed if the cladding loses its integrity. Any failure criteria must necessarily be conservative and applicable at all burnups. Each initiating mechanism might have associated with it a failure criteria. For example, gas blanketing could raise the temperature of the cladding to failure without any fuel melting, whereas a power transient may cause center line fuel melting without any significant increase in cladding temperature. The molten fuel could conceivably find a path to the cladding and burn a hole through it.

The fuel failure criteria depends upon the fuel rod design. For example, lower density fuel can survive more extensive fuel melting during power transients than higher density fuel if all other design parameters were the same. For the same limiting strain, an unvented fuel rod would fail before a vented fuel rod during a power excursion. On the other hand, the problem of growth of undetected blockages from long term effects such as fuel swelling in logged sodium favors the use of unvented design.

In the fuel rod designs under study, the cladding is assumed to fail if it exceeds 0.2% strain under normal or near normal operating conditions. This might be very conservative early in life, but at high burnups the cladding becomes brittle. Analysis shows that if the fuel rod in Fig. 2 has an initial density of 90% TD (theoretical density), it can survive up to 10% weight fraction of molten fuel at the top of the core or 20% at the core midplane. If the initial density is 85% TD it will be able to survive up to 15% weight fraction of molten fuel at the top of the core or 60% at the core midplane whichever occurs first. Under operating conditions the following fuel failure criteria appears to be conservative. The inception of center line melting during an overpower accident and the cladding temperature rising above 1350°F for the other accidents would cause the fuel rod to fail. For example, if fission gas release degrades heat transfer for the surrounding pins, then the rate of fuel failure propagation depends upon how rapidly neighboring fuel rod cladding attain a temperature of 1350°F. Once boiling begins and leads to Na-fuel interaction, the fuel failure criteria is changed since this is a condition far from normal. Now it is assumed that a neighboring pin fails by molten fuel ejection.

4. GAS BLANKETING

In an unvented fuel rod a breach or rupture in the cladding can cause fission gas to be released. The gas release rate depends upon the internal gas pressure (burnup), the rupture characteristics (area and shape), the internal impedance of the pin, etc. The effect on adjacent pins depends upon the gas release rate, the geometry and the flow into which the gas is released.

It is now established (2) that the effects of fission gas release are largely hydrodynamic and so the ability to predict the possibility of fuel failure propagation produced by fission gas release depends largely upon the ability to predict the resulting flow transient.

It is convenient to define three regimes of gas release depending upon their effects on the hydrodynamics of channels and possibly on fuel failure propagation.

A. Rapid release of fission gas occurs if it causes flow reversal in the channel or in the whole assembly. The hydraulic transient causes thermal insulation of adjacent pins for the period of flow reversal.

B. Medium rates of gas release produces a persistent gas jet which can impinge on adjacent fuel rods and could cause adjacent rod failure due to local overheating of the cladding. The gas jet does not have enough energy to reverse the flow.

C. Slow rates of gas release into a sub-channel causes reduction in local flow. This is because of an increase in pressure drop in the channel as a two-phase mixture flows upwards. The gas release rate may not be high enough to penetrate through the liquid and impinge on adjacent rods. A significant reduction in local flow rates could cause overheating of the pins.

4-1: Gas Release Rates

The following important parameters were varied in the gas release studies by Carelli (3):

a. rod burnup (up to 75,000 MWD/T)

b. fission gas pressure inside the fuel rod (up to 300 psi)

c. area of rupture in fuel rod 10^{-4} to 10^{-1} in.^{2}

d. location of rupture: bottom, middle and top of core and bottom of the fission gas plenum

e. fission gas internal impedance
    1. annulus between fuel and cladding at low burnups (up to 25,000 MWD/T)
    2. through cracks in fuel and internal void (a conservative estimate of ten cracks was assumed)

The thermal-hydrodynamic analysis has been done separately for each regime, using Carelli's gas release rates.

4-2: Rapid Gas Release

Experiments performed at ANL (4) have shown that flow reversal occurs in a 19 pin assembly if high pressure fission gas is released into the coolant stream from large holes. If the initial pressure of the fission gas was 800 psi, the critical size was approximately

10^{-2} in.^{2}. For a typical LMFBR assembly containing 217 pins with fission gas plenum at 800 psi, flow reversal does not occur until at least three pins fail simultaneously and gas is released from a hole larger than the rupture size mentioned before. Fig. 3 shows that if ten pins fail in the FFTF simultaneously, flow reversal would occur in the whole assembly for 100-200 msec before complete flow recovery. The cladding temperature rise would not be greater than 100°F. Moreover the possibility of ten pins failing simultaneously in this manner, under normal conditions of operation, is quite remote.

4-3: Medium Rate of Gas Release

PFR experiments (5) were performed for the intermediate gas release rates using water flowing through a 7 rod bundle with an axial velocity of about 20 ft/sec. The experiments show that if the gas pressure inside the fuel rod exceeds the flow channel pressure by about 30 psi, gas will impinge on the adjacent rod.

For the LMFBR under consideration if the fuel rod is blanketed by the vapor for less than 0.35 sec. its temperature does not exceed 1350°F. Carelli's gas release rate curves were plotted for pressure vs. time for various hole sizes for the worst case of internal gas pressure of 300 psi. It was found that rupture holes in excess of 0.015 in. diameter cannot cause sustained blanketing that will lead to failure of adjacent pins. With the help of additional PFR data (6) it was possible to show that jets from ruptured holes smaller than 0.015 in. diameter caused blanketing of only a very small portion of one adjacent rod. This would at the most cuase paired failures A to B, B to A type, without any further propagation. Further evidence of this is seen in the Mark II A assembly in Dounreay where, despite failure of 23 high burnup pins in buoyant downflow conditions where released gases could remain for a considerable period, there was no evidence of propagation beyond possible paired failures.

4-4: Slow Rate of Gas Release

Gas will be released slowly for an extended period of time if the impedance in its path before emergance from the fuel rod, is high. A very small area of ruptured hole can provide high impedance as can a flow through the fuel rod cracks. Fig. 4 shows the variation of fission gas mass flow rate and pressure when a rupture occurs at the center of the core. The path followed by the gas before it emerges is from the top plenum through the fuel cracks into the central void and again through the fuel cracks to the ruptured cladding (shown in dotted in Fig. 2). Fig. 4 also shows the variation of sub-channel velocity. Fig. 5 shows the maximum cladding temperature in adjacent rod for various sizes of rupture areas. Flow mixing by diversion cross-flow were included in calculating these temperatures. Diversion cross-flow from one channel to another would occur if there is a radial pressure difference between adjacent channels. It appears that the maximum temperature attained by an adjacent rod does not exceed 1250°F. The probability of fuel failure of an adjacent rod and fuel failure propagation is quite remote.

5. OVER POWER TRANSIENT

During the lifetime of its first core, an LMFBR may be expected to experience some over power transients. Such an over power limit would not exceed 120% of full power.

The current LMFBR designs (e.g., FFTF) take this into account by insuring no fuel melting at the hot spot location at the over power condition. Nevertheless it is necessary to have a knowledge of the safety margins for the design pins to establish what design features increase these margins.

During an over power transient fuel failure could occur by molten fuel contacting the cladding. The driving force for the molten fuel is the fission gas pressure. Since fuel expands by about 10% in volume on melting, the fission gas in the central void can be compressed to very high pressures. Hikido and Field (7) found that rods that allow pressure relief could withstand considerably more melting in a power excursion accident. This perhaps is due to the fact that the large driving force necessary to push a very viscous fluid like molten fuel through very tiny cracks in the fuel, is not available. For the same smear density of the fuel rod a pressure relief system would offer a bigger safety margin.

Fig. 6a shows a fuel rod with built-in pressure relief system. A sudden increase in central void pressure due to fuel melting could be relieved by fission gas passing into the upper plenum through a hole drilled in the axial blanket. The author suggests that a fuel pellet sit on top of the axial blanket to act as a valve, permitting flow of gas out of the central void but not permitting flow in the reverse direction. The advantage of such a valve is that it prevents the fission gas from acting as a driving force for molten fuel in case of cladding rupture in the active part of the fuel rod.

Fig. 6b shows a considerable reduction in the fuel-cladding interface pressure during a reactivity insertion accident for the fuel rod design with pressure relief. It is obvious that fuel failure propagation can be delayed considerably, if not avoided, even in accidents with a large rate of reactivity addition. The computer program FORE-II was used to determine the fuel melting rate during reactivity addition of 25 cents per second.

More experiments are necessary to get an optimum design of such a fuel rod. However, it is very unlikely that fuel failure will initiate or propagate during an over power transient.

6. DEFECTIVE FUEL ROD AND FLOW BLOCKAGE

A defective pin is one with an undetected defect in the cladding. Even though the possibility of such a pin passing quality assurance inspections is remote, a pin might become defective during transient and cycling, and might be a source of fuel failure propagation. Two other sources of failure propagation, though very unlikely, exist. A high enriched subassembly containing a defective fuel pin is erroneously loaded into a low enrichment core position. The other possibility is that a high burnup assembly containing a defective fuel pin is erroneously reloaded into the core in a higher rated position than it previously occupied.

Flow blockage can occur as a result of clad deformation, pin motion, or fuel debris. Small scale coolant blockages appear to be potentially more serious problems than do large coolant blockages. The latter can be detected and the reactor shut down in a timely manner without extensive propagation or the potential for large object blockage may be designed out.

Partial or full blockage of sub-channels is likely to lead to high localized temperatures. As pointed out by Gast and Smidt (8) if some sub-channels are blocked locally by objects at the spacers, behind the blockage there will be a wake. If this occurs in the area of a 7-rod cluster at the center rod boiling may occur over a length of several cm. The bubble expands to all sides into the subcooled sodium outside of the 7-rod cluster and recontracts very quickly. Because of the rapid recondensation rate it will probably completely collapse and again start growing. The authors also indicate that experimental investigations do not exist so far. The Fuel Failure Mockup (FFM) experiments (9) should provide valuable insight into the flow blockage problem in the near future.

At this time the possibility can not be dismissed that the localized voiding and condensation behind a blockage might lead to fuel failure propagation. Fig. 7 shows the cladding temperature rise for various periods of loss of cooling in the FFTF operating at about thirteen kw/ft. It is obvious that the bubble voiding and collapse period determines how soon cladding failure in the adjacent rods occurs. The bubble voiding and collapse period would depend upon sodium super-heat, degree of subcooling in the average fluid, area available for condensation of the void, rate of evaporation of a thin film left behind on the cladding walls, etc. Once the cladding fails and fission gas is released behind the blockage further degradation of heat transfer could cause fuel melting. If heat transfer is lost to a part of the fuel at full reactor power fuel melting starts within about 1.5 sec. The worst consequence of fuel rod failure with a part of the fuel inside in the molten state is that molten fuel might eject out of the fuel rod and come in contact with the flowing sodium outside. The resulting-sodium-fuel interaction can cause high pressure pulses, structural deformation and fuel failure propagation (10). The probability of fuel failure propagation and its rate of propagation is discussed in the next section. The initiating mechanism is flow blockage with or without the effect of other initiators. It must be made clear that section 7 discusses the worst case, where flow-blockage might have led to sodium-fuel interaction. It is also important to note that only one fuel pin is assumed to initially contain fuel in the molten state. Once molten fuel ejects from this pin it interacts with the sodium flowing in the adjacent sub-channel [initially the ratio of mass of sodium to mass of fuel would be very large (low work-energy) and would gradually decrease (higher work energy) to a critical ratio (maximum work energy)]. The sodium vapor void formed due to sodium fuel interaction behaves initially in a manner similar to the boiling void description of Gast and Smidt, i.e., it expands, condenses and contracts bringing with it liquid sodium which again interacts with the molten fuel. This process is repeated until adjacent pins fail by deformation or degradation in heat transfer. Once a large number of pins fail by molten fuel ejection the consequences of sodium-fuel interaction would be to first void the whole assembly, and then this void expands upwards and downwards (11).

7. FUEL FAILURE PROPAGATION DUE TO SODIUM-FUEL INTERACTION

7-1.1 Model for molten fuel ejection

The driving force for the molten fuel is the fission gas pressure within the rod. The rate of molten fuel ejection depends upon the driving force, the area of rupture, frictional resistance to flow, and the molten fuel properties. A simplified but conservative model (Fig. 8, Ref. 3) assumes molten fuel driven by fission gas with negligible fuel impedance to flow. The area of the rupture is varied. The fission gas pressure for the purpose of this study is assumed to be 800 psi and the initial pressure in the coolant channel is 100 psi. If a large volume of fission gas is present its pressure falls slowly, and the rate of molten fuel ejection remains high. If somehow a high impedence can be introduced between the fission gas and the molten fuel, the driving force for molten fuel would rapidly fall. This is the reason for the fuel pellet valve shown in the fuel rod design of Fig. 6a.

Two extreme cases of molten fuel ejection were considered. First, it was assumed that the molten fuel ejects through a ruptured hole of 10^{-2} in.^{2}, for 0.1 sec. In the second case it was assumed that molten fuel ejects continuously. These two cases are extremes, and all other cases would fall in between.

7-1.2 Model for Sodium-Fuel Interaction

The magnitude and duration of the pressure pulse and the work-energy of sodium-fuel interaction depends upon numerous factors. The exact value of these parameters is the subject of numerous investigations. A parametric study is the best resort, till better experimental data is available. The size of dispersed fuel particles, the heat transfer coefficient from particle to sodium, the presence and the amount of fission gas, the liquid superheat and condensation heat transfer coefficient are but a few parameters studied using computer models (11) developed at B&W. The destructive work-energy is also very much dependent on the mass of sodium and mass of fuel involved. For very high rates of M_{Na}/M_{fuel} and for low masses of fuel (first case of molten fuel ejection) work energies are low.

Appendix I contains a brief description of the basic models used to evaluate pressure pulse and sodium-fuel interaction. The model described is modified to predict growth and collapse of a 3-dimensional void within a reactor subassembly.

7-1.3 Model for Rod-Deformation

Fuel rods can use one of a number of kinds of spacers to support them axially. It appears from a safety point of view that wire wraps might be superior to grid types since considerable deformation due to high pressure pulse can occur at midspan between grids. In this study, analysis on rod deformation due to pressure pulse was not performed. Instead it was assumed that the pressure pulse deformed the rod such that it deflects by 10, 25, 40 and 50 mils. This was done to get conservative results and also to retain a geometry that was easily amenable to thermal-hydraulic calculations.

7-2 Molten Fuel Ejects for a Short Duration (∿0.1 sec.)

The duration of molten fuel ejection is chosen arbitrarily. If molten fuel ceases to eject after a short duration, fuel failure propagation is mainly governed by the extent of damage due to the pressure pulse. The maximum pressure attained was about 950 psi in the accoustic dominated region, but the energy of the shock wave was too low to cause damage. In the inertially constrained phase the maximum pressure was less than 400 psi at 0.0165 sec. and rapidly decreased. The total work-energy was less than 0.004 MW-sec. Its damaging effect was very small and it appears fuel failure propagation will not occur if no more Na-fuel interaction takes place and if void condensation and coolant re-entry takes place within about a second. Nevertheless, consider the worst case of Na-fuel interaction which causes an adjacent rod to be displaced by 10, 25, 40 or 50 mils due to the loading as shown in Fig. 9. Channels 28 and 29 are reduced in area and boiling may initiate in these channels due to reduced coolant flow. Fig. 10 shows the temperature rise as a function of rod displacement for various mixing coefficients. The computer program COBRAII was used for channel thermal-hydraulic calculations. We see that with 3% mixing the maximum temperature in channel 28 due to a 50 mil displacement is only 1300°F. If 0% mixing is considered, channel 28 boils. In the former case, fuel failure propagation might not occur whereas in the latter case it might.

It appears then that if only a small amount of molten fuel ejects, fuel failure propagation depends upon damage caused by the sodium fuel interaction. Interchannel mixing could delay or possibly avoid fuel failure propagation. It also appears that wire wraps might promote mixing and prevent rod deformations and hence seem to be superior to spacer grids.

7-3 Continuous Ejection of Molten Fuel

If molten fuel is released continuously only from the initially failed rod, the rate of fuel failure propagation would depend not only on the structural damage, but also on the number of rows of rods the void (formed due to Na-fuel interaction) extends in the radial direction. This, in turn, depends upon the axial constraints and the energy generated during sodium fuel reaction, the geometry, the resistance coefficient to void expansion in transverse direction, etc. Once sodium-fuel interact a three-dimensional void is formed. As the pressure in the void reduces due to void expansion and condensation, it collapses. Sodium is again accessible to the fuel. It voids again, and this may continue as long as molten fuel ejects out of the original pin or an adjacent pin that has just failed due to degradation in heat transfer rate.

Fig. 11 shows the minimum rate of fuel failure propagation as a function of the average number of rows of rods the void extends to when it is formed. If the inertial restraints in the axial direction are large (i.e., static head, frictional force, etc.) compared to that in the radial direction, void spreads to the can wall rapidly. For short fuel assemblies with wire wraps the ratio of lateral to axial resistance would be relatively higher, and in the initial period of fuel ejection when we have a high ratio of mass of sodium to fuel, the type of void shown in Fig. 12 were formed. An analytical model for resistance coefficient to void expansion in transverse direction was incorporated in the analysis.

Once the majority of fuel pins fail and eject molten fuel, the work-energy in the sodium-fuel interaction may be very high. The consequences of sodium-fuel interaction would be different if a substantial amount of fuel in the assembly was molten, and then it came in contact with sodium. In this case the destructive effect of sodium-fuel interaction might predominate and cause fuel failure propagation from assembly to assembly.

8. IRRADIATION INDUCED METAL GROWTH

Swelling of non-fuel material in the core is very briefly discussed in this section, because its consequences appear to be a major problem for the reactor designer. The core-life time in a LMFBR may depend upon how economically swelling of non-fuel materials can be accommodated and not by the burnup capability of the fuel. Another reason for discussing swelling before section (9) is that it greatly effects sub-assembly can design. The subassembly wrapper cans are expected to act as a major barrier to damage propagation between assemblies.

A recent study at B&W indicates that, based on present day predictions and correlations, swelling (18) of non-fuel materials would necessitate modifications in core design. For example, it was found that a definite need for core-clamping existed. One of the advantages of a clamped core is that it would be expected to bow outwards during an accident. The other consequence of swelling included lowering cladding temperature and fluence, reduction in pin size and a greater ratio of cladding thickness to fuel diameter, increase in assembly length, lower discharge burnup and fuel cycle life. The two major considerations to account for swelling were to change fuel cycle life from 3 to 2 years and decrease average temperature level in the core. In order to accommodate fuel assembly deflections expected as a result of metal swelling gradient, the sodium gap between fuel assembly cans was extended.

Other safety implications, implicit in designs which account for swelling, included the effect of Doppler, sodium density and radial expansion coefficient. For example, if a core clamping scheme is selected for the core modified to account for swelling, it would effect the nature of radial expansion coefficient, e.g., currently radial expansion coefficient may be calculated on basis of uniform radial core expansion. A clamped core would have a non-uniform expansion which is a function of transient type, power level, power gradient, etc. Thus the bow is not only non-uniform axially, but the degree of bow may also be a function of radial position.

9. ASSEMBLY TO ASSEMBLY FUEL-FAILURE PROPAGATION

The pin to pin failure propagation study in section 7 assumed that each succeeding failure was of the same order of magnitude. If succeeding failure of pins becomes larger in as much that the work-energy continuously increases by order of magnitudes damage propagation to adjacent assemblies is possible unless the wrapper cans can present an adequate barrier to propagation.

Wrapper cans cannot be designed to totally prevent fuel failure propagation between assemblies if one assumes that the sodium-fuel interaction results in work-energy near its upper limit. At best, the cans may be expected to delay fuel failure propagation. From the safety point of view the longer this delay the better it is as it provides time for detection and operation of counteraction.

Some assembly wrapper can designs account for swelling by tapering (reducing the can thickness) the can in the active core region. From a safety point of view one desires the maximum can thickness in the active core region. A thicker can could withstand higher energy loadings and could delay penetration of the wrappers by molten fuel. One solution would be to increase the spacing between adjacent wrapper cans since thicker cans can now be accommodated. This would increase the core size which is an economic disadvantage.

The solution of the problem may at first sight appear to be a direct trade-off study. This would be reasonable if heavy weightage is given to reactor safety. It is the author's judgement that initial LMFBRs will have to give safety the first and the highest consideration. As the better analytical and experimental information on fuel failure, fuel failure propagation, swelling, better incore failure detection devices, etc. become available, it will be possible to have a more economical Fast Breeder Reactor.

The intent in this section was to give a qualitative analysis of the design-safety problems. Much experimental and analytical work is necessary to predict inter-assembly failure propagation.

10. CONCLUSION

Four potential causes of fuel failure propagation under normal operating conditions have been investigated. Present methods indicate that fission gas-blanketing would not lead to failure propagation. The presence of fission gas during sodium-fuel interaction might even be helpful as it reduces peak pressures in the accoustic region considerably (11). Apart from reducing the rate of heat transfer from molten fuel to sodium, it provides a cushioning effect, thereby further deviating the sodium-fuel interaction from a constant volume heat addition process.

Overpower transients should not lead to fuel failure propagation. A good fuel rod design would increase the safety margin.

Defective fuel rods and small flow blockage are the most serious mechanisms which could lead to fuel failure propagation. Good mixing could prevent fuel rod failure behind blockage and also prevent fuel failure propagation. Fuel Failure Mockup experiments would give much needed insight into the problem.

If boiling begins behind a blockage and if this leads to fuel melting and sodium-fuel interaction, fuel failure propagation may or may not occur as discussed earlier. The ratio of mass of sodium to fuel involved in the interaction may initially be very large and if fuel failure propagates, it decreases. First, the failure propagation would perhaps be by degradation of heat transfer to adjacent rods. As more rods fail, the destructive effect may begin to dominate, and subassembly to subassembly fuel failure propagation becomes important. A high ratio of lateral restraints to axial restraint and good mixing may delay assembly failure propagation. In other words, a small axial length of the assembly is desired. This not only reduces axial inertia but decreases the time of clad insulation by permitting a faster re-entry of the cold sodium. If the lateral resistance to void growth is large, (this can be accomplished by having small pitch wire wraps, closer spacing or rods, etc.) void growth in the transverse direction is reduced and pin to pin fuel failure propagation is delayed. A good can design may delay subassembly to subassembly propagation. For example, can walls may delay molten fuel penetration by about 30 sec. (17). LMFBR cans should be designed to withstand the high loadings arising from fuel-sodium interaction.

The effect of design-safety interaction on the rate of fuel failure propagation needs to be studied experimentally. The purpose of the paper was to indicate areas where further work needs to be done. For example, vented pins have several advantages. The problem of heat transfer degradation by fission gas release does not exist. A smaller fuel rod length and assembly lengths would be beneficial from a safety view point. On the other hand, the problem of swelling by sodium logging of pins exists for vented rods, and it appears that fission gas fuel failure propagation is not a problem anyway.

Fuel-density and fuel rod design could play an important role in increasing safety margins. Even though the designer would like to have the maximum fuel density for economic reasons, an increase in safety margin may require lowering the fuel density.

The spacer design, wire wraps vs. twisted ribbons vs. spacer grids can also be very important from the safety view point. Mixing by flow-sweeping and turbulent exchange could possibly prevent large flow disturbance, like boiling which could lead to more severe consequences. Mixing could also delay in-assembly fuel failure propagation (16).

Assembly wrapper cans play an important role in delaying fuel failure propagation between subassemblies. One aspect of design vs. safety implications in the design of these cans was discussed earlier. If fuel failure propagation can be delayed within an assembly and then from subassembly to subassembly, then with reliable in-core detection devices and timely operation of protective systems, further propagation can be prevented. The need for reliable and sensitive reactor instrumentation can not be over-emphasized.

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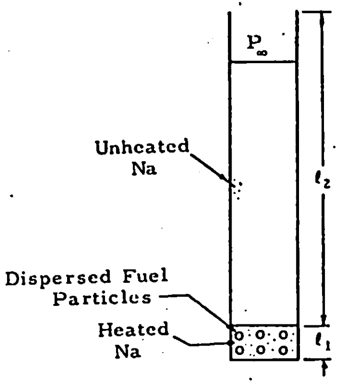
APPENDIX I: MODEL FOR NA-FUEL INTERACTION

1. INTRODUCTION



The simplified MFCDYN model consists of (1) a mixing region (length ℓ_1) where hot molten fuel is assumed to disperse instantaneously into small particles and transfers heat to sodium, and (2) an unheated column of sodium (length ℓ_2). Modified forms of this model have been used to predict a 3-D void growth described before.

Two approximations are made in evaluating the time effects of sodium-molten fuel interactions. The first is the acoustic approximation, which is followed by the inertial approximation.

1.1. Acoustic Approximation

The expansion of the heated volume produces compression (acoustic) waves in the unheated coolant. As this wave travels upward, it compresses layers of unheated liquid sodium. The liquid is assumed to be compressible, and the compressibility effects are dominant up to the time the wave first reflects back from the nearest reflecting surface. Further reflections of the wave are neglected. Hence, the approximation is valid only for the period of time up to $2(\ell_1 + \ell_2)/c_\infty$ where c_∞ is the speed of sound in the unheated sodium. Nonlinear propagation velocity and convection motion are also neglected. The "acoustic-constraint-dominated" period of the sodium-molten fuel interaction is much shorter than the inertial-dominated effect.

1.2. Inertial Approximation

This is a long-term effect. The liquid surrounding the "heated zone", which is the liquid column of height ℓ_2 here, is assumed to be incompressible. The expansion of the heated volume is resisted by the friction and inertia of the surrounding coolant. The approximation is valid for times greater than $2(\ell_1 + \ell_2)/c_\infty$.

The inertial constraint period could be further subdivided into two regions - one where the liquid in the heated volume has partially vaporized and the other when it has fully vaporized. It is possible for the fluid to remain in either of these regions for a considerable length of time, depending chiefly on the ratio of sodium and fuel mass.

2. FORMULATION

The mass, momentum and energy equations are solved simultaneously along with the equation of state both in the acoustic constrained and inertial constrained regions. Since the maximum pressures and temperatures reached in the interaction can be near the critical point, the Himpan (14) equation of state was used in the vapor phase.

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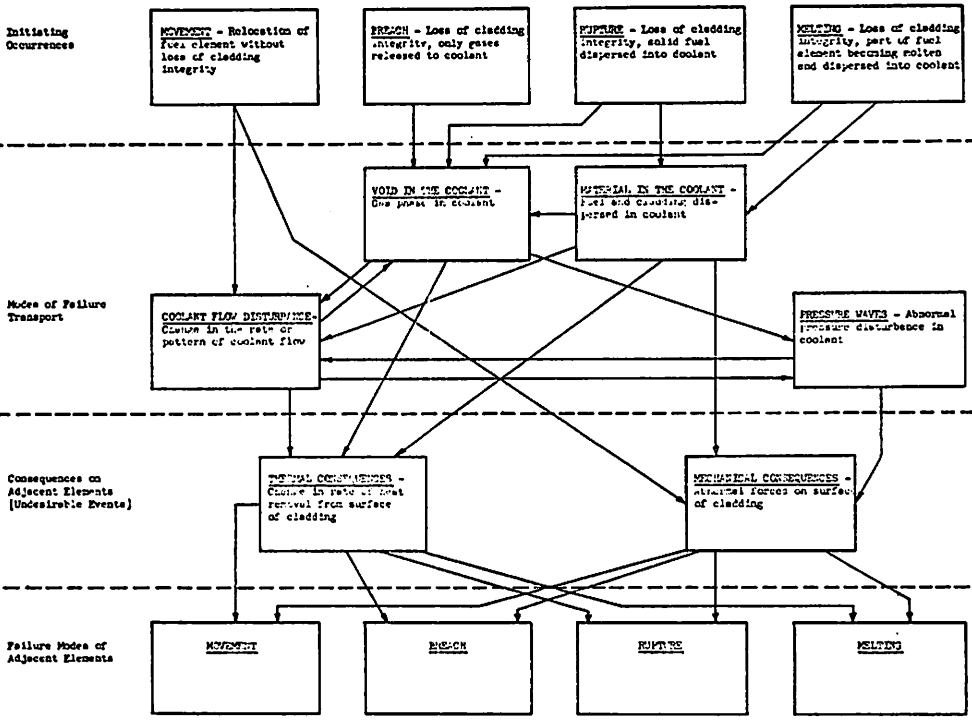

Figure 1. Sequence of Events in Failure Propagation Chain (1)

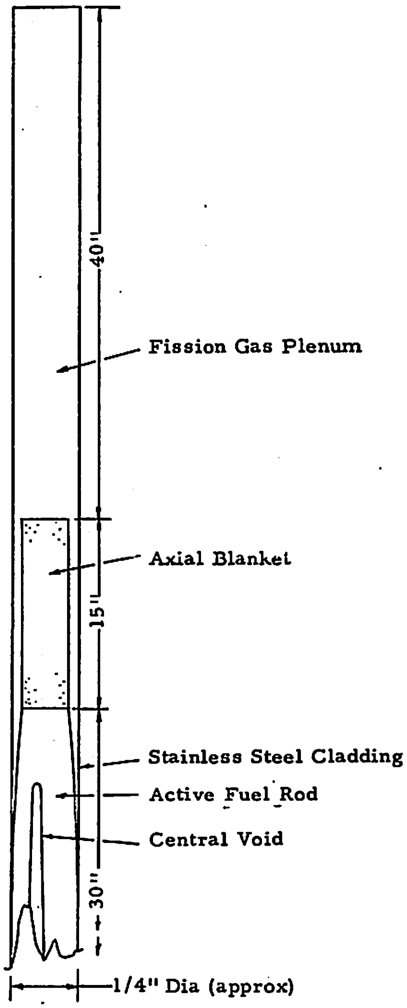

Figure 2. Typical LMFBR Fuel Rod at High Burnup — Schematic Drawing

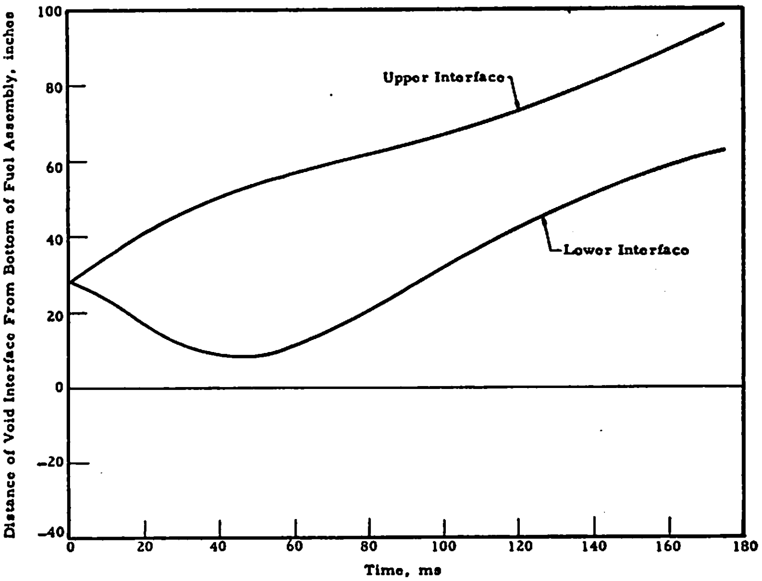

Figure 3. Voiding Due to Rapid Fission Gas Release if 10 Pins Fail Simultaneously

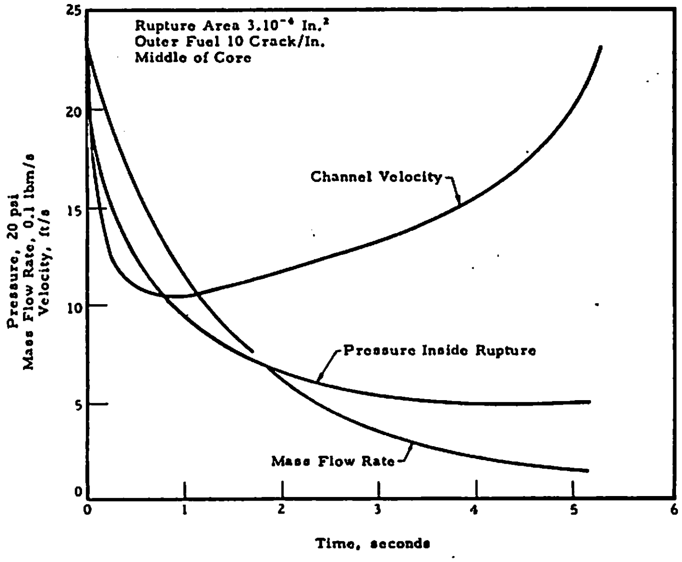

Figure 4. Velocity Variation Due to Fission Gas Injection Into Coolant

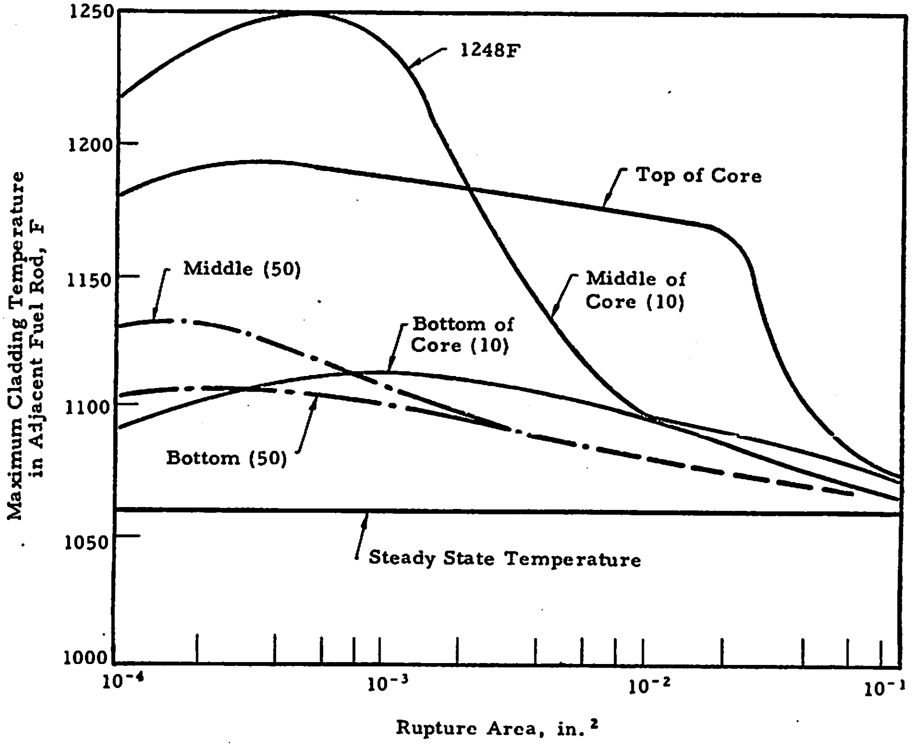

Figure 5. Consequences of Gas Ejection From High Burnup Fuel Rod

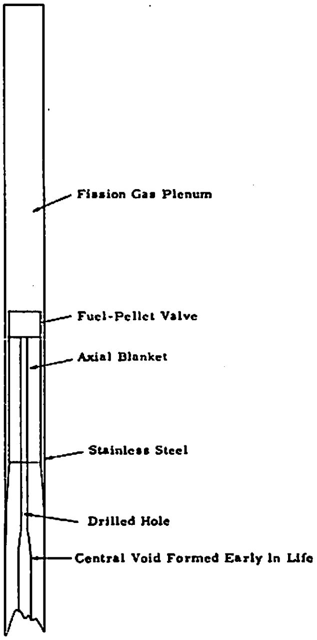

Figure 6a. Fuel Rod Design With Built-in Central Void and Valve

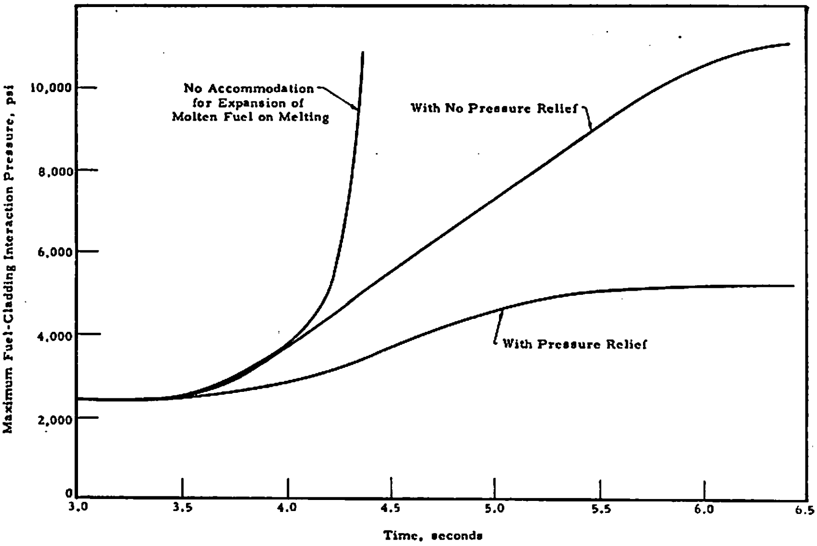

Figure 6b. Variation of Fuel-Cladding Interaction Pressure With Time for Reactivity Addition Accident of 25¢/s With No Scram

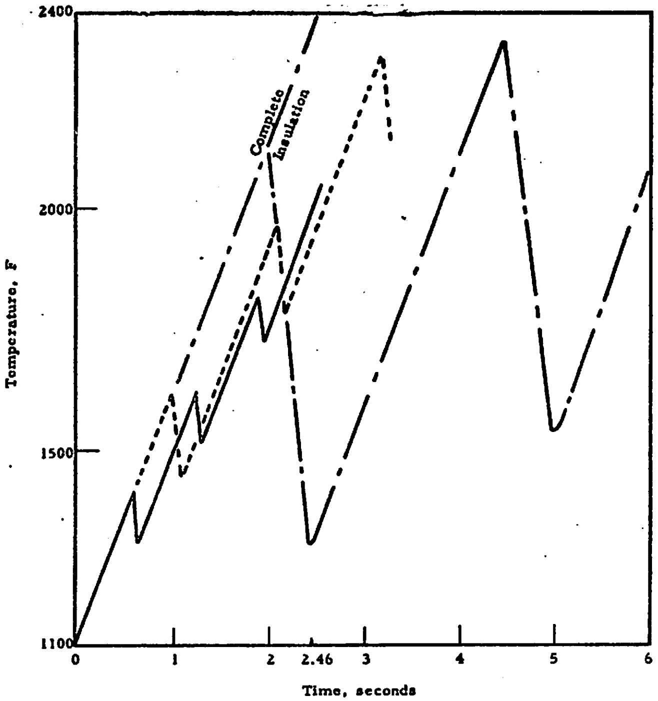

Figure 7. Cladding Temperature Rise During Chugging for Three Chug Cycles

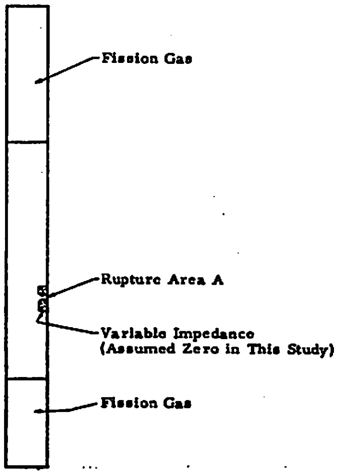

Figure 8. Conservative Model to Simulate Molten Fuel Ejection

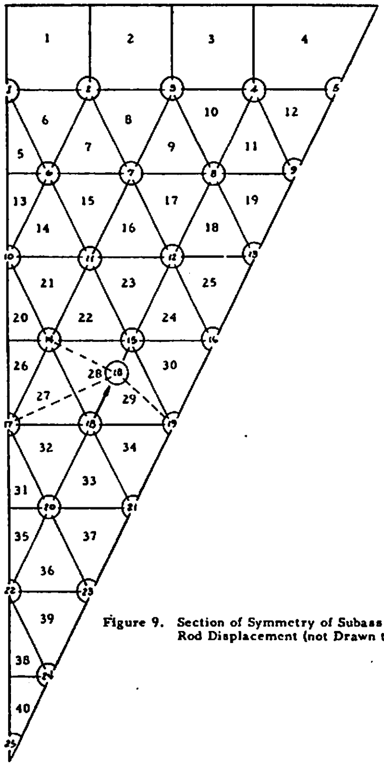

Figure 9. Section of Symmetry of Subassembly Showing Rod Displacement (not Drawn to Scale)

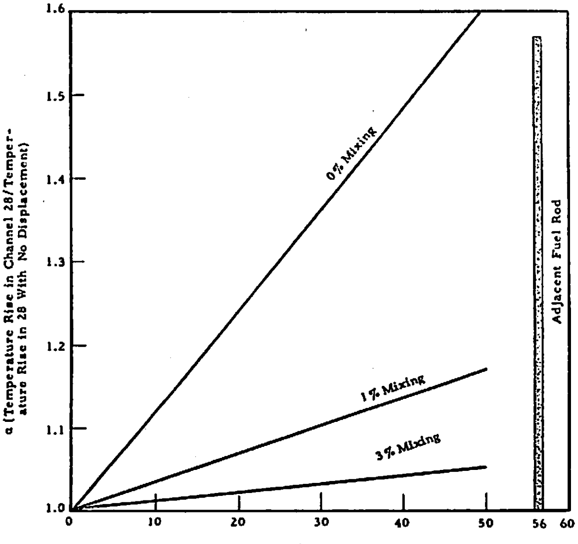

Figure 10. Temperature Rise in Channel 28 as Function of Rod Displacement

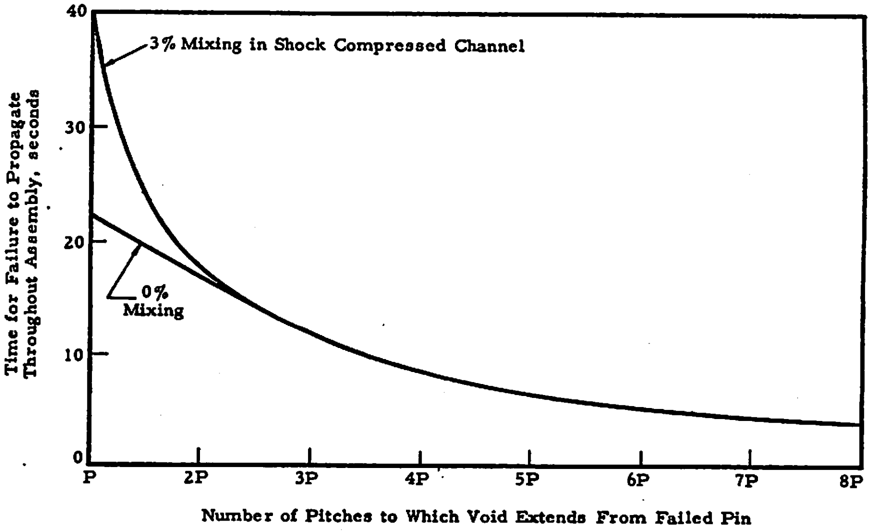

Figure 11. Effect of Radial Void Growth on Failure Propagation

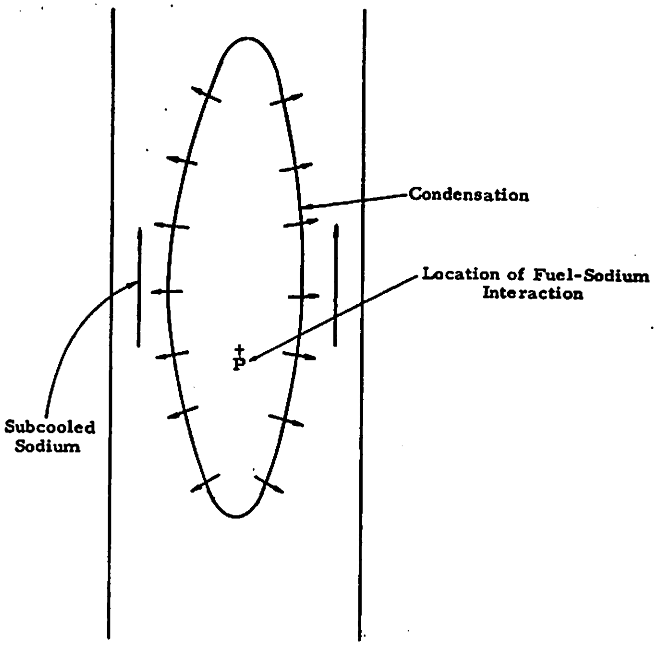

Figure 12. Three-Dimensional Void Formed in Early Stages of Na-Fuel Interaction (Fuel Rods not Shown)

DISCUSSION

Q M. BENDER, U. S. A.

Would the speaker comment on the use of probability analysis as a basis for evaluating nuclear safety experimental results ?

A E. U. KHAN i. a. R. A. VALENTIN, U. S. A.

I doubt whether probabilistic methods have any great future in the near-term. Exact analyses will be the order of the day until a great deal of operating experience has been gained.

C K. GAST, Germany

I would like to comment on the author's statement that failure propagation to adjacent subassemblies can be retarded by proper design of the wrapper tubes. I don't think that penetration of wrapper tubes by molten fuel is the most critical mechanism since it is rather slow. We are mainly concerned with the possibility that the sodium fuel interaction might cause reactivity effects and/or jam control rods.