2

Conf-921110--22

WSRC-MS--92-231

DE92 019678

# THE STEAM EXPLOSION POTENTIAL FOR AN UNSEATED SRS REACTOR SEPTIFOIL (U)

by

D. K. Allison, M. L. Hyder, and W. W. F. Yau

Westinghouse Savannah River Company
Savannah River Site
Aiken, South Carolina 29808

and

D. C. Smith

Science Applications International Corporation
Albuquerque, NM



A paper proposed for presentation at the
*1992 ASME Winter Annual Meeting*
Anaheim, CA
November 8 - 13, 1992

and for publication in the proceedings

# The Steam Explosion Potential for an Unseated SRS Reactor Septifoil

D. K. Allison, M. L. Hyder, and W. W. F. Yau
Westinghouse Savannah River Company
Aiken, SC

D. C. Smith
Science Applications International Corporation
Albuquerque, NM

## Abstract

Control rods in the Savannah River Site's K Reactor are contained within housings composed of seven channels ('septifoils'). Each septifoil is suspended from the top of the reactor and is normally seated on an upflow pin that channels coolant to the septifoil. Forced flow to the septifoil would be eliminated in the unlikely event of a septifoil unseated upon installation, i.e., if the septifoil is not aligned with its upflow pin. If this event were not detected, control rod melting and the interaction of molten metal with water might occur. This paper describes a methodology used to address the issue of steam explosions that might arise by this mechanism. The probability of occurrence of a damaging steam explosion given an unseated septifoil was found to be extremely low. The primary reasons are: (1) the high probability that melting will not occur, (2) the possibility of material holdup by contact with the outer septifoil housing, (3) the relative shallowness of the pool of water into which molten material might fall, (4) the probable absence of a

trigger, and (5) the relatively large energy release required to damage a nearby fuel assembly. The methodology is based upon the specification of conditions prevailing within the septifoil at the time molten material is expected to contact water, and upon information derived from the available experimental data base, supplemented by recent prototypic experiments.

## Introduction

Control rods in the Savannah River Site's K-Production Reactor are contained within housings called septifoils. Each septifoil (Figures 1 and 2) has space for seven rods suspended from the top of the reactor. At least two of the seven rods, including the central rod, are completely withdrawn prior to full power operation. The rods remaining in the core during operation are subject to neutron and gamma heating such that cooling is required.

Cooling water is supplied to individual septifoils via one inch lines connected to upflow pins upon which the septifoils must be seated (Figure 3). The septifoil outer housing is solid except for slots located just below the top shield of the reactor. When the septifoil is seated properly forced flow enters the septifoil through the upflow pin, exits through these slots, and mixes with the moderator in the reactor tank.

Forced flow through the septifoil would be eliminated if the septifoil were not seated upon its upflow pin (Figure 4). Such an event is extremely unlikely, especially in light of current installation and inspection procedures. However, the possibility of an unseated septifoil is still considered part of the design basis for the reactor and must be analyzed accordingly. With the loss of forced flow, cooling is possible only by natural convection. While calculations indicate that natural convection would be adequate to cool the control rods within the septifoil, enough uncertainty remains that overheating and melting of control rods must be considered. Of primary importance is the possibility that a damaging steam explosion, resulting from the contact of molten control rod material and water within the septifoil, lead to propagation of melting to nearby fuel assemblies.

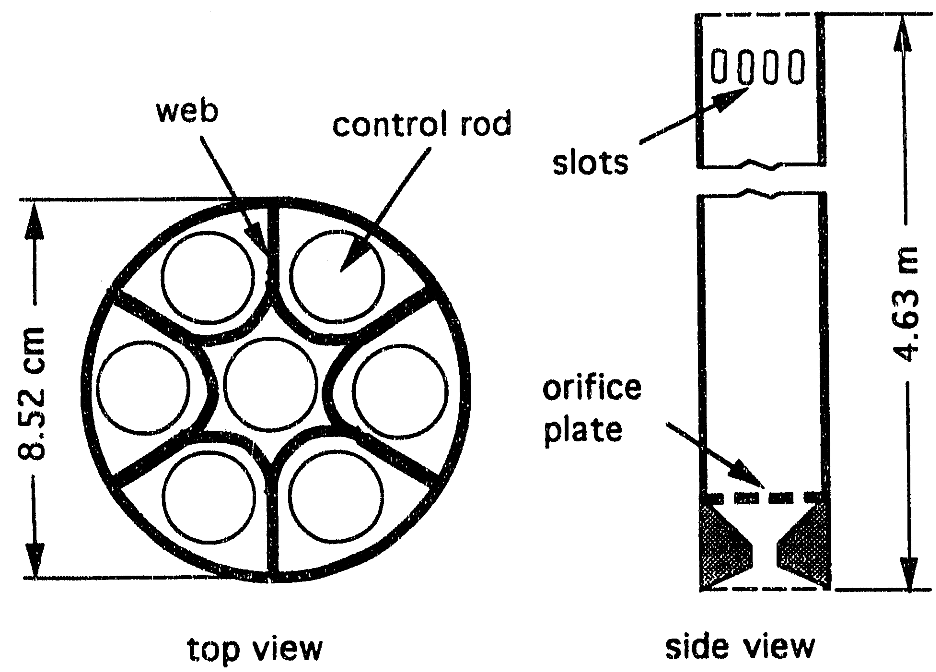



Figure 1. SRS Septifoil

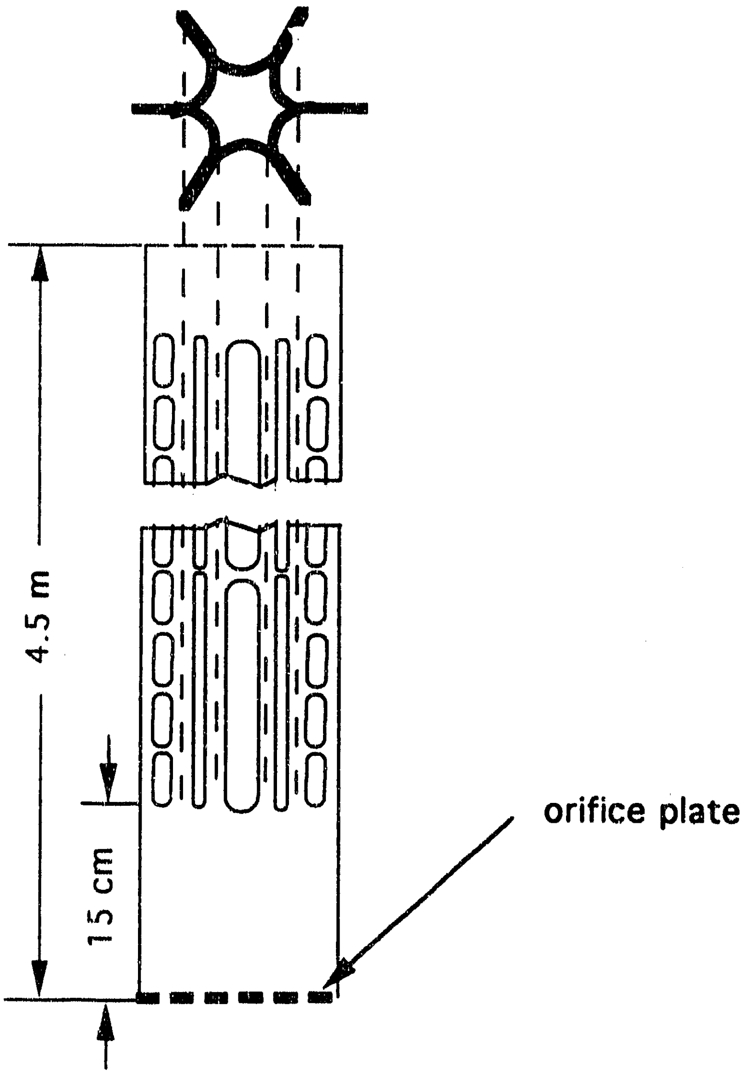



Figure 2. Septifoil Web

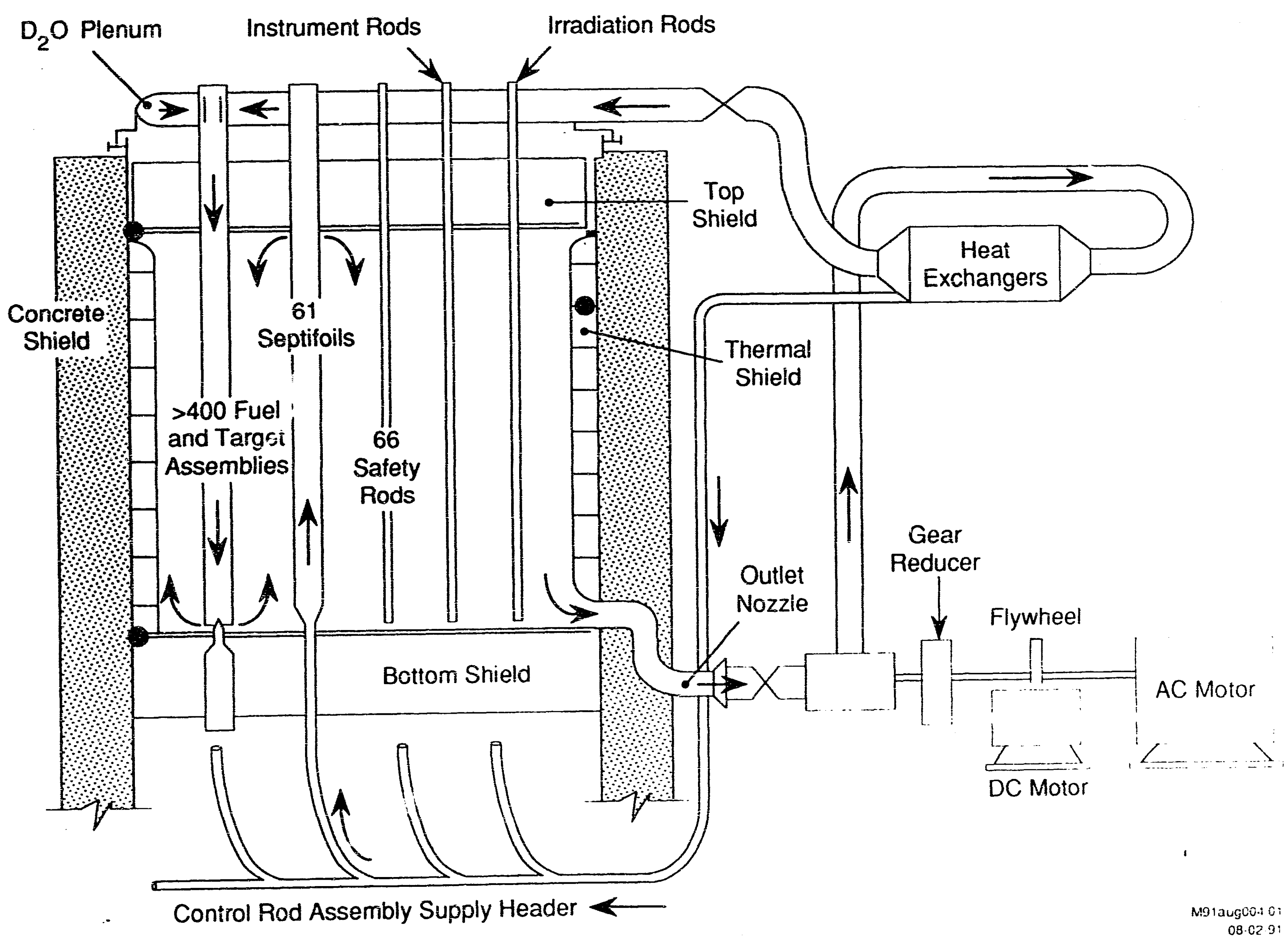



**Figure 3. Schematic diagram of the reactor coolant system**

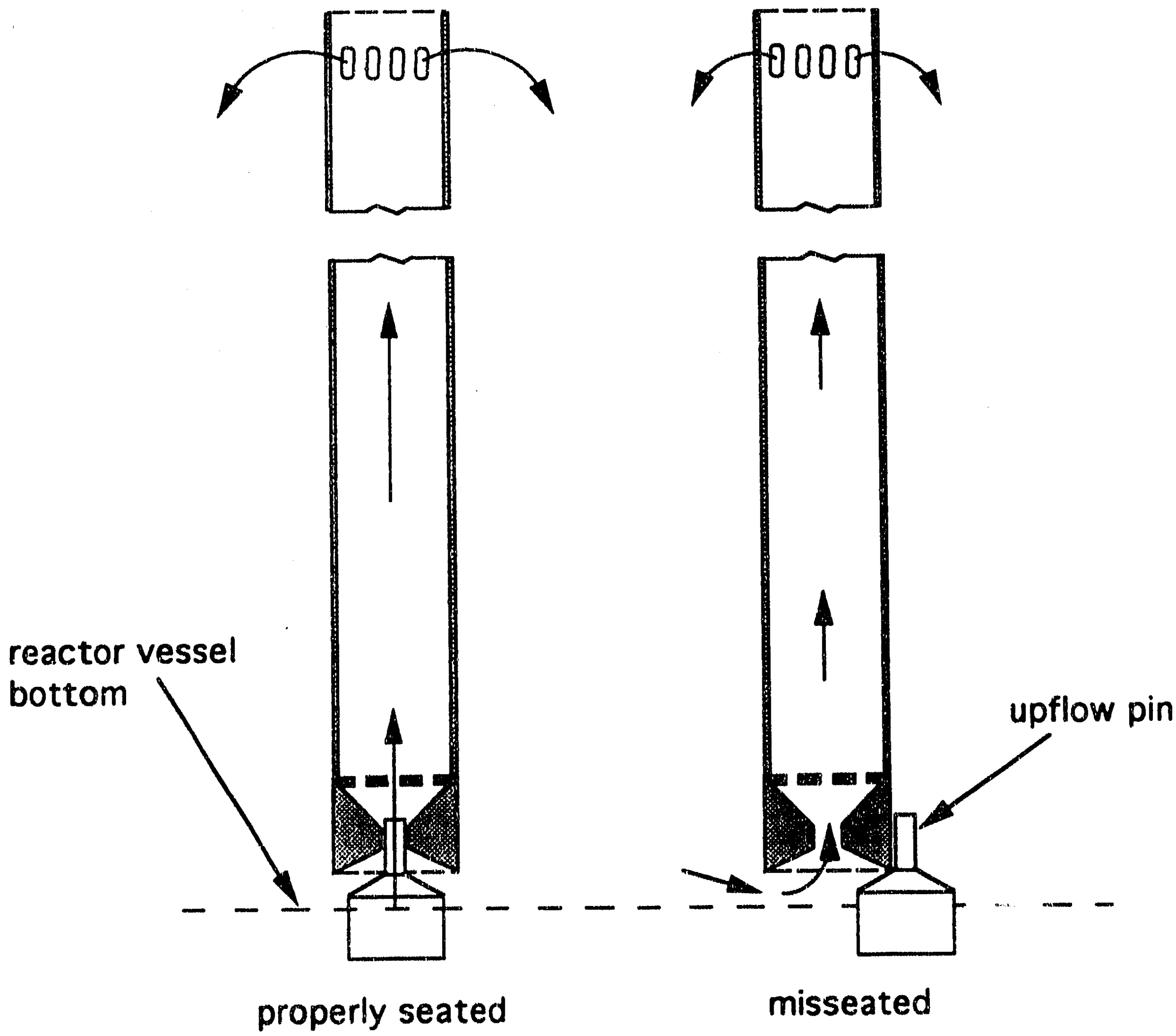



Figure 4. Septifoil Misseating

The term steam explosion refers to the rapid energy transfer that may occur when a hot fluid (such as a molten metal) is rapidly mixed with water. Experiments have shown that mixing alone is insufficient to cause an explosion; the system must be triggered by a pressure pulse that causes the breakdown of the vapor film surrounding the hot fluid. The pressure pulse may originate from without the system (an externally triggered explosion) or from within the system (a spontaneously triggered explosion). In either case, local breakdown of the vapor film propagates rapidly through the mixture until a significant amount of material is involved.

At present it is not possible to predict with certainty when an explosion will be triggered. Experiments have loosely determined what conditions favor triggering. The experimental data base is sparse, however, especially with regard to Al-Li alloys, the material of which the control rods are fabricated. Conclusions drawn from the data base are suspect and, for the present case, prototypic experiments were deemed necessary.

This paper describes work done to quantify the probability that a damaging steam explosion result from an unseated septifoil. This probability was obtained by examination of the expected progression of the accident and by comparing predicted conditions to those found experimentally to favor the triggering of steam explosions. Prototypic experiments were performed to strengthen the conclusion drawn from the experimental data base. The aim of this work was to determine if a steam explosion resulting from an unseated septifoil in the K-Production Reactor might be excluded from the rigorous treatment required of design basis accidents. Such exclusion would follow from an extremely low probability of occurrence.

## Method

Events resulting from reactor operation at power with an unseated septifoil are difficult to predict. A conservative calculation is precluded by the complexity of the situation. Reasonable estimates of conditions prevailing within the septifoil as a function of time have been made but much uncertainty remains. It was decided, therefore, to use a 'mechanistic tree' approach to the problem. With this approach, conditions necessary for the initiation of a steam explosion are considered sequentially, the result being the probability that all conditions prevail, i.e., the probability that a steam explosion occurs. For a steam explosion to occur, molten material must contact water. The rods must, therefore, experience critical heat flux (CHF) and melt, the melt must not be arrested by freezing on cooled surfaces or other rods, and a triggering mechanism must occur. Furthermore, the interaction must result in sufficient energy release to damage nearby assemblies before substantial core damage would occur.

## Occurrence of CHF and Melting

With the elimination of forced flow, cooling of the control rods occurs by natural circulation. Natural circulation cooling was analyzed using a simple steady state model, and using the Transient Reactor Analysis Code (TRAC) (reference 1). The analytical models predict that boiling will occur in the septifoil housing, and that a two-phase mixture will be discharged from the holes at the top of the housing. Melting of the control rods is prevented if nucleate boiling is maintained on the surface of the control rods. On the other hand, if the control rods exceed critical heat flux and transition to film boiling, the rods will probably melt.

Many empirically derived correlations for CHF in flow boiling exist in the literature. Many of the correlations, such as that presented by Katto (reference 2) indicate that nucleate boiling can be supported at very high vapor void fractions, corresponding to very high septifoil powers. These correlations were generally derived from data taken in uniformly heated circular tubes. Correlations published by Mishima (references 3 and 4) and El Genk (reference 5), however, suggest that geometry has a profound effect on CHF. In particular, the Mishima correlation indicates that for an annular geometry heated on the inside surface, premature dry-out occurs at a low void fraction, associated with the establishment of film flow on the unheated outer surface. The septifoil geometry is very complex, but incorporated a large amount of unheated surface. The Mishima correlation was therefore applied to the analytical results for septifoil cooling.

The results of the simple steady-state model indicated that CHF did not occur below approximately 50% of historical reactor power in an unseated septifoil. This study employed the homogeneous two-phase flow model that was found to be more conservative than either the Martinelli-Nelson model (reference 6) or the drift-flux model.

A detailed three-dimensional TRAC model was used to model the septifoil at 40% of historical reactor power. The TRAC code predicted a complex oscillatory flow pattern. TRAC did not predict the occurrence of CHF. The TRAC code employs the Biasi correlation (reference 7). This correlation does not, however, account for the geometrical effects that are apparent in the Mishima correlation. The TRAC results were therefore compared to the Mishima correlation. The comparison concluded that margin existed between the 40% power case and CHF. This tended to support the simple analysis.

Because the analysis held significant uncertainty, an experiment was conducted on a sub-scale model of the SRS reactor septifoil. The model consisted of a four-foot section of an actual septifoil housing complete with top and bottom fittings. Electrical heaters were substituted for the control rods. The test results indicated an unsteady oscillatory flow similar to the TRAC predictions, but CHF and transition to film boiling occurred at a power level below that anticipated based on the simple one-dimensional analysis of the test fixture using the Mishima CHF correlation. A detailed examination of the test fixture led to the conclusion that the results were likely an artifact of a discharge geometry that was not prototypic of the septifoil in the reactor. Insufficient instrumentation was available on the test to confirm these conclusions, however. The test results can be matched by globally increasing the two-phase flow resistance of the septifoil in the simple steady-state model by a large factor. Application of this modification to the analysis of the septifoil in the reactor reveals that CHF is still avoided in an unseated septifoil up to 31% of historical reactor power.

The foregoing gives a high probability that the septifoil is coolable at the proposed operating power of 30% historical power. This probability is estimated to be on the order of 99 in 100.

### Holdup Because of Contact with Cold Surfaces

If control rods within the septifoil can not be cooled by natural convection, melting and relocation of control rod material may ensue. Cooling is still possible if good thermal contact is made between the rod and the septifoil housing. Contact may occur because of swelling below the melting point or bridging of the gap between the rod and the housing by molten -material extruded through cracks in the housing. (The cladding has a higher melting point than the Al-Li alloy within the rod.)

Prior to reaching its melting temperature, a control rod may undergo substantial swelling as its temperature increases. Swelling results from volumetric expansion as gases within the rod expand. The assumption of a coolable geometry via control rod swelling alone (without melting) is unlikely unless the rod and housing are able to mold themselves together in such a way as to increase the surface area for heat transfer. However, control rod swelling will be accompanied by clad cracking followed by melting of the inner core of the control rod and extrusion of molten or foamed material through the cracks in the clad. Contact of this material with the outer housing of the septifoil will increase the effective heat transfer area and will, therefore, increase the likelihood that a coolable geometry will be assumed. Limited data exist, however, concerning the extent of swelling and clad cracking for control rods under accident conditions; predictions are difficult. It is estimated that material holdup and cooling because of swelling and cracking will occur approximately one third of the time. This judgment is based upon the experimental evidence concerning swelling and experiments with irradiated fuel which show the postulated behavior.

## Molten Material Falling into Water

If the control rod is not cooled and held up by contact with the septifoil housing, it will probably fail at a point near the point of maximum heat generation and separate into two pieces: one remaining in place; the other, falling to the orifice plate at the bottom of the septifoil. Molten material is expected to relocate in a continuous stream or in a series of drops from the bottom of the hanging portion of the rod (Figure 5).

Molten material contacting the piece of fallen control rod will freeze before it can travel a large distance down the side of the rod. Remelt of the relocated material will occur only if the fallen piece of control rod melts. This piece of control rod, if not cooled by residual water, will melt in much the same way as the intact control rod except separation of the piece into two smaller pieces will not occur. The fallen piece will candle beginning at its top. Within a few centimeters, sufficient material will relocate producing sufficient contact area with the outer housing to cool the system.

TRAC calculations were performed to estimate the thermal-hydraulic conditions within the septifoil in the case where melting occurs. To induce melting, a fully blocked septifoil had to be assumed. These calculations, performed at 30% historical power (the proposed operating power), show the void fraction to be high at elevations above ~ 1 m from the orifice plate because of vigorous boiling. Therefore, a portion of control rod extending initially more than ~1 m below core midplane will extend above the 'surface' of the water after it has fallen. Material relocating from the bottom of the hanging portion of control rod will be prevented from reaching the pool, at least in a manner favoring rapid mixing, and a steam explosion will not occur. A steam explosion is possible only with rods whose positions are such that they extend no more than ~ 1 m below core midplane during normal operation or with rods extending more than ~1 m below core midplane when the reactor power profile has a peak below core midplane. Technical specifications regarding the positioning of control rods during operation restrict to one the possible number of rods not extending more than ~1 m below core midplane.

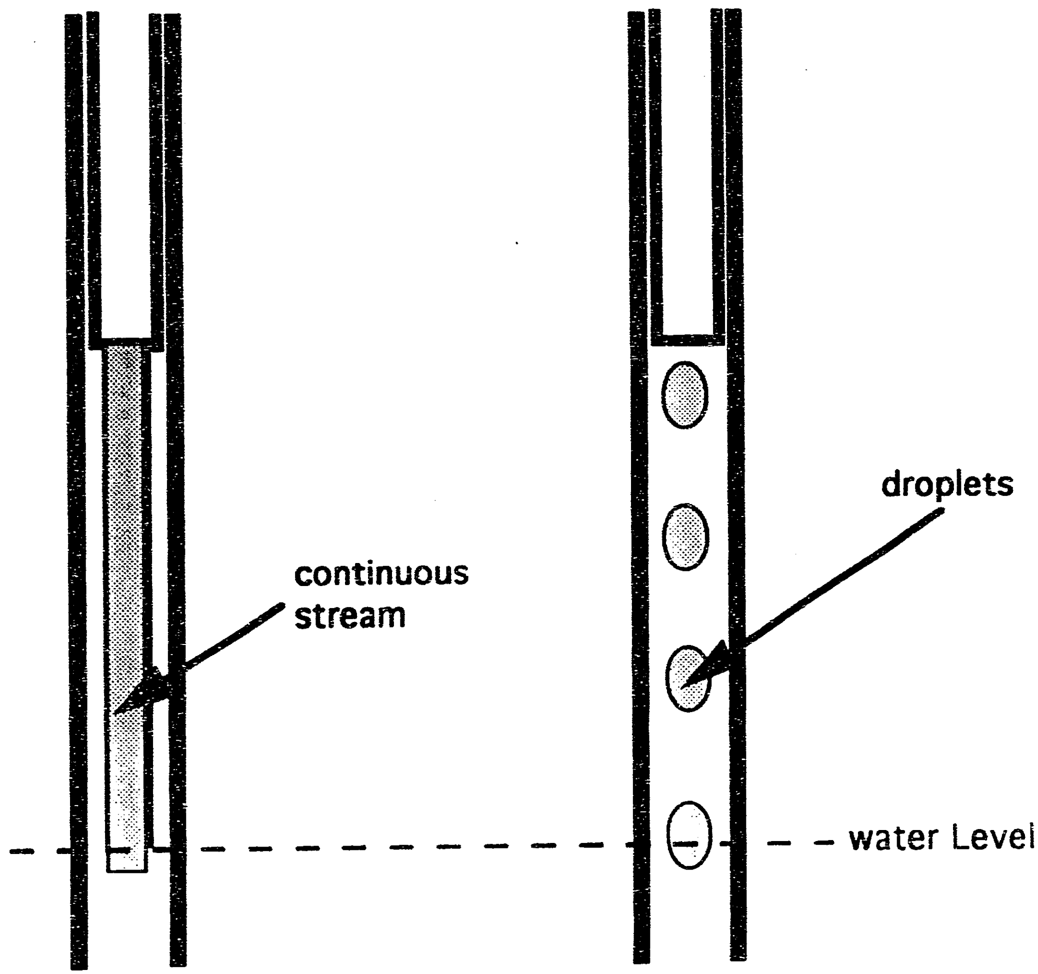



Figure 5. Contact Modes

Based upon an examination of past reactor power profiles and control rod positions, the likelihood that a control rod be in a position for which a steam explosion is possible is put at 20%

**Probability of Triggering**

Given that molten material has contacted water, the probability of steam explosion initiation can be estimated from the existing experimental data base. The aluminum industry and others have conducted numerous experiments over the years (see, e.g., references 8-10). Most have been 'pour' type experiments wherein molten material has been poured into a stagnant pool of water. Experiments have been performed with and without the application of external triggers. The results of untriggered experiments are thought to be most applicable to the current situation although a few plausible triggering scenarios have been investigated by G. A. Greene during the course of this work.

The important variables, as indicated by the data base, are the temperature of the melt relative to its melting temperature, the height and temperature of the pool of water into which the melt is poured, the diameter of the stream of molten material, the condition of the surface of the water container, and whether certain alloying elements, especially lithium, are present in the molten material. The probability of steam explosion initiation has been observed to increase as the melt superheat is increased; decrease as the pool depth is increased; increase as the stream size is increased; decrease as the water temperature is increased; increase as the wettability of a contacting surface is increased; and increase as the Li content of the melt is increased.

The effect of melt superheat on the triggering of steam explosions was found by Long (reference 11) to be strongly coupled to the pool depth.

The available experimental results indicate that non-externally triggered steam explosions with aluminum alloys are very rare without the assistance of a submerged surface. In a typical explosive experiment, molten metal traps water against a submerged surface and, it is hypothesized, the vaporization of this trapped water provides the trigger for the ensuing explosion. If one ignores the possibility of steam explosions initiated before the melt reaches a submerged surface and the possibility of initiation upon impact with the pool surface, the likelihood of steam explosion initiation can be expressed in terms of the likelihood that molten material contact a submerged surface and the likelihood that an interaction involving the surface trigger the explosion. If molten material can be prevented from reaching a submerged surface by freezing, aided possibly by fragmentation as it falls through the water, a steam explosion can be considered very unlikely

The superheat of the melt, the depth of the water, and the size of the stream of molten material directly affect whether the material will contact, before it freezes, the bottom of the vessel into which it is poured. Melt superheat in the present situation is low because of the relatively low heat generation rate within a control rod and the absence of a mechanism by which the melt could be held up and heated. The maximum value for superheat was calculated to be 32°C based upon the free fall of material through the power generating region of the core. The depth of the water pool has been estimated to be ~1 m and the size of the stream entering the water is constrained to the size of the septifoil channel (~ 2.5 cm). The distance of travel of the molten material through the water is a function of these three factors as well other factors such as local hydraulic conditions and the thickness and properties of the oxide film surrounding the material. In Long's experiments, slightly superheated aluminum would not explode unless dropped into a shallow pool (< 15 cm - 25 cm depth). In addition, explosions were not observed, regardless of the superheat, when the stream diameter was less than 6.4 cm - 7.0 cm. Assuming the Al-Li alloy used here behaves in a manner similar to Al, it seems very unlikely that molten material produced during this event will reach and be triggered upon the surface at the bottom of the septifoil. The effect of the presence of Li will be discussed later.

Perhaps a more likely scenario is for molten material to be triggered upon the surface of a piece of fallen rod or upon the vertical wall of the channel. The aluminum surfaces within the septifoil are not thought to be especially conducive to steam explosion initiation. There is some experimental indication that aluminum surfaces may be less conducive to triggering than steel surfaces (reference 12), upon which most of the data is based. However, septifoil surfaces will be oxidized, and therefore wettable to some degree, but the extent of wettability has not been determined.

The TRAC calculations predict water temperatures ranging from 50°C to 70°C at the bottom of the septifoil to saturation at the surface of the water pool. Steam explosions involving aluminum are much rarer at temperatures above ~60°C (references 11 and 12). Only water residing in the bottom of the septifoil, therefore, has a temperature favorable for triggering. Material descending through the pool is expected to solidify before encountering this water.

Conflicting evidence exists regarding the effect of lithium on steam explosion triggering. A limited number of experiments performed by one group pointed to a marked increase in the likelihood as well as the violence of steam explosions when Al-Li alloy with a Li concentration similar to that in SRS control rod material was used compared to the likelihood and violence of explosions occurring with pure aluminum. These experiments used a large quantity of material (50 lb) poured in a large stream (8.3 cm). They calculated that in one test the explosion occurred, without the aid of an external trigger, before the melt reached the bottom of the container.

Higgins (reference 13), however, reported no spontaneous explosions in a limited number of tests involving Al-Li of considerably higher Li concentration than present in a control rod. The samples were 150 g and were poured in 2.5 cm streams. These tests are more prototypic of the present situation than the aforementioned Al-Li tests. Although the melt temperature for these tests was not specified, it is thought to exceed the superheat expected in the reactor, making steam explosions more likely in the experiments than in the present situation.

A large number of tests involving Al-Li similar to control rod material were performed by Page et al. (reference 14). All but a few tests were externally triggered. A steam explosion occurred in none of the tests that were not externally triggered. The molten material was poured in a small stream of unspecified diameter and was of the order of a Kg in mass. The mechanical energy output from each externally triggered explosion was measured with the aid of crushblocks. The experimenters observed an exponential increase in the yield as a function of the lithium content of the melt.

Based on the foregoing, the likelihood that a steam explosion is triggered when molten control rod material reaches water within the septifoil is estimated to be quite low, on the order of 1 in 100. This estimate involves considerable uncertainty especially with regard to the propensity for triggering upon surfaces other than that at the bottom of the septifoil and with regard to the effect of lithium. Because of these uncertainties, experiments were deemed necessary to lend support to the probability estimate. Attempts were made to make the tests as prototypic as possible with respect to the conditions expected to prevail at the time of the accident.

Experiments were performed by G. A. Greene at Brookhaven National Laboratory, D. H. Cho at Argonne National Laboratory, and L. S. Nelson at Sandia National Laboratories. A range of conditions and configurations were examined corresponding to best estimates of the conditions and modes of contact of molten material with water during the hypothetical event. Various triggering scenarios were examined by G. A. Greene.

The experiments at Argonne (reference 15) involved pouring streams of control rod material into an actual septifoil with web insert. A total of five tests were done. In one test, material was poured into a single channel of the septifoil in a stream of 1.4 cm diameter resulting in a total mass of 0.4 kg delivered at a rate of ~0.3 kg/s. In the other four tests, molten material was poured into five exterior channels of a septifoil in a stream of 1.2 cm diameter and at a rate of 0.9 kg/s. In one of these tests, a total mass of ~0.5 kg was delivered; in each of the other three, a total mass of ~0.8 kg was delivered. In all five tests, the superheat of the melt was kept under ~50°C and the water temperature was kept at 85°C. Also in all five tests, a piece of control rod was positioned beneath the pool surface, in each channel, to simulate the fallen portion of a failed rod. The height of water above the tops of these pieces was set at 12.7 cm or 33 cm. In none of the tests did a steam explosion occur although overpressurizations on the order of 0.1 MPa were observed.

A total of fifteen tests were done at Brookhaven (reference 16), again using an actual septifoil and web. Of the fifteen tests, seven involved postulated external triggers: the pouring of the melt into a thermally stratified pool, the pouring of the melt into a two phase pool, and the dropping of a solid rod in an adjacent channel of the septifoil simultaneous with the entry of molten material into one channel. The timing of the falling solid rod was varied. In the majority of the tests, from 75 to 100 g of material was poured into a single channel of the septifoil in a jet of 0.635 cm diameter. The pool depth was varied from 30 cm to 100 cm; the water temperature, from 33°C to 100°C. A steam explosion was not observed in any of the tests. Transient overpressurizations ranging up to 18 psig were observed in a few tests.

The tests performed at Sandia National Laboratories (reference 17) used globules of molten Al-Li of mass in the range: 1 g to 10 g. These tests were intended to simulate a scenario in which molten material falls from the bottom of a rod, not in a continuous stream, but in a series of drops. In twenty five experiments, a spontaneous explosion was not observed either as the drop fell through the water or upon contact with the bottom of the chamber. Aluminum and stainless steel chamber bottoms were used. The septifoil wall and web are composed of aluminum. The stainless steel surfaces were used in an attempt to gauge the difference between steel and aluminum.

The experimental results described above support the original conclusion that a steam explosion is highly unlikely during the postulated accident. It is recognized that a limited number of experiments were performed and that considerable uncertainty exists in the modeling of the accident sequence. The 1 in 100 probability assigned to this level of the tree is considered to be a reasonable best-estimate of the true probability.

**Potential Steam Explosion Magnitude**

The criterion assumed for propagation of this event to a nearby fuel assembly is the collapse of the outer wall of that assembly by the shock wave created by the explosion. For a nearby fuel assembly to be affected by an explosion, the outer septifoil housing must first be failed by the explosion. Failure of the septifoil housing is assumed if its ultimate stress is exceeded. The ultimate stress equals the hoop stress which is estimated by

$\sigma = c\rho R$ equation 1

where c is the sonic velocity of aluminum (0.2 X 106 inches/second); $\rho$, the density of the housing material (2700 kg/m3); and R, the radial velocity imparted to the housing by the impulse of the explosion.

The radial velocity can be expressed as

$R = p(\Delta t)/(2\rho h)$ equation 2

where p is the peak overpressure from the explosion; $\Delta t$, the duration of the impulse; and h, the thickness of the housing.

The peak pressure from an explosion occurring within a tube can be estimated with the equation (reference 18):

p = 500W/R3 equation 3

where W is the TNT weight equivalent in pounds for the explosion; R, the tube radius in ft; and p, the pressure in psi.

For $\sigma$ = 50,000 psi, equation 1 gives a radial velocity of 1060 ips. For R = 1060 ips, dt = 2 X 10 -6 s and h = 0.5 in, equation 2 gives 12,500 psi as the overpressure required to fail the septifoil outer housing. According to equation 3, with R = 0.14 ft, the explosion magnitude in units of TNT weight equivalent required to fail the housing is 0.08 lb. This weight of TNT equals 160 KJ of energy released in the explosion.

Given that an explosion has occurred of sufficient energy to fail the septifoil outer housing one asks the question: does an explosion of this magnitude threaten a nearby fuel assembly? Part of the output of the explosion will be dissipated in rupturing the septifoil housing. The energy required to tear away a segment of the housing can be estimated by

$U = \sigma\varepsilon V$ equation 4

where $\sigma$ is the ultimate stress; $\varepsilon$, the ultimate strain; and V, the volume of the material. For $\sigma$ = 50,000 psi, $\varepsilon$ = 0.05 and V= 2 in3, equation 4 gives an energy of 0.6 KJ, less than 1% of the energy output from the explosion. Therefore, a negligible amount of energy is lost in rupturing the septifoil outer housing.

A nearby fuel assembly housing if the shear stress acting on the outside of the housing exceeds its ultimate shear stress. The shear stress given by

$\tau = qL/h$ equation 5

where q is the radial pressure; h, the housing thickness; and 2L, the length of the region under radial pressure. For an ultimate shear stress of 20,000 psi, a housing thickness of 0.05 in, and L = 2.03 in, the same as the housing radius, equation 5 gives q = 500 psi. An overpressure of 500 psi is therefore required to fail the outer housing of a fuel assembly.

The closest fuel assemblies are 7 inches away from the center of the septifoil. Using the scaling laws for overpressure as a function of distance from the initiation point of an explosion (reference 19), an explosive output of ~160 KJ would result in an overpressure of 500 psi at a distance of 7 inches from the initiation point, i.e., the output required to fail a nearby fuel assembly is approximately the same as required to fail the septifoil housing. Therefore, if the septifoil outer housing is failed by a steam explosion, so will the outer housings of nearby fuel assemblies and the definition of accident propagation defined above as damage to a nearby fuel assembly can be defined equivalently as failure of the septifoil outer housing.

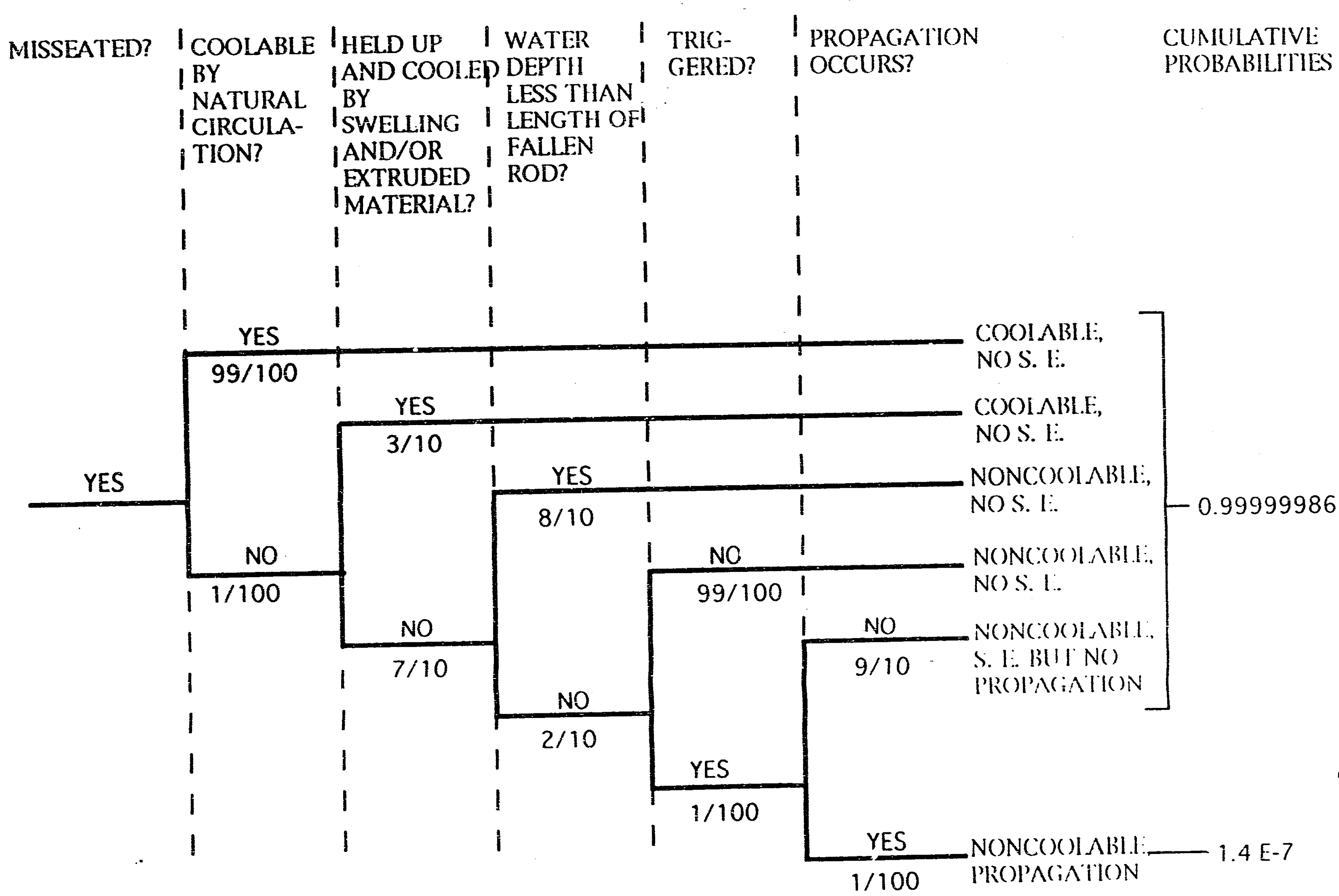
The energy release from a steam explosion is proportional to the mass participating in the explosion. An energy output of ~ 50 KJ/Kg has been observed with 3 weight percent lithium aluminum (reference 3). This output corresponds to ~ 5 % thermodynamic efficiency, a value typical of the efficiency observed by others. The participation of 3.2 Kg of molten material is required to fail the outer housing of a nearby fuel assembly, assuming an output of 50 KJ/Kg. Calculations based on adiabatic heatup and relocation of material by gravity indicate that the maximum amount of material that may be molten at any one time is on the order of hundreds of grams. Therefore, it is very unlikely that damage to a nearby fuel assembly will accompany a steam explosion within a septifoil. The probability that propagation occur, given the occurrence of a steam explosion, has been put at 1 in 100.

## Resultant Probability of a Damaging Steam Explosion

The event tree for an unseated septifoil is shown in Figure 6. The questions along the top of the figure represent the considerations expressed in the preceding discussion. Three branch probabilities clearly dominate: coolability by natural convection, self triggering, and propagation. The cumulative probability for the occurrence of a damaging steam explosion is extremely low. The uncertainty in these numbers is huge, perhaps an order of magnitude for each of the major contributors to the overall probability; therefore, an estimate of the upper bound on the cumulative probability of propagation is 1.4 E -4/Rx-yr/rod. If the control rod positions and power profiles are assumed to be such that any one of three rods in a septifoil may produce a steam explosion (see the discussion under Molten Material Falling into Water), a very conservative assumption, the upper bound estimate becomes 4.2 E -4/Rx-yr.

The frequency of occurrence of an unseated septifoil has been calculated to be 2.4 E -6/Rx-yr. The ANSI criterion for exclusion of an event from design

Figure 6. Mechanistic Event Tree with Branching and Cumulative Probabilities



basis is 1E-6 core melt/Rx-yr (reference 20). This criterion and the analysis described in this paper were used to argue for the exclusion from design basis of steam explosions resulting from an undetected unseated septifoil. Using the upper bound conditional probability from above, the total probability of initiation of a damaging steam explosion during the unseated septifoil event is 1.0 E -9/Rx-yr, well below the ANSI criterion.

## Conclusion

Based upon the work described in this report, the exclusion from the design basis of steam explosions during the unseated septifoil event is justified. The initiating event probability is nearly low enough to support exclusion without the need for further analysis. The extremely small value obtained for the conditional probability of a steam explosion given an unseating event puts the total probability three orders of magnitude below the probability required by the ANSI standard. It was concluded, therefore, that K reactor could operate at 30% of historical power without an inordinate risk from steam explosions during a possible unseated septifoil event.

## References

1. Schnurr, N. M., et al., TRAC-PF1/MOD2: An Advanced Best-Estimate Computer Program for Pressurized Water Reactor Thermal Hydraulic Analyses, Los Alamos National Laboratory Report LA-12031-M, Volumes i-iv, NUREG/CR-5673, Draft.

2. Katto, Y., Prediction of Critical Heat Flux for Annular Flow in Tubes Taking Into Account the Critical Liquid Film Thickness Concept, International Journal of Heat and Mass Transfer, Vol 27, No. 6, pp. 883-891 (1984)

3. K. Mishima and M. Ishi, Experimental Study on Natural Convection Boiling Burnout in an Annulus, 7th International Heat Transfer Conference, Munchen, 1982, Vol. 5, pp.309-314, Hemisphere, 1985.

4. K. Mishima and H. Nishihara, The Effect of Flow Direction and Magnitude on CHF for Low Pressure Water in Thin Rectangular Channels, Nuclear Engineering and Design, vol. 86, pp. 165-181 (1985)

5. El Genk, et al., Experimental Sudy on Natural Convection Burnout in Vertical Annuli at Near-Atmospheric Pressure, International Journal of Heat and Mass Transfer, Vol. 31, pp. 2291-2304 (1988)

6. R. C. Martinelli and D. B. Nelson, Prediction of Pressure Drop during Forced Circulation Boiling of Water, Trans. ASME, 70, 695 (1948).

7. L. Biasi et al., Studies on Burnout, Part 3: A New Correlation for Round Ducts and Uniform Heating and Its Comparison with World Data, Nuclear Energy, Vol. 14, pp. 530-536 (1967)

8. P.D. Hess, and K.J. Brondyke, Causes of Molten Aluminum-Water Explosions and Their Prevention, Met. Prog. 95(4), p. 93-100 (April 1969).

9. A.W. Lemmon, Jr., Explosions of Molten Aluminum and Water, Light Metals 1980, Las Vegas Nev. (February 24-28, 1980)

10. W.O. Alexander, A.T. Chamberlain, and F.M. Page, ECSC Research Report 7205-16/801/08 (1982).

11. G. Long, Explosions of Molten Aluminum and Water - Cause and Prevention, Met. Prog., 71(5), p. 107-112 (May 1957).

12. P.D. Hess, R.E. Miller, W.E. Wahnsiedler, and C.N. Cochran, Molten Aluminum/Water Explosions, Light Metals 1980, Las Vegas, Nev. (February 24-28, 1980).

13. H. M. Higgins, A Study of the Reaction of Metals and Water, Aerojet-General Corporation Report, AECD-3664, (April 15, 1955).

14. F. M. Page, A. T. Chamberlain, and R. Grimes, The Safety of Molten Aluminum-Lithium alloys in the Presence of Coolants, 4th International Aluminium Lithium Conference, Paris (June 10-12, 1987).

15. D. H. Cho, J. D. Gabor, R. T. Purviance, and J. C. Cassulo, Scoping Tests on the Potential for Lithium/Aluminum Steam Explosions in an SRS Septifoil, Westinghouse Savannah River Company Report, WSRC-RP-91-0952 (September, 1991).

16. G. A. Greene, C. C. Finfrock, C. E. Schwarz, M. L. Hyder, and D. K. Allison, Brookhaven National Laboratory Report, BNL-52324 (January, 1992).

17. L. S. Nelson, P. M. Duda, D. A. Hyndman, Interactions Between Drops of Molten Al-Li Alloys and Liquid Water, Paper to be presented at the 28th ASME/AICHE/ANS National Heat Transfer Conference, San Diego, CA, (August, 9-12, 1992)

18. W. Johnson, Impact Strength of Materials, Chapter 9, Edward Arnold Limited, London (1972)

19. The Effects of Nuclear Weapons, Chapter 3, USAEC (1962)

20. American National Standard - Nuclear Safety Criteria for the Design of Stationary Pressurized Water Reactor Plants, American Nuclear Society Standards Committee Working Group, ANSI/ANS-51.1 (1983).

## Acknowledgments

Initiating event probabilities were determined by M. D. Brandyberry, D. S. Cramer, and V. E. Logan of SRS. The thermal-hydraulic experiments were performed by H. W. Randolph, S. L. Collins, D. T. Verebelyi, and D. J. Foti with assistance from I. K. Paik, all of SRS. Contributors to the thermal-hydraulic analysis included: T. C. Easterling, M. G. Beck, B. A. Byrne, T. W. Burnett, N. T. Hightower, III, and L. A. Wooten of SRS, and C. N. Amos, K. W. Ross, D. C. Thoman, F. V. Frierson of SAIC. The authors wish also to thank J. E. Jacoby and R. E. Miller of ALCOA for valuable discussions.

This work was performed under Department of Energy Contract No. DE-AC09-89SR18035.

DATE
FILMED
10/9/92