PARTICULATE PHENOMENA AND MULTIPHASE TRANSPORT

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Evaluating Effects of Debris Transport within a PWR Reactor Coolant System during Operation in the Recirculation Mode

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ABSTRACT

It has been postulated that paint coatings inside of a Pressurized Water Reactor (PWR) containment building may become dislodged from the surfaces to which they were applied during a hypothetical Loss of Coolant Accident (LOCA) event. It has been further postulated that some of this paint debris would be transported into the containment sump by the coolant escaping from the reactor coolant system (RCS) piping. Once in the containment sump, the paint debris could then be ingested into the RCS through the Emergency Core Cooling System (ECCS) upon realignment of that system to operate in the recirculation mode by drawing suction from the containment sump. The preceding scenario has been used as a basis for developing a methodology for evaluating the operability of the ECCS should paint debris be ingested into the ECCS recirculation flow path. The methodology accounts for physical properties of paint coatings, ECCS component design, wear and blockage of ECCS components, and development of blockages in the reactor core that would result in degraded heat transfer. The application of the methodology described here has been used to support a favorable Safety Evaluation Review (SER) issued by the U.S. Nuclear Regulatory Commission (NRC) for the Commanche Peak Steam Electric Station concerning the potential failure of paint coatings inside containment.

NOMENCLATURE

F_D = drag force acting on particle (N)

F_G = gravitational force acting on particle (N)

F_H = hydrostatic force acting on particle (N)

cs,

INTRODUCTION

During a postulated Loss of Coolant Accident (LOCA), primary coolant flows from a break or breach in the reactor coolant system (RCS) piping into the containment. Depending upon the time of the event and the size of the break, the break flow can be either steam, a steam-water mixture, or water. Steam break flow will be condensed on heat sinks inside the containment building and by the operation of containment fan coolers. The condensed and escaping liquid break flow, as well as containment spray flow (if containment spray is actuated) then drains into the containment sump, potentially carrying failed paint debris with it.

During the early stages of a hypothetical LOCA the Emergency Core Cooling System (ECCS) pumps borated water from the Refueling Water Storage Tank (RWST), located outside of the containment building, into the RCS cold legs. After the water level in the RWST reaches a minimum set point value, the ECCS is realigned so that the residual heat removal (RHR) pumps draw suction from the coolant collected in the containment sump. When this realignment occurs, failed paint debris suspended in solution in the containment sump could be ingested into the ECCS and RCS.

The function of the ECCS is to provide for long term core decay heat removal capability following a hypothetical LOCA. The occurrence of significant degradation of performance or the failure of ECCS components due to the action of suspended particulates in the recirculating flow drawn from the containment sump may preclude the successful functioning of the ECCS. Also, the formation of significant core blockage due to debris being carried into the core by the recirculating flow and collecting behind grid straps within the core may result in degraded cooling of the core downstream of the blockage. Thus, the methodology described here was developed so as to provide a framework to evaluate the effects of suspended paint debris ingested into the ECCS from the containment sump during the recirculation mode of operation.

The operational requirements of the ECCS formed the basis for evaluating the effect of suspended paint debris in the recirculating flow on the ability of the ECCS to provide for long term decay heat removal from the core. Specifically, the evaluation is separated into the following topical areas;

1. Debris Cleanup/Settle Out
2. Potential Degradation Effects
3. Paint Chemical Evaluation

A discussion of each of the preceding three topical areas is presented. Where appropriate, separate discussions identifying differences in ECCS operation or performance due to break size (large break versus small break) or recirculation mode (cold leg versus hot leg) are presented. It should be noted that the actual performance of a given plant is dependent upon plant-specific parameters. The evaluation presented here is based on a reference plant design, is generic in nature, and should not be taken to be representation of any specific plant.

DEBRIS CLEANUP/SETTLE OUT EVALUATION

Calculations using reference plant design data were performed to assess the ability of the RCS and ECCS to filter or settle out paint debris during ECCS recirculation. The results of these calculations address both hot leg and cold leg recirculation modes of operation.

General Methodology

An assessment of the separation of paint debris out of solution in the reactor vessel (RV) lower plenum during cold leg recirculation following either a postulated cold leg or a hot leg break was made based on the following assumptions:

1. Debris density is 1.54 kg/m^3 (paint with a specific gravity of 1.6).
2. Thermodynamic properties of water are evaluated at 43°F and 4.14×10^5 N/M^2
3. Debris geometry is approximately spherical.

Using the preceding assumptions, a force balance that accounts for drag, gravity, and hydrostatic forces acting on a spherical particle in a vertically flowing fluid with a given velocity can be written as:

$$F_G = F_D + F_H \tag{1}$$

Each of the forces identified in Equation (1) may be expressed as a function of two or more of the following parameters; debris geometry, specific weights of debris and coolant, thermodynamic properties of the coolant, and local coolant velocity. Substituting the appropriate expressions for these parameters into Equation (1), it is readily noted that the terms may be arranged to express debris geometry as a function of the other parameters. For debris having spherical geometry, the characteristic geometry parameter is the sphere radius, r. The expression for sphere radius obtained by the previously identified substitution and rearrangement of terms was solved for a range of vertical fluid velocities. A plot of the results of the calculation using the assumptions given above is given in Figure 1. These data identify the sphere size for which, at a specific fluid velocity, the three forces identified in Equation (1) will be in equilibrium.

Cold Leg Recirculation

The minimum vertical fluid velocity in the reference plant RV lower plenum occurs in the region between the lower support plate and the core support plate, the region with the largest cross-sectional flow area. A typical fluid velocity in that region during cold leg recirculation following a cold leg break for the reference design plant is estimated to be about 0.018 m/sec. Using the data of Figure 1, forces on particles having a diameter of about 0.018 cm will be in equilibrium. Thus, for the reference plant design debris particles smaller than 0.018 cm will be carried into the core region, and debris particles larger than 0.018 cm will settle out of solution in the RV lower plenum.

The fluid velocity in the core and RV lower plenum during cold leg recirculation following a cold leg break is independent of the number of RHR trains operating. Water level in the RV is maintained at the elevation of the break in the primary piping, with excess flow spilling out the break. The operation of one RHR train is adequate to maintain that water level in the RV when the ECCS is realigned to the cold leg recirculation mode. The fluid velocity in the core and RV lower plenum during cold leg recirculation following a hot leg break, however, is dependent upon the number of RHR pumps operating; all flow supplied by the RHR pump(s) must flow through the core before spilling out the break and returning to the reactor sump. The fluid velocities in the core during cold leg recirculation for either one or two RHR pumps operating following a hot leg break are summarized in Table 1. Using these fluid velocities and the data of Figure 1, the largest particle sizes that can be carried into the core during the operation of either one or two RHR pumps was determined for the reference plant design. These particle sizes are also listed in Table 1.

[redacted]

From the data of Table 1, the largest debris size that will enter the core of the reference design plant during cold leg recirculation is predicted to be 0.048 cm. Using the geometry data for the reference plant core design, it was determined that local vertical fluid velocities in the reference plant lower plenum will not support transport of debris into the core region that is of sufficiently large size to form flow blockage.

An assessment was also made of the rate at which the mass concentration of paint debris in solution would change due to settle out in the RV lower plenum for a reference plant design. Significant assumptions of the evaluation are:

1. Debris size is uniformly distributed over the range 0.002 cm to 0.318 cm.
2. RHR flow delivery to the RCS is 240 m/sec per RHR pump.
3. No credit was taken for settle out of debris in the containment building.
4. Once in solution, the size of debris particles remained constant.
5. Paint debris concentration in the containment sump, although changing with time, is assumed to be spacially uniform within the sump.

The rate at which debris mass concentration is decreased, or the debris removal efficiency, was found to be dependent on the mass flow through the core. A cold leg break, having the smallest core flow during cold leg recirculation of the three cases studied, requires the longest time to clean the recirculating flow by means of debris settling out in the RV lower plenum. A hot leg break with 2 RHR pumps running, having the largest core flow during cold leg recirculation, requires the shortest time for reducing the concentration level in fluid by settling out of debris. Time histories of the debris mass concentration for each of the three cases considered for a reference plant design are given in Figure 2.

In studying the debris removal efficiency of the RV lower plenum, it was noted that some amount of debris always remains in solution. For a given debris geometry and debris density, two parameters determine the amount of debris remaining in solution; the vertical fluid velocity (which determines the maximum particle size that can be carried by the fluid) and the distribution of particle sizes. The mass of paint debris remaining in solution expressed as a percentage of the total debris mass that is initially in the system is given for each of the three cases considered in the debris removal efficiency study in Table 1. The data of Figure 2 show that for the three cases considered, no more than 1.0 percent of the initial debris mass remains in solution for the reference plant design.

Hot Leg Recirculation

At about 18 hours after the hypothetical LOCA occurs, emergency procedures typically require that the ECCS be realigned to prevent boron precipitation in the reactor vessel; delivery of RHR flow is changed from the cold legs to the hot legs. Now, debris in the RHR flow is delivered to the core without passing through a separation volume such as the RV lower plenum and the delivery of large debris particles to the hot leg could result in the formation of flow blockages in the core. From Figure 2, however, it is noted that after 18 hours of cold leg recirculation there is less than 1% of the initial debris mass remaining in solution.

For hot leg recirculation following a cold leg break, it is possible that debris deposited in the RV lower plenum during cold leg recirculation may be reentrained in solution since all RHR flow must pass through the core and lower plenum prior to spilling out the break. Fluid velocities in the RV core barrel annulus under these conditions are estimated to be about 0.075 m/sec for one RHR pump operating and about 0.150 m/sec for two RHR pumps operating. From Figure 1, the maximum debris size that can be reentrained by the hot leg recirculation flow is found to be 0.07 cm and 0.19 cm for the operation of one and two RHR pumps, respectively. Since the maximum debris size that can be entrained is less than the debris size determined to be critical for the formationof core blockage in the reference plant design, the operation of a single RHR pump does not present a concern that re-entrained debris will result in flow blockage in the core.

For two RHR pumps operating, the fluid velocity in the RV core barrel annulus of the reference design plant is sufficient to re-entrain debris that may cause core blockage if it is re-introduced to the RV. Typically, the fluid velocity in the lower plenum is a maximum where the fluid turns to flow up the downcomer. Figure 3 shows the relationship between vessel flow rate, debris bed height, and fluid velocity as it turns into the downcomer from the lower plenum for the reference plant design. For the reference design plant, it is desirable to have fluid velocities in this region no greater than 0.10 m/sec. From Figure 3, the velocity of the turning fluid is predicted to be less than 0.10 m/sec for debris bed heights less than 1.37 meters.

The volume of debris required to generate fluid velocities at the turning keys equal to 0.101 m/sec is evaluated from the data of Figure 4, a plot of debris bed volume versus debris bed height in the RV lower plenum. For the reference plant RV design, the volume of paint debris required to develop a bed height of 1.37 meters is about 10.5 cubic meters. Thus, it is concluded that the collection of less than 10.5 cubic meters of paint debris in the RV lower plenum is not likely to promote reentrainment of large size debris that could potentially result in the development of core blockage when the ECCS is realigned to hot leg recirculation.

In summary, during cold leg recirculation following a hypothetical LOCA, the RV lower plenum of the reference plant design can separate up to approximately 10.5 cubic meters of large paint debris from solution, without the potential of reentraining the debris when the ECCS is realigned to hot leg recirculation.

POTENTIAL DEGRADATION EFFECTS

Failed coatings debris carried into the ECCS by recirculating coolant could carry with it abrasive material, such as particles of concrete or sand. Thus, if paint debris is to be postulated to be ingested into the ECCS, the ability of the ECCS to withstand the potential erosive and corrosive effects of that ingested debris must be evaluated. Several ECCS components which are potentially susceptible to degradation due to suspended abrasive debris in the recirculating fluid have been identified. These components include the RHR pumps, the system valves, heat exchangers, containment spray pumps, and charging and safety injection pumps.

RHR Pumps

The data presented in NUREG/CR-2792 [1] identifies the effects of insulation and paint debris suspended in the recirculating fluid on RHR pumps hydraulic performance. Those data shows that, for the RHR pump designs included in the report, pump hydraulic performance degradation is negligible for particulate concentrations less than 1 (0.1 percent abrasive) by volume. The RHR pumps could ingest insulation and paint debris concentration levels less than 1 percent by volume (particles uniformally mixed with the full RWST and RCS loop inventory) without significantly affecting pump performance. Thus, to assess the potential for RHR pump degradation, the transport of failed coatings into the containment sump from locations within the containment building must be evaluated on a plant-specific basis to assess the particulate concentration levels in the recirculating fluid.

TABLE 1. Summary of Sample Paint Debris Settle-Out Cold Leg Recirculation

Event/Conditions	Lower Plenum Velocity (m/sec)	Max. Dia. of Debris in Solution (cm)	Residual Debris Mass[1] (Per Cent of Total Initial Debris Mass)
Cold Leg Break 1 or 2 RHR Pumps Operating	0.018	0.018	< 0.007%
Hot Leg Break 1 RHR Pump Operating	0.027	0.025	< 0.03%
Hot Leg Break 2 RHR Pumps Operating	0.055	0.048	< 0.72%

[1] Mass not separable from solution; attained within first 18 hours of cold leg recirculation.

Containment Spray Pumps

Again, the data presented in NUREG/CR-2792 [1] is applicable for evaluating containment spray pump performance with particulates suspended in the pumped fluid. The designs of the containment spray pumps are similar to those of the RHR pumps for the reference plant design. Thus, conclusions of pump operability and survivability with suspended debris in the pumped fluid reached for the RHR pumps would also generally applicable to containment spray pumps.

RHR Valves

The RHR system valves would be susceptible to erosion damage due to suspended abrasive particles in the ECCS fluid. The design of the valve internals may provide some degree of erosion resistance to the suspended particles. The impingement of abrasive material over a period of time may result in surface pitting on the hardfaced valve components which could effect the leak tightness capability of the various RHR valves. Again, this pitting and potential degradation in leak tightness must be evaluated on a plant-specific basis which accounts for debris concentration and composition.

RHR Heat Exchangers

The RHR heat exchangers in the reference plant design are vertical two-pass, shell and U-tube heat exchangers. Reactor coolant is on the tube-side and Component Cooling Water (CCW) is on the shell-side. The RHR heat exchanger tubes would be susceptible to abrasive erosion due to suspended particulate debris in the recirculating coolant.

Again, this wear must be evaluated based on the plant-specific design and account for the following; wear characteristics of the component material, local fluid velocities, concentration of abrasive material, and component integrity requirements.

Charging And Safety Injection Pumps

The performance of these multi-stage pumps would tend to be more sensitive to entrained solids in the pumped fluid than single stage pumps, such as the RHR pumps. The most troublesome areas for these pumps would be the running clearances; impeller to casting wear rings, balance drum to bushing, etc. The wear characteristics of these areas must be performed on the specific component design, and account for wear characteristics of the component material and the concentration of abrasive material in the pumped fluid.

PAINT CHEMICAL EVALUATION

The impurity contribution of paint systems to the potential contamination of the Emergency Core Cooling System (ECCS) is considered in this section.

Chloride Contamination

Chlorides in solution in the recirculating fluid may, at sufficiently high concentrations, induce stress corrosion and cracking of sensitized austenitic stainless steels in the ECCS and RCS. As a safeguards against this occurrence, coatings typically used inside containments are generally formulated without the use of chlorides. However, to provide assurance that chloride contamination will not present a challenge to sensitized austenitic stainless steels in the ECCS and RCS flow path, a plant-specific chemical evaluation of coatings used inside containment must be made.

Fluoride Contamination

If Fluorides were present in the paints in question and should be leached into solution, they would form Fluoroborates. Fluoroborates do not cause cracking of sensitized austenitic stainless steels. Thus, Fluoride contamination does not present a concern for the long term operation of the ECCS.

FUTURE WORK

The data of Figure 1 was based on the assumption that a sphere reasonably approximates the hydraulic behavior of the failed coatings debris in the recirculating fluid. This assumption was based on the aspect ratio (ratio of length to thickness of the debris) of the debris being 8:1 or less. However, due to varying thicknesses of coatings and the size of debris that can pass through sump screens into the ECCS, aspect ratios in excess of 8:1 are possible. Thus, the applicability of the spherical geometry approximation needs to be considered on a plant-by-plant basis.

Additional analytical work may be done to evaluate the effects of non-spherical debris in the RV lower plenum as opposed to the spherical gemoetry considered here. Settling curves for these geometries, similar to that of Figure 1, may be generated and used to evaluate transportability of the debris into the core. Also, the hydraulic stability of the debris in the flow path as it turns in the lower plenum to flow up into the core, and the resulting effect on debris settle out can be readily studied experimentally. Such experimental work can be accomplished for a range of debris geometries and densities at near-ambient conditions using plexiglass models, enabling visual observation of the debris behavior. The additional analytical and experimental efforts would provide for a more complete basis for evaluating debris settle out in the RV lower plenum and the potential for fluid channel blockage due to larger debris being carried into the core region.

CONCLUSIONS

Using a reference plant design, a methodology was developed to evaluate the effects paint debris suspended in coolant flow on the operation of the ECCS in the recirculation mode. The methodology accounts for the following:

1. Potential for core blockage.
2. Debris settle out in RV lower plenum.
3. Potential for equipment degradation.
4. Potential for chloride attack of sensitized austenitic stainless steels.

The methodology described herein was successfully applied to the Commanche Peak Steam Generating Station, demonstrating that the volume of failed coatings predicted to be ingested into the ECCS during the recirculation mode following a hypothetical LOCA will not significantly impact the successful operation of that system [2]. Additional future analytical and experimental work has been identified to extend the methodology to other debris geometries beyond the spheres considered here. Furthermore, the methodology described here is generally applicable to evaluate any debris that may be ingested into the ECCS and RCS during the recirculation mode following a postulated LOCA.

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2. NUREG-0797, Supplement No. 9 - Safety Evaluation Report Related to the Operation of Commanche Peak Units 1 and 2, Docket Nos. 50-445 and 50-446, U.S. Nuclear Regulatory Commission, Washington DC, March 1985.

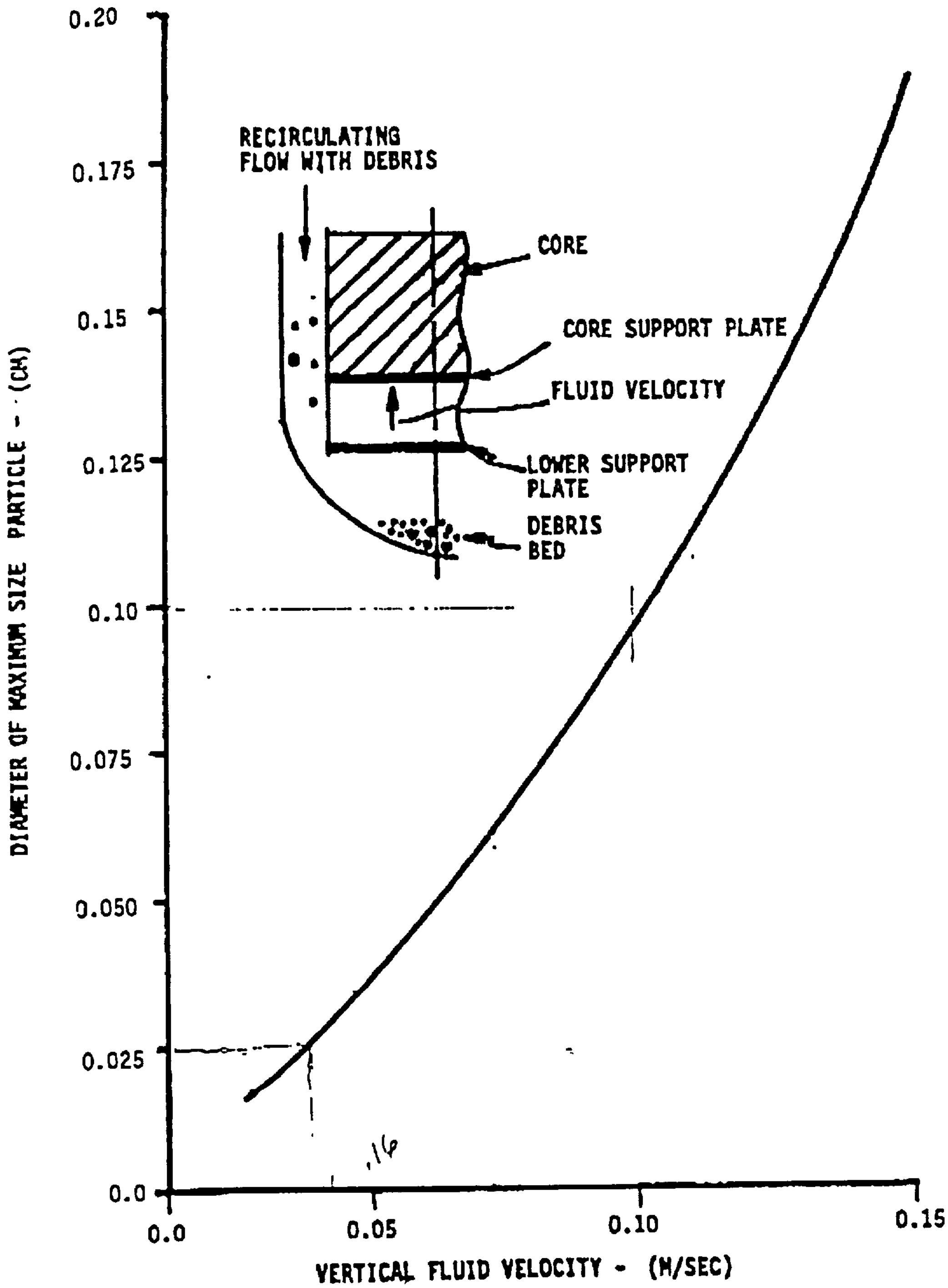

Figure 1. Maximum Debris Size to Enter Core Versus Lower Plenum Fluid Velocity

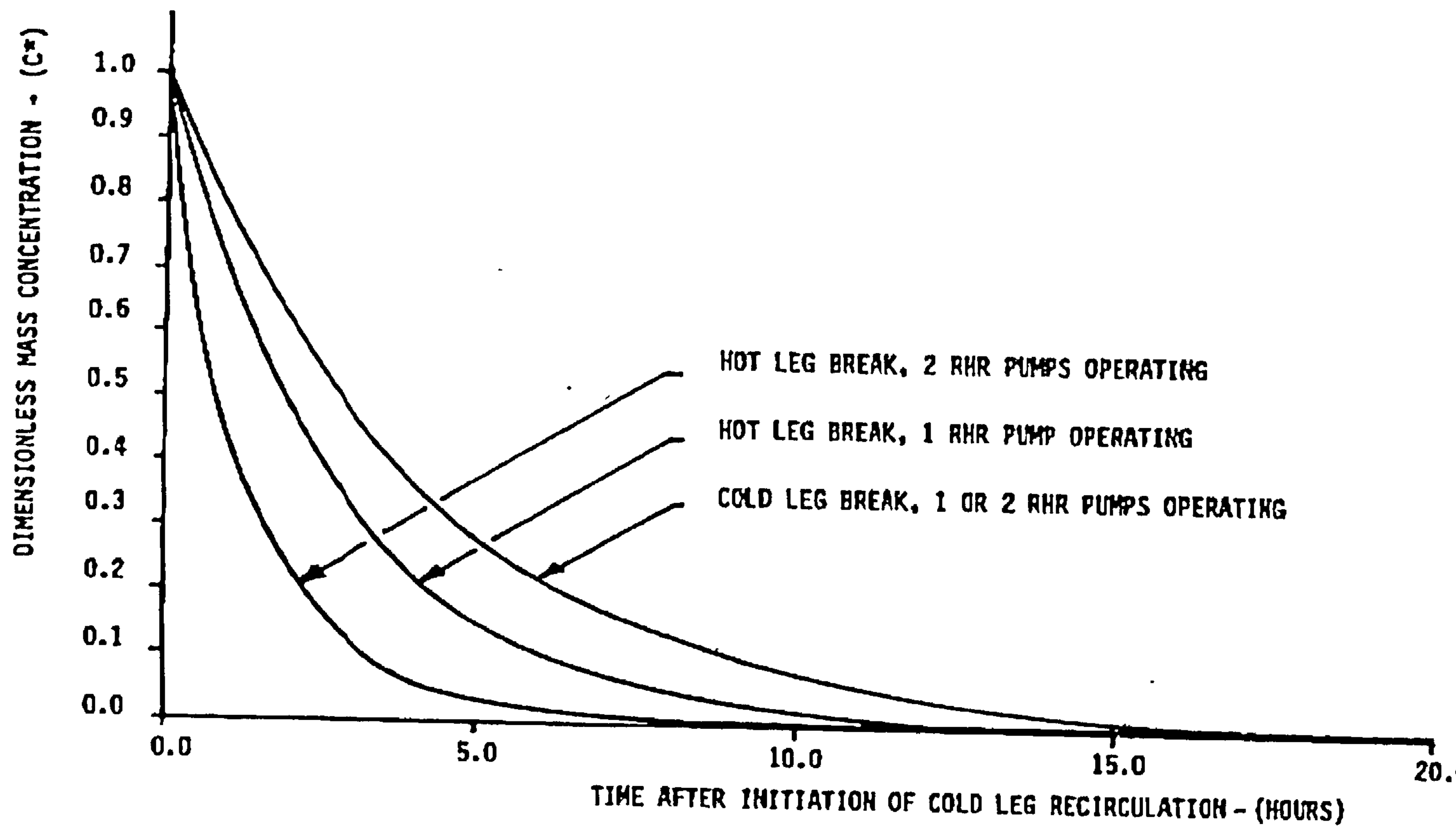

Figure 1. Mass Concentration of Paint Debris in Containment Sump Versus Time After Initiation of Cold Leg Recirculation

FLUID VELOCITY AT RV SUPPORT KEYS - (M/SEC)

Fig. . oncentration of Paint Debris in Containment Sump Versus Time After Initiation of Cold Leg Recirculation

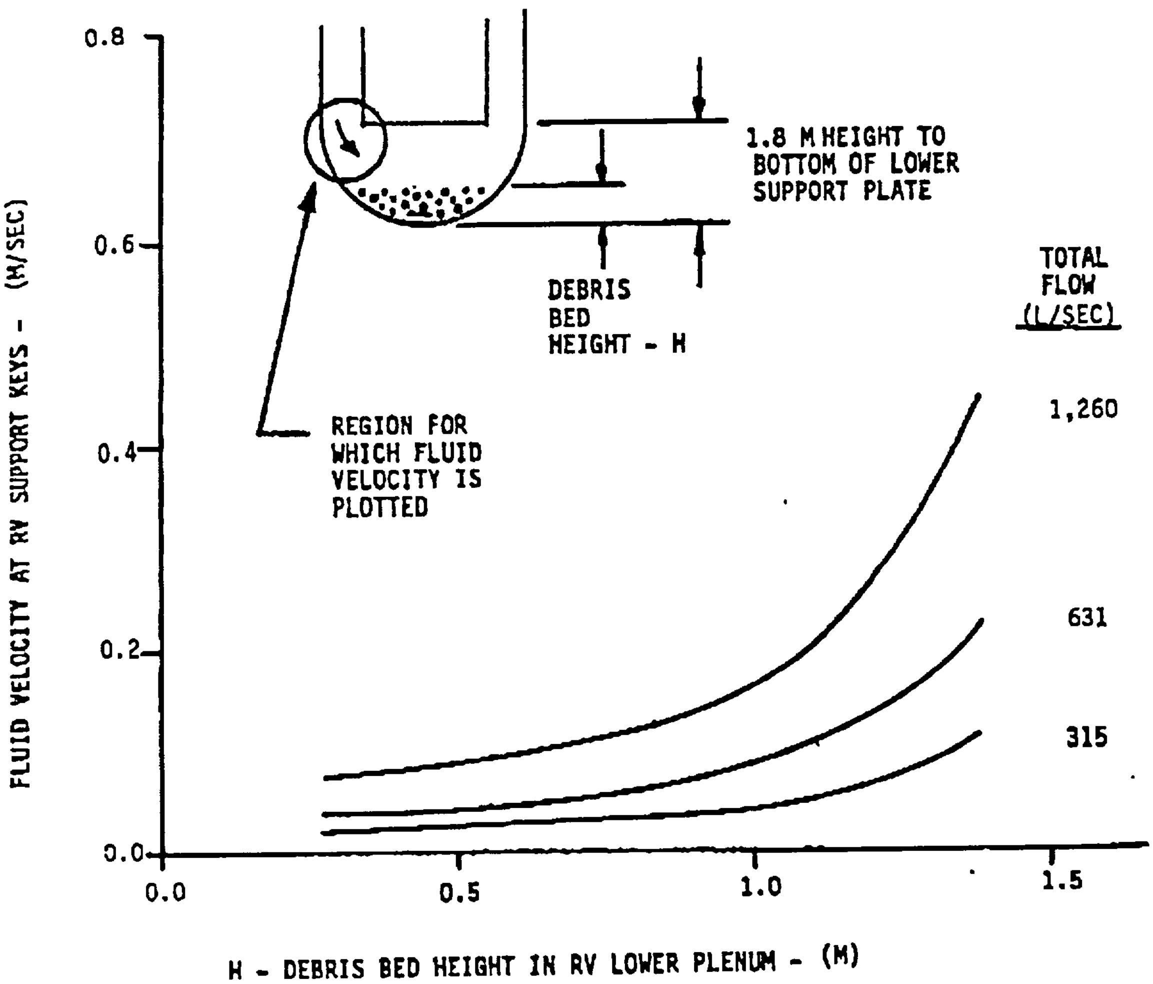

Figure 3. Fluid Velocity at Reactor Vessel Support Keys Versus Debris Bed Height in Reactor Vessel Lower Plenum

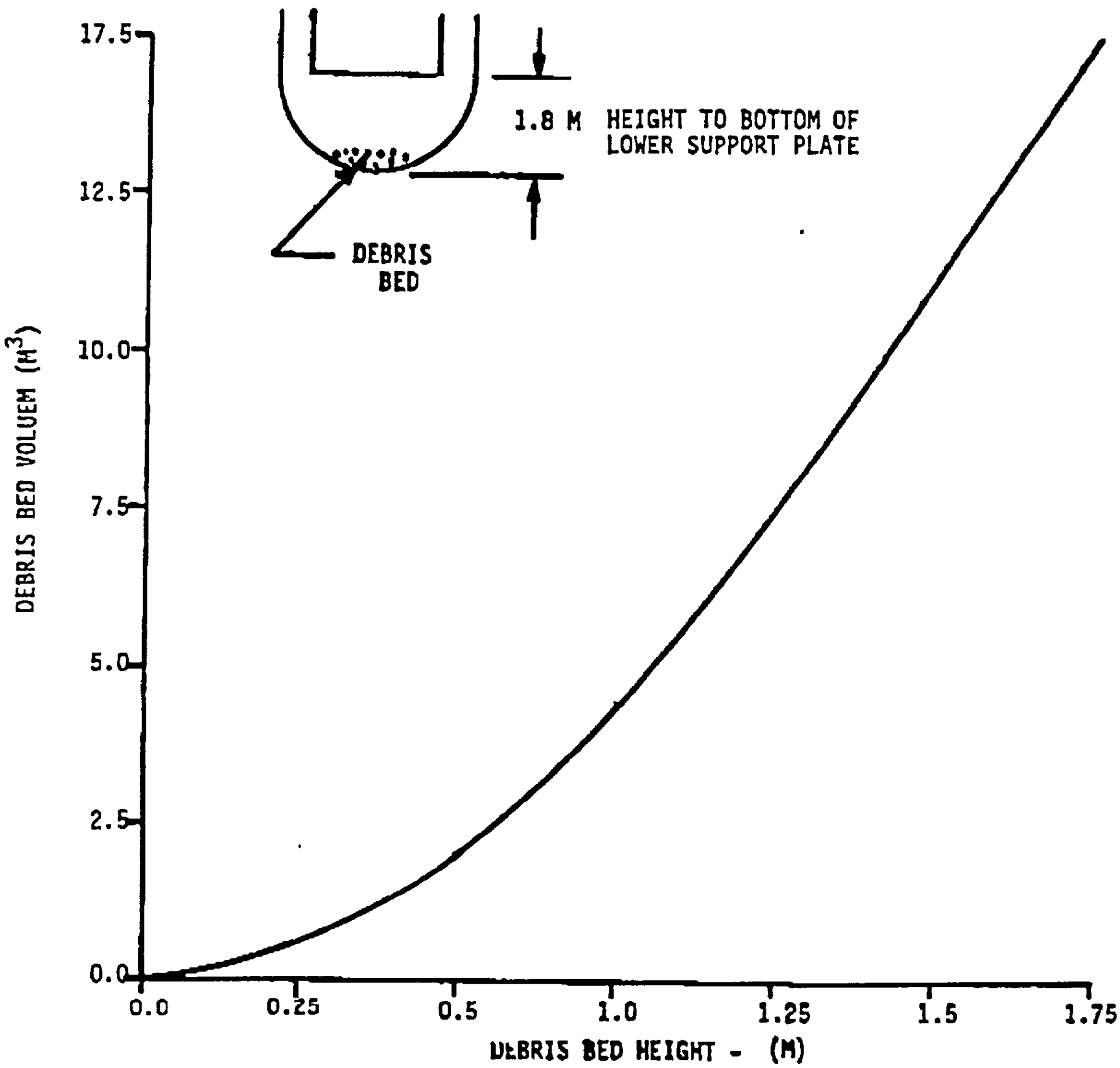

Figure 4. Debris Bed Volume Versus Debris Bed Height