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A CORE MELTDOWN ASSESSMENT IN THE GAS COOLED FAST REACTOR

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ABSTRACT

This paper discusses the chronological sequence of events and supporting analysis during a total loss of all coolant circulation in the GCFR with top supported core. Redundant and diverse cooling systems provided for decay heat removal reduce the probability of this postulated event below the range of plant design bases. It is nevertheless considered to investigate the potential for consequence mitigation and containment margin. Two distinct phases of the sequence are discussed: 1) the core response to a total loss of coolant circulation and 2) the capability of the PCRV to retain molten fuel debris. GCFR specific design features to prevent recriticality and fuel vaporization due to fuel slumping are under investigation. Analytical and experimental work is in progress to evaluate the feasibility of such early accident termination mechanisms. Several concepts for post accident fuel containment have been identified and appear technically feasible.

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INTRODUCTION

The safety philosophy adopted for the GCFR demonstration plant includes two basic elements. First, safety systems are developed which assure that the occurrence of a plant condition exceeding the core safety limits is so remote that all accidents leading to loss of coolable core geometry are beyond the plant design basis envelope. This objective is accomplished through a comprehensive design, design analysis and experiment support program, where the design adequacy is established against safety criteria which include both safety limits for core temperatures and reliability targets for the prevention of core damage. Secondly, postulated accident sequences which lead to core damage are investigated in spite of design provisions that remove these sequences from the design basis envelope. The objective is to investigate the consequences from these low probability events in order to assess if adequate containment margins exist to adequately limit the risk. This is accomplished through mechanistic analyses of the accident progression from event initiation through the core damage phase, the post accident fuel containment phase, the containment response and the radiological and environmental consequences. Experimental programs support the development of analysis methods where large uncertainties exist in the physical phenomena involved or in the relative timing of the principal accident phenomena. This paper discusses the sequence of events inside the PCRV during a postulated total loss of flow in the shutdown GCFR. This accident sequence is referred to as Protected Loss of Flow (PLOF). Two distinct phases are addressed: 1) The core wide heatup, melting and relocation of core materials during the initial damage phase and 2) the containment of molten fuel and steel on the floor of the central PCRV cavity.

CORE RESPONSE DURING A PROTECTED LOSS OF FLOW EVENT

Protected loss of flow (PLOF) is initiated by a postulated loss of all coolant circulation in the shutdown reactor. Its probability of occurrence is predicted to be very low, but higher than unprotected transient undercooling and transient overpower events [Ref. 1]. Some conceptual work on this accident has been previously reported [Refs. 2, 3]. This paper presents analyses of the core-wide progression of the event sequence and identifies the key phenomena associated with it in a top supported core without lateral or bottom core restraint.

The phenomenological event sequence for PLOF shown in Figure 1 reflects the current understanding of the sequence and has been updated from Ref. 4 to reflect the results of analyses performed since 1976. The two most significant modifications relate to the refreezing of molten steel in the lower axial blanket which is now considered very likely and the possibility of fuel column crumbling following decladding. Furthermore, the event sequence is substantially the same whether the reactor is tripped by the plant protection system or is already shutdown when circulator coastdown begins. However, the length of time between each significant event in Figure 1 is extended as the loss of flow is delayed after shutdown.

The PLOF event proceeds in phenomenologically and chronologically distinct phases. Analysis of the first phase predicts that the cladding melts, relocates downward and refreezes in the lower axial blanket. The lower axial blanket coolant channels are expected to be blocked by this process. Next the assembly walls begin to melt due to direct thermal radiation from the declad fuel columns. The axial progression of melting along the hexagonal assembly wall flat is greater than the circumferential progression [Ref. 3]. The added molten steel inventory backfills the assembly coolant channels above the blockage until steel can spill into the interassembly spacing or until circumferential duct melting induces duct fallaway. This is chronological competition between circumferential duct melting, molten steel spillover and fuel crumbling. If duct fallaway precedes steel spillover and fuel crumbling, the event sequence is terminated early and recriticality is prevented. Alternatively, if duct fallaway is delayed, steel spillover will cause a refrozen steel blockage between assemblies in the lower axial blanket region, which is likely to prevent duct fallaway. The fuel melting phase commences after most of the assembly walls have melted. Fuel slumps onto the lower axial blanket blockage and displaces that molten steel which has not solidified. Remelting of the blockage by contact with molten fuel, subsequent fuel drainage, and the potential for hanging assemblies to drop out of the core are criticality preventing phenomena which chronologically compete with the buildup of a critical mass. Another mode of fuel relocation which may result in recriticality is the crumbling and compacting of fuel columns. One cause of crumbling may be stresses induced by bowing of fuel columns near the assembly walls and by mechanical interaction of fuel columns with the wall and each other.

The cladding, duct wall and fuel melting radial progression across a GCFR core is shown in Figure 2. It was assumed for this analysis that the electric drive helium circulators inertially coastdown such that flow ceases in 230 seconds when the Reynolds number in the hottest channel reaches 2300. The reactor is tripped when circulator power is lost. Incipient cladding, assembly wall and fuel melting would occur at 370, 490 and 650 seconds, respectively. In contrast, if PLOF would occur one week after shutdown, incipient cladding, assembly wall and fuel melting would occur at 1050, 1600 and 2900 seconds, respectively. These results have been generated by a new computer program called SCORIA (Slumped Core Integrated Analysis). SCORIA is essentially a lumped heat capacity, thermal network analysis tool which includes conduction, forced convection and radiation heat transfer from one node to another and accounts for the change of phase of steel and fuel. Currently, it solves the heat transfer problem in one dimension and has the capability to model many axial locations although the axial components of conduction and radiation are neglected. SCORIA also includes a model which accounts for the buildup of steel from the lower axial blanket blockage, the backfill of the assembly coolant channels by molten steel to spillover into the interassembly spacing, and the blockage buildup in the interassembly spacing. A GCFR has been modeled rod by rod including assembly walls from the center of the core through the radial blanket during a PLOF. The transient model begins at steady state, proceeds through circulator coastdown and reactor trip, to the adiabatic core heat-up culminating in complete core melting. Figure 2 is representative of the results on the core midplane. It is noted that cladding melting initiates fairly uniformly throughout the core with an increasing delay in the outer ring of core assemblies next to the radial blanket. This is explained by the strong thermal coupling between assemblies which substantially reduces the more pronounced effects of the normal power profile during this slow heatup. Duct melting is distinctly delayed beyond cladding melting. Side to side incoherence in duct melting is small in the center core region but begins to increase in the outermost two rings of core assemblies. Fuel melting is again distinctly delayed beyond duct melting in each assembly.

As cladding and duct walls melt, molten steel is expected to drip or flow by gravity toward the lower axial blanket. This process has been modeled as a laminar film flow. The molten steel cannot permanently resolidify in the core because the cladding melt front progresses eventually to the core bottom. The penetration of molten steel into the lower axial blanket and the buildup of a steel crust which blocks the coolant channels has been modeled. This calculation assumes conduction heat transfer in the solidified steel layer and the cladding, convection heat transfer from the flowing steel, and Newton's Cooling Law between the cladding and the fuel. The model is similar to the integral (profile) approach recommended by Epstein [Ref. 4]. The major difference is that the current work models cladding as the "thermally thin" wall of a cylindrical tube. The results predict that complete blockage of the coolant channels in the lower axial blanket and the spacing between assemblies is expected to occur within 50 mm below the core bottom. The rate of radial buildup of a solidified steel layer in the channel is between 2 and 5 mm per second.

The rate of molten steel buildup on the blockage relative to the progression of duct melting is shown in Figure 3. It is noted that the steel buildup rate accelerates markedly when duct melting begins and that spillover occurs about 80 seconds after duct midflat melting and at the same time as duct corner melting. The 80 second delay in duct corner melting relative to the midflat is a direct consequence of the unfueled corner support rods in the assembly. If the corner tie rods were replaced with normal fuel rods, the corner melting delay would reduce to 30 seconds and duct fallaway before steel spillover would be predicted.

During the heatup to duct melting a radial temperature gradient develops in the fuel rods adjacent to the duct wall which induces fuel rod bowing. The deflections have been analyzed assuming that the declad fuel rods are fixed at the core/lower axial blanket interface due to molten steel refreezing. At the normally cold interface between the core and the upper axial blanket, it is assumed that the fuel rods are free and only restrained by the duct wall or by neighboring fuel rods. Bonding between fuel pellets is assumed to occur during normal operation and during heatup to cladding melting. All the evidence from TREAT fuel melting experiments indicate that even under much more rapid heatup, fuel collapse due to crumbling is not a concern although fuel rods may break after cladding melting. Figure 4 shows the fuel rod deflection profiles at the time of duct midflat melting. The stresses calculated from these deflections would cause the first two rods adjacent to the duct wall to break near the bottom. Following such a break, temporary stress relaxation would occur and the subsequent behavior of the rods is not well understood at this time, however, extensive and core-wide crumbling of fuel before duct melting is not currently expected. Fuel swelling under these accident conditions will be substantial and will tend to stabilize the declad fuel rods, further reducing the extent of fuel crumbling. In order for recriticality to occur, over 50% of the core fuel would be required to crumble into a packing fraction of 60%. Fuel swelling alone, if fully effective, would prevent recriticality from fuel crumbling.

Fuel melting and slumping, therefore, remains the principal concern for recriticality. Sufficient fuel to cause recriticality has melted about 320 seconds after first fuel melting starts or about 480 seconds after duct melting starts. This time interval is, thus, available to effect fuel removal by fuel meltout or duct fallaway to avert recriticality. The Duct Melting and Fallaway Test Program at Los Alamos Scientific Laboratory has as its objective to experimentally investigate the behavior of molten cladding and duct walls and to define the conditions required for duct fallaway. The first partial size experiment (FLS-1) consisted of a Full Length Subgroup of 37 electrically heated rods including axial blankets. It was completed in June 1978 and the next experiment is scheduled for May 1979. The first full size experiment is scheduled for the fall of 1979. The principal objective of the FLS-experiment series is to qualify the electrically heated rods for use in the full-size tests. However, significant information was derived from the FLS-1 test, most noticeably the observation that natural convection within the rod bundle is an effective axial heat transport mechanism, which caused duct melting in the FLS-1 experiment at an elevation 25 cm higher than expected. This effect could significantly enhance duct fallaway by delaying the time of molten steel spillover.

In the event that duct fallaway could not be conclusively demonstrated, backup solutions to the prevention of recriticality are being investigated to effect molten fuel removal from the core region prior to recriticality.

POST ACCIDENT FUEL CONTAINMENT FOLLOWING A PLOF ACCIDENT

The Gas-Cooled Fast Reactor (GCFR) utilizes a Prestressed Concrete Reactor Vessel (PCRV) which contains the core and all primary heat transport equipment. The PCRV is lined with a steel liner that is cooled by cooling tubes attached to the concrete side of the liner. Thermal and radiation shielding is located on the inside of the liner. The normally cooled liner and shielding presents a barrier for the containment of molten fuel in the GCFR. To establish the degree to which this barrier could contain molten fuel, several conceptual design options have been evaluated because of the space limitation imposed by the liner dimension and because of the absence of a liquid coolant that can absorb the upward flowing heat from a molten fuel pool.

The analytical methods used for the evaluation of alternate concepts include Baker's [Ref. 6] empirical model for two dimensional heat transfer in internally heated pools, conduction heat transfer through the side and bottom structures and convective and radiative heat transfer from the pool surface to the PCRV internal structures.

Post accident fuel containment concepts for the GCFRs have been developed in Germany [Ref. 7] and in the U.S. [Ref. 8]. Among the many concepts, the ceramic crucible, the borax bath, the uranium metal bath and the steel bath concepts have been studied for the GCFR. These concepts have been evaluated and compared.

The ceramic crucible utilizes a buildup of refractory materials forming a crucible inside the liner to contain the molten core debris without melting or chemical attack to the crucible surface and at the same time provide the required shielding for normal operation. Previous analysis [Ref. 3] for a 300 MWe GCFR have shown that this concept can be applied to the current GCFR design with some modifications. The thick crucible wall provides a stored heat capacity that can last some 30 hours after core meltdown. The peak heat flux which eventually reaches the cavity liner is sufficiently low that an enhanced liner cooling capacity could remove the entire downward flowing heat. However, because of the thick crucible wall, the debris pool temperature reaches 3200°C and the margin for fuel boiling under depressurized conditions is small. Also, most of the core debris decay heat is driven upward which makes this concept depend on upward heat removal. The delayed startup of a single CACS loop is sufficient to remove all the upward flowing decay heat even at fully depressurized conditions. Furthermore, a residual pressure of 6 atm in the PCRV is sufficient for upward heat removal by natural convection in the CACS loops. Even if no convection, forced or natural could be established in the CACS loops, the melting of substantial portions of the central cavity internals is delayed by approximately 24 hours. The addition of these internals to the debris pool represents a substantial incremental heat capacity that would depress pool temperatures for a substantial time period, following which the reduced upward flowing heat may be removed through the liner insulation to the liner cooling in the upper portion of the central cavity. Therefore, maintaining PCRV liner integrity following a core meltdown appears technically feasible but requires design attention for the unique aspects of a core meltdown condition, such as liner cooling capability, PCRV penetrations, crucible material flotation, etc.

The BORAX bath concept was proposed by Dalle Donne, et al [Ref. 9] for the GCFR. Steel boxes filled with borax ($Na_2B_4O_7$) are installed in the lower reactor cavity. Following a core meltdown, the oxide fuel is expected to dissolve in the liquid borax to form a compound solution pool. The dissolving process is controlled by steel box melting so that the liquid borax is already at the melting point of steel where a fast dissolving rate may be achieved. The low boiling point of borax (1700°C) may cause a borax vapor blanket to form at the fuel-borax interface so that the fuel and steel may sink through the borax bed without dissolving the fuel. In addition, the borax pool may become separated from the fuel by an intermediate steel layer to interrupt the dissolving process.

Small scale simulation tests performed by Dalle Donne, et al [Ref. 2] indicate the UO_2 dissolution can be accomplished in the presence of steel and larger experiments are currently in progress. Only 20 to 30% of the decay heat flows upward because of the low pool temperature. Sideward and downward heat fluxes are increased but the peak heat flux does not occur until about 10 hours.

The heavy metal bath concept utilizes a large mass of high density, low melting point uranium metal alloy installed inside the lower reactor cavity. Following a core meltdown, a low temperature pool of the uranium alloy is expected to form with solid fuel fragments in suspension. The molten pool is contained by the unmelted solid edge of the heavy metal. The principal advantage of this concept is its self-sealing feature. Gaps between structural alloy blocks will become filled by the melted uranium alloy which is of higher density than UO_2, thereby preventing the penetration of molten UO_2 into structural gaps and cracks, which otherwise can locally increase the heat flux to the cavity liner. A heat transfer study [Ref. 10] for a 1500 MWe GCFR has shown that heat removal from the heavy metal bath is feasible with a wide range of suitable pool temperatures. Disadvantages of this concept include the high cost of uranium materials, the potential for metal water reactions if the liner is breached and the possibility of crusting on top of the heavy metal that could suspend a significant fraction of the UO_2 above the pool. Uranium alloys also have a low heat capacity requiring a 2 m thick layer for a 4-hour heat capacity.

A steel bath concept employs a large mass of stainless steel plates that will melt following a core meltdown to form a "light metal bath". This concept is similar to the uranium bath except that the core debris is heavier than the pool material and will be collected at the bottom of the steel pool. A refractory layer placed between the steel and the cavity liner is thus needed to protect the liner from potential hot spot effects. Analysis of the steel bath heat transfer [Ref. 11] has shown that a steel core retention system has a greater stored heat effect than the uranium system and therefore the liner heat flux and temperatures are lower. Similar to the ceramic crucible concept, this concept can be accommodated without a large cost or significant design changes.

As a comparison of the four concepts, the important parameters are listed in Table 1 and each concept is evaluated against these parameters. The ceramic crucible is the simplest concept but is most dependent on upward heat removal; whereas the borax bath and the uranium bath concepts offer better performance but would require major design changes and experimental development. The steel bath concept appears to be an interesting compromise concept. Furthermore, a combination of the essential features of two concepts, i.e. a heavy metal base with an overlaying steel bath, may offer further concept improvements. It is concluded that several diverse concepts for molten fuel containment inside the PCRV appear promising to exploit the normally provided cooled liner barrier for post accident fuel containment.

All in-vessel molten fuel containment concepts depend on the availability of liner cooling for the indefinite retention of molten fuel. The time decay available for the restoration of liner cooling depends on the heat capacity provided by the structural material in the lower cavity region and is typically in the range of 4 to 10 hours. Since the probability of restoring offsite power in 2 hours is typically 90%, the dependence on liner cooling is not unreasonable. Nevertheless, the consequences of a longer loss of liner cooling was investigated in order to determine likely failure modes of the PCRV. Three specific failure modes have been identified and analyzed: 1) Failure of PCRV tendons due to sideward growth of the fuel pool penetrating into the concrete slab, 2) failure of the refueling penetration by molten fuel penetration into the clearance between the plug and the PCRV base and 3) molten fuel penetration through the concrete base mat of the PCRV. Failure times for these failure modes are shown in Table 2. Failure of the first row of axial prestressing tendons at 31 hours after core meltdown is predicted as the earliest failure mode. This failure mode would only be of importance if the PCRV is still pressurized, a very unlikely condition, because a pressure reduction would either be expected through the PCRV relief valves or through the failed liner. In addition, sufficient time for manual depressurization following liner failure is available. PCRV concrete failure near the top of the refueling penetration occurs at about 40 hours and near the locking ring at about 80 hours. For the current plug support concept, the most likely plug failure would occur at 80 hours and it may be possible to further delay the failure to more than 200 hours. Failure by PCRV bottom head penetration requires even longer times. It is concluded that it appears feasible to delay the currently indicated failure time of 80 hours to more than 200 hours if necessary.

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PLOF EVENT SEQUENCE DIAGRAM

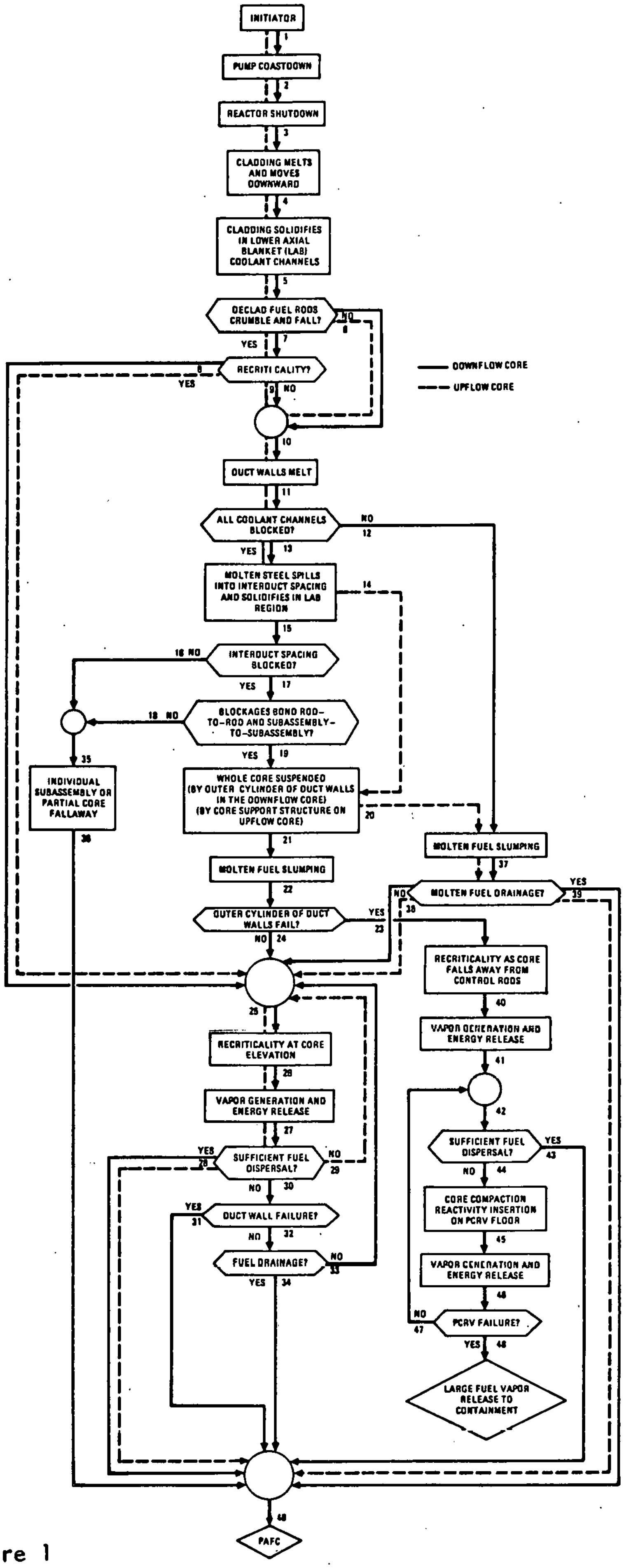

Figure 1

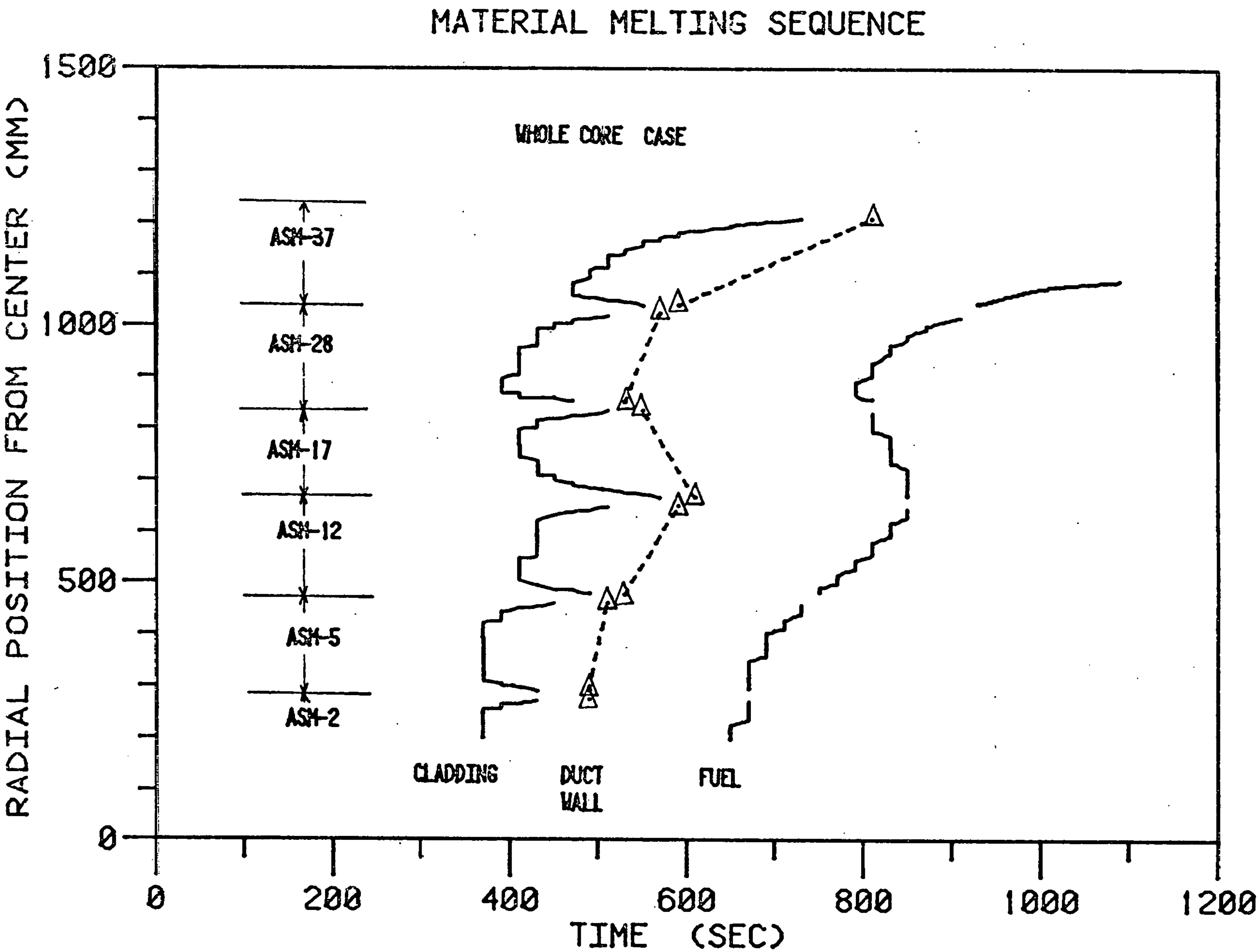
MATERIAL MELTING SEQUENCE
WHOLE CORE CASE
ASM-37
ASM-28
ASM-17
ASM-12
ASM-5
ASM-2
CLADDING
DUCT WALL
FUEL
RADIAL POSITION FROM CENTER (MM)
0
500
1000
1500
TIME (SEC)
0
200
400
600
800
1000
1200

FIGURE 2

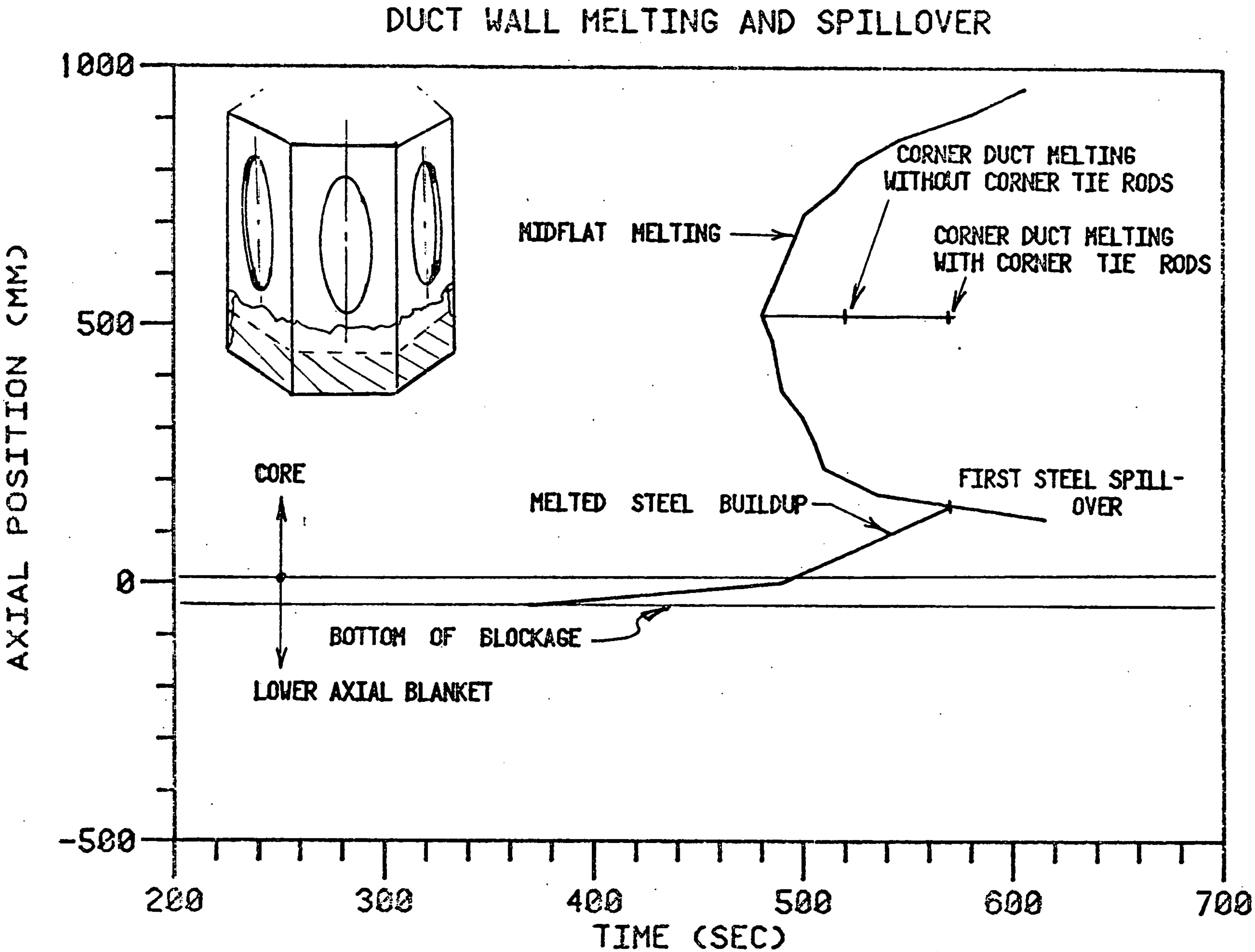

FIGURE 3. Duct Melting and Steel Buildup During a Protected Loss of Flow Accident

(Deflections amplified 25x)

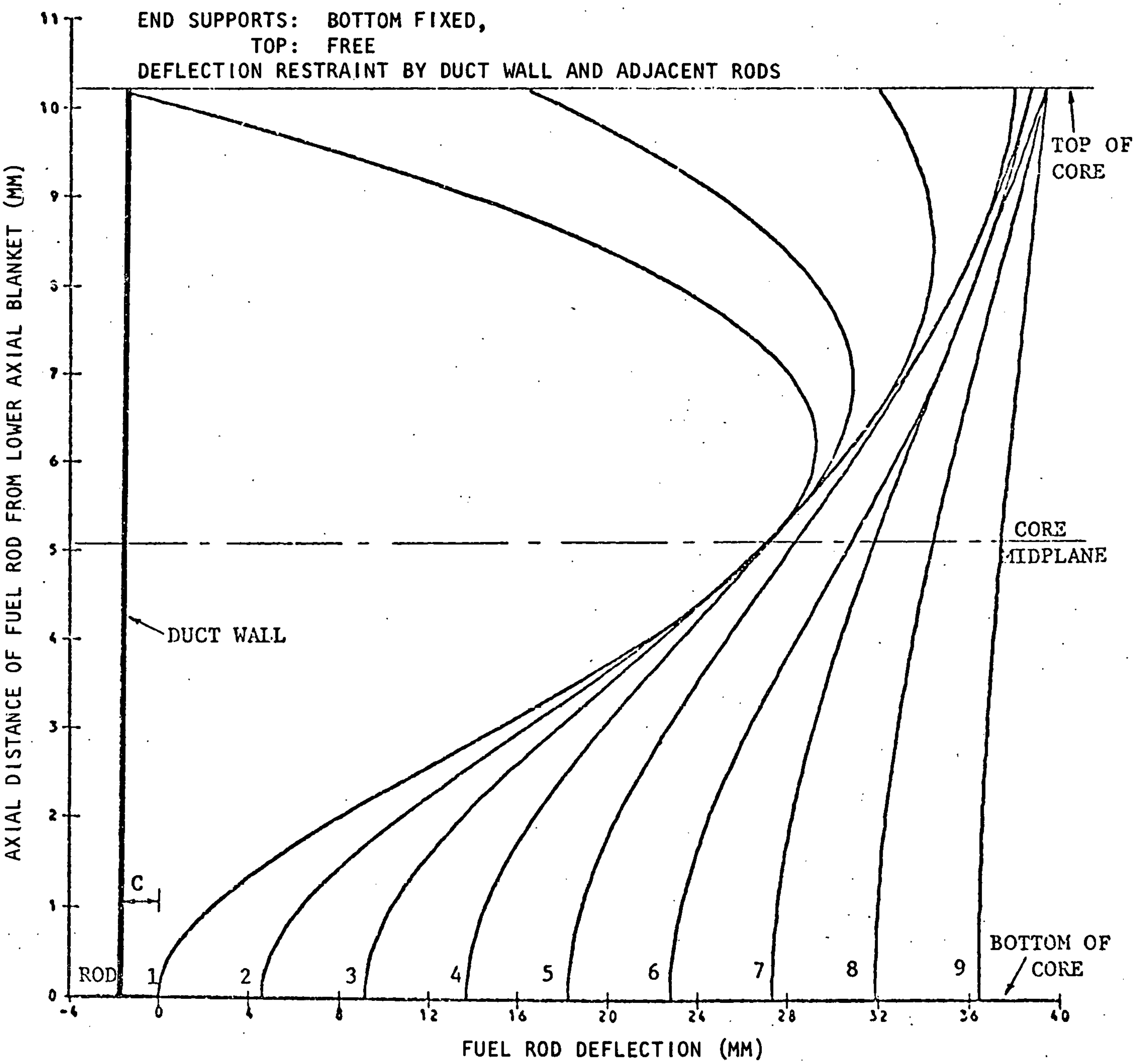

Figure 4. Thermal deflection of declad fuel rod along a traverse to the midflat at the time of 50% heat of fusion at the duct midflat.

Table 1. Comparison of Molten Core Retention Concepts

Parameter	Molten Core Retention Concepts			
	Ceramic Crucible	Borax Bath	Uranium Bath	Steel Bath
Pool temperature	High (>3000°C)	Low (1427°C)	Low (>1200°C)	Low (>1500°C)
Cavity liner temperature	Low (150-200°C)	High (250-300°C)	High (280-350°C)	High (250-300°C)
Time of maximum liner heat flux	Long (28-40 hrs)	Medium (∿10 hrs)	Short (3-4 hrs)	Medium (6-10 hrs)
Fraction of upward heat removal	High (0.6-0.8)	Low (0.2-0.3)	Medium (0.3-0.4)	Low (0.1-0.3)
Request for design changes	Minor	Major	Major	Minor
Need for experimental work	Low	High	High	Medium
Pool manageability	Medium	Low	High	High
Fuel penetration and material flotation	Yes	Yes	No	Yes
Scaleability	High	Low	Medium	Medium
Cost	Low	Medium	High	Low

Table 2. Comparison of the PCRV Failure Modes

Cause of PCRV Failure	Time of Failure (After Core Meltdown)
Failure of 1st row of PCRV tendons	31 hours
Failure of PCRV concrete (near fuel in refueling gap)	40 hours
Failure of PCRV concrete (near locking ring of the refueling plug)	80 hours
Failure of the lower shoulder of the refueling plug	>200 hours
Failure of the locking ring of the refueling plug	>200 hours
Melt penetration through 50% of the lower PCRV head	256 hours
Melt penetration through the full PCRV head	48 days

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