CONF-790816--84

GA-A15556

MASTER

EVENT SEQUENCE QUANTIFICATION FOR A LOSS OF SHUTDOWN COOLING ACCIDENT IN THE GCFR

by
M. FRANK and J. REILLY

OCTOBER 1979

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

GENERAL ATOMIC COMPANY

DISCLAIMER

GA-A15556

EVENT SEQUENCE QUANTIFICATION FOR A LOSS OF SHUTDOWN COOLING ACCIDENT IN THE GCFR

by

M. FRANK and J. REILLY

This is a preprint of a paper presented at the Fast Reactor Safety Conference, Seattle, Washington, August 19-23, 1979.

Work supported by
Department of Energy
Contract DE-AT03-76SF71023

GENERAL ATOMIC PROJECT 6114
OCTOBER 1979

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

GENERAL ATOMIC COMPANY

EVENT SEQUENCE QUANTIFICATION FOR A LOSS OF SHUTDOWN COOLING ACCIDENT IN THE GCFR

M. V. Frank and J. T. Reilly

General Atomic Company
P.O. Box 81608, San Diego, California 92138

ABSTRACT

This paper presents a summary of the core-wide sequence of events of a postulated total loss of forced and natural convection decay heat removal in a shutdown Gas-Cooled Fast Reactor (GCFR). It outlines the analytical methods and results for the progression of the accident sequence. This hypothetical accident proceeds in the distinct phases of cladding melting, assembly wall melting and molten steel relocation into the interassembly spacing, and fuel relocation. It identifies the key phenomena of the event sequence and the concerns and mechanisms of both recriticality and recriticality prevention.

I. INTRODUCTION

In April 1979 the Gas-Cooled Fast Reactor (GCFR) program changed the GCFR reference design from a top supported downflow core to a bottom supported upflow core in order to provide the capability for pressurized decay heat removal by natural coolant circulation from the core to the ultimate heat sink. An accident sequence considered in the GCFR is initiated by a loss of all forced circulation and the postulated failure to establish natural convection in a shutdown reactor. This hypothetical accident is analyzed to investigate the potential for consequence mitigation and containment margin because its potential for core disruption may be greater than for unprotected accidents. It has been named the Loss of Shutdown Cooling Accident or LOSC. Some conceptual work on this accident in a downflow core design has been previously reported [Refs. 1, 2]. This paper presents analyses of the progression of the accident sequence up to recriticality and identifies the key phenomena associated with this event sequence. In particular, the paper addresses:

1) Definition of the expected accident sequence of events

2) Detailed core-wide material melting progression

3) Cladding and assembly melting, relocation and solidification, and

4) Recriticality mechanisms and concerns.

This type of postulated accident has several characteristics which are distinctly different from loss of flow accidents initiated at full power and without scram. The initial fuel heating rates are dominated by decay heat. Therefore, the time scale of melting is two to three orders of magnitude longer. At the time of initial fuel melting, the reactor is shutdown and delayed neutron precursor concentrations are orders of magnitude smaller. Therefore, larger amounts of reactivity may be inserted before fission power can become a significantly greater heat producer than decay heat and before doppler feedback is important. Furthermore, as fission power increases, the neutron spectrum is harder because of the control rod insertion and nearly complete decladding of fuel rods. Hence, the doppler coefficient is smaller than in the unprotected case. Work is in progress to determine realistic magnitudes of reactivity feedback.

II. SEQUENCE OF EVENTS

The initiating event phase of the hypothetical LOSC accident sequence requires a series of common mode failures to be postulated that leads to a total loss of decay heat removal. The reference scenario considered for analysis of the core melting progression postulates the following occurrences:

1. A simultaneous loss of all drive power to the electrically driven main circulators is assumed to occur as the initiating event.

2. A common mode failure of the main circulator pony motors is postulated to fail the Shutdown Cooling System when the main circulators have coasted down to the pony motor design speed.

3. Failure of the Core Auxiliary Cooling System (CACS) to energize by common mode is postulated which disables the CACS forced convection cooling mode, and

4. A common mode failure of the CACS isolation valves to open by gravity is postulated to prevent the removal of decay heat by natural circulation.

Cladding and assembly wall melting is expected within several minutes in the absence of loop coolant circulation under decay heat generation because of the limited core heat capacity. The accident sequence summarized in Figure 1 and the phenomenological event timing below are based on neglecting interassembly and intra-assembly natural convection in an upflow GCFR core. These will be included in future analyses. This postulated accident sequence is substantially the same whether the reactor is tripped by the engineered plant protection system signals or is already shutdown when circulator coastdown begins. However, the length of time between each significant event is extended as the loss of flow is delayed after shutdown.

Based on the experimental observation in the LASL experiments FLS-1 and FLS-2, a substantial delay in the time of cladding melting is expected owing to natural circulation heat transport from the core to the upper plenum structures. Natural convection is expected to continue even after cladding melting. Therefore, a reduction in the clad and duct melting progression and delay in the fuel melting time are also expected. Analysis capability to include these effects is under development.

Event	Time (sec)	
Reactor scrams and circulators begin coastdown	0	
Circulators are braked upon laminar flow in the core	230	
Cladding melting begins	370	Clad relocation phase
Duct wall melting begins (hot side)	490	
Duct wall melting begins (cold side)	510	Assembly wall relocation phase
First interassembly spacing plugs	590	
Fuel melting begins	650	Fuel relocation phase
Fuel slumping induced recriticality	∿1000	
Disassembly or transition phase		Recriticality and transition or disassembly phase

Approximately six minutes after a simultaneous reactor trip and circulator trip, the cladding begins to melt. It relocates downward and refreezes in the lower axial blanket within 50 mm of the core bottom. Nearly all lower axial blanket coolant channels may be blocked by this process. Only those adjacent to the assembly walls are calculated to remain partially open at this time. The cladding melts over 50% of the core length in 20 seconds for the hot rod.

Exposure of the assembly walls to thermal radiation from the declad fuel columns causes their melting at the hottest axial level about two minutes after incipient cladding melting. Melting of a duct wall adjacent to a control rod assembly (cold side) is delayed about 20 seconds compared to wall melting adjacent to a fuel assembly. The axial progression of melting along the hexagonal assembly wall flat is initially faster than the circumferential progression [Ref. 2]. The added molten steel inventory blocks the remaining lower axial blanket coolant channel. The modeling presumes that melting of the assembly walls also results in a buildup of relocated steel which solidifies on the assembly wall over the lowest 200 mm of the core. This results in a steel "cup" in each assembly. The bottom of the cup is a platform of solidified cladding in the lower axial blanket reaching to the core/blanket interface. The sides of the cup are solidified assembly wall steel and unmelted assembly wall. The buildup of steel retards the axial progression of the assembly wall melt front. As the assembly walls continue to melt, the molten steel flows into the cup forming a molten steel pool. Continued addition of molten steel backfills the cup until the pool is able to spill over the sides and into the interassembly spacing. Analytical modeling of assembly wall melting, pool buildup and spillover is illustrated in Figure 2. The spilled steel is calculated to solidify within 50 mm of the core bottom in the lower axial blanket region of the interassembly spacing. There is sufficient molten steel inventory to completely block the spacing around the hexagonal assembly.

The fuel melting phase commences after most of the assembly walls have melted. The molten fuel has been postulated to slump into the steel formed cups and settle upon the solidified steel platform in the lower axial blanket. The molten steel is postulated to be displaced upward, hence contributing to steel spillover. Steel vaporization is not expected to occur at this time because the 8.8 MPa system pressure raises the steel vaporization temperature to over 4500°K [Ref. 3]. The high pressure would also limit fission gas volume fractions within the molten fuel. Eventually, the assembly walls and solidified cladding completely melt down to the core bottom. The molten fuel and steel are assumed to uniformly spread over all such assemblies such that a molten fuel layer is between a molten steel layer above and steel blocked lower axial blanket below. The sections of unmelted fuel columns above and below the central molten region are assumed to join such that a void space (filled with helium) is left between the top of the unmelted fuel columns and the upper axial blanket.

Approximately five minutes after incipient fuel melting, enough fuel to overcome the shutdown margin would have slumped and compacted upon the lower axial blanket blockage. The approach to a critical configuration is determined by a number of reactivity insertions in addition to fuel compaction: a) Steel relocation from the core toward the lower axial blanket, b) spectrum hardening induced loss of rod worth, and c) neutron reflection from the molten steel layer above and solid steel layer below appear to be the most important.

III. DETAILED CORE-WIDE MATERIAL MELTING AND METHODS

A new computer program called SCORIA (Slumped CORe Integrated Analysis) has aided in this event sequence quantification. 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 parametrically 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 in one dimension rod by rod including assembly walls from the center of the core through the radial blanket during a LOSC. 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 3 is representative of the results on the core midplane. It shows the cladding, duct wall and fuel melting radial progression across a GCFR core. Each explicitly denoted assembly (ASM-2, ASM-5, etc.) represents the hexagonal ring of assemblies in which it is found.

It was assumed for this result that the helium circulators inertially coast down such that flow ceases in 230 seconds. The reactor is tripped 0.5 second after circulator power is lost. In contrast, if the accident occurs one week after shutdown, incipient cladding, assembly wall and fuel melting would occur at 1050, 1600 and 2900 seconds, respectively.

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 would progress 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 assumed conduction heat transfer in the solidified steel layer and the cladding, convection heat transfer from the flowing steel, and an input temperature boundary condition at the fuel surface. The model is similar to the integral (profile) approach recommended by Epstein [Ref. 4]. The major difference is that the current work models cladding at the "thermally thin" wall of a cylindrical tube. The results show 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.

IV. RECRITICALITY RESULTS AND CONSIDERATIONS

A timewise series of core material distributions deduced from SCORIA was analyzed with an R-Z diffusion theory model using 2DB [Ref. 5]. The purpose was to determine the approximate time and ramp rate of a postulated recriticality. The following table presents the results and Figure 4 is a schematic of the critical configuration.

Transient Time (sec)	Configuration Detail	k_{eff}
0	Hot shutdown	0.89
300	44% of clad slumped Top 77 mm of lower axial blanket plugged	0.91
770	6.6% of fuel molten Nearly all cladding slumped Some duct wall melting	0.92
870	21% of fuel molten Most of assembly walls melted Molten fuel in every assembly	0.93
970*	31% of fuel molten All but outermost assembly wall slumped	0.99
1110	45% of the fuel molten	1.09

*Figure 4 is the configuration at this time.

The ramp rate at recriticality is about 17¢/sec. Since fission power as the reactor approached critical was not included, this ramp rate is probably an underestimate.

Melting of the lower axial blanket blockage by contact with molten fuel and subsequent fuel drainage may chronologically compete with the buildup of a critical mass.

Another mode of fuel relocation which may induce a criticality 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. Fission gas induced solid fuel swelling under substantially isothermal heat-up conditions may tend to stabilize the declad fuel columns. Two-dimensional transport theory calculations using TWOTRAN [Ref. 6] have been performed to determine the packing of fuel fragments required for criticality if an entire core should crumble. These model a core which has all control rods inserted, all cladding and assembly wall steel layered up from the core bottom, and all the core fuel (which is still solid) crumbled into this steel layer. It was found that this configuration would be critical if the non-fuel fraction in the fuel region is less than 60%. Molten cladding filled the spaces between the crumbled fuel fragments.

The major phenomena which lead to concern over the potential for recriticality should this accident occur are:

- Steel blockage formation in the lower axial blanket,

- Subsequent axial assembly wall melting and molten steel pool buildup leading to molten steel spillover into the interassembly spacing and solidification there,
- Declad fuel column crumbling prior to melting, and
- Molten fuel slumping.

The accident sequence also suggests mechanisms for preventing recriticality. The most important are:

- In-situ poisoning of a molten core with a dispersed and mixed poison material,
- Molten fuel drainage,
- A combination of poisoning and drainage.

The potential for fuel drainage may prove to be an attractive feature of gas-cooled systems. The feasibility of these mechanisms is currently under investigation at General Atomic.

ACKNOWLEDGEMENTS

This paper was prepared under Department of Energy Contract No. DE-AT03-76SF71023. The authors wish to thank A. Hess for performing the criticality calculations.

REFERENCES

1. A. TORRI and D. R. BUTTEMER, "Loss of Flow Accident Phenomenology in the GCFR", ANS Trans., 21, 1975, p. 295.

2. A. TORRI and J. L. TOMKINS, "Accident Termination by Element Dropout in the GCFR", Proceedings of the Fast Reactor Safety Meeting, Chicago, Oct. 1976, pp. 1183-1194.

3. Properties for LMFBR Safety Analysis, April 1976, ANL-CEN-RSD-76-1.

4. M. EPSTEIN, "The Growth and Decay of a Frozen Layer in Forced Flow", Int. J. Heat Mass Transfer, Vol. 19, 1976, pp. 1281-1288.

5. W. W. LITTLE, JR., and R. W. HARDIE, "2DB User's Manual - Revision 1", BNWL-831, Rev. 1, Pacific Northwest Laboratory, 1969.

6. K. D. LATHROP and F. W. BRINKLEY, "TWOTRAN-II: An interfaced Exportable Version of the TWOTRAN Code for Two-Dimensional Transport", USAEC Report LA-4848-MS, Los Alamos Scientific Laboratory, July 1973.

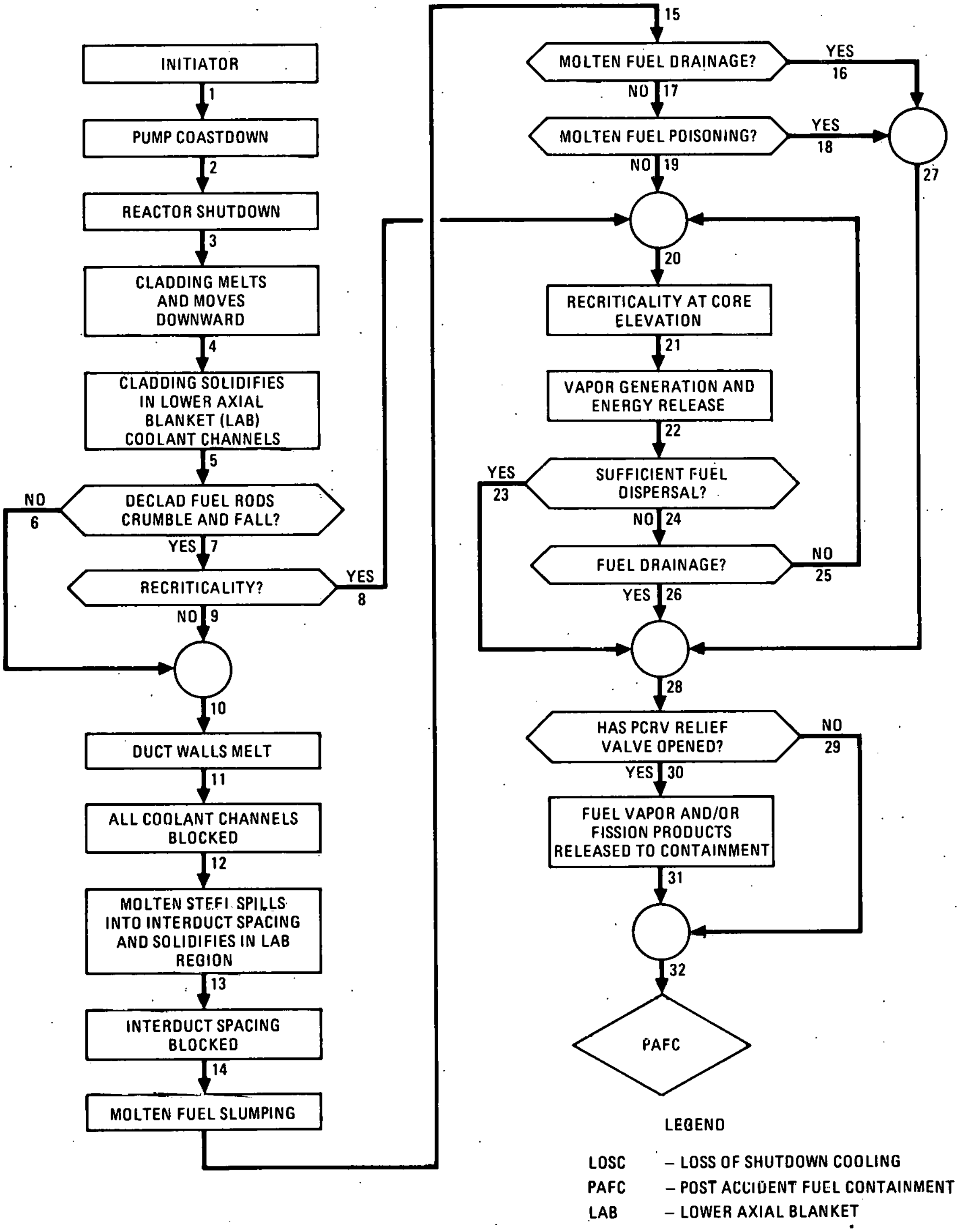

Fig. 1. LOSC event sequence diagram -upflow core- (pressurized case)

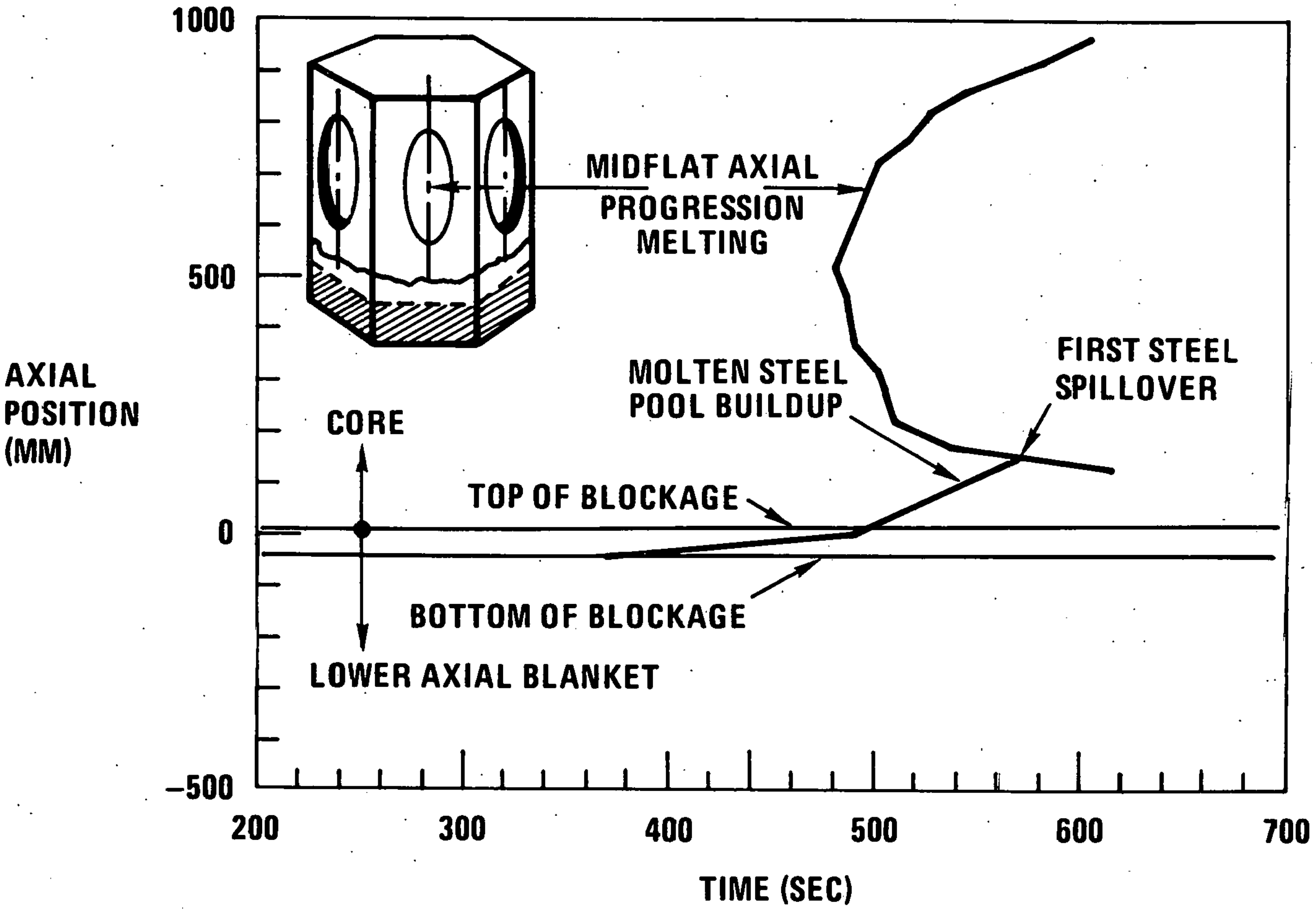

Fig. 2. Assembly wall melting, pool buildup, and spillover

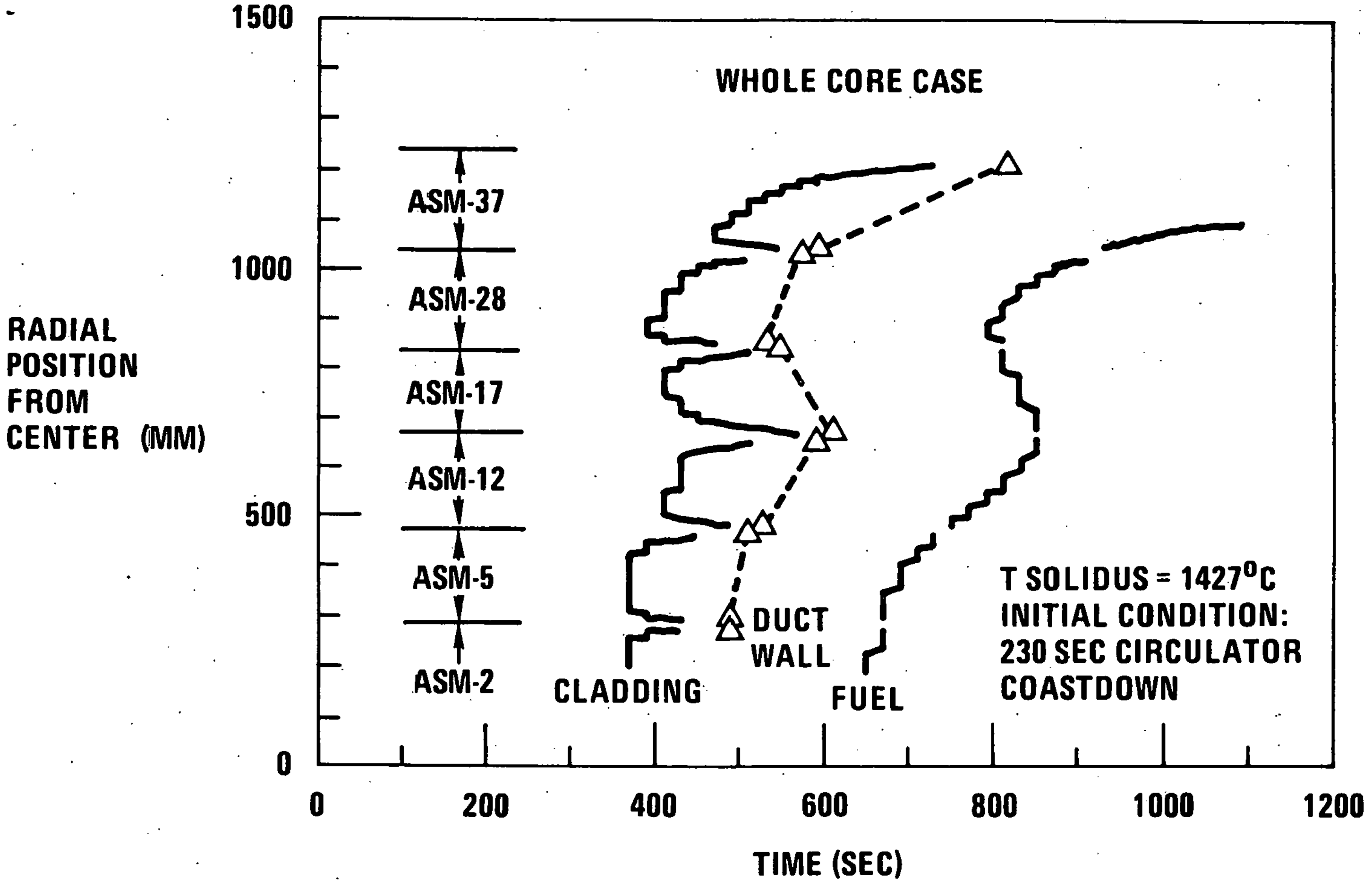

Fig. 3. Material melting sequence during an LOSC accident

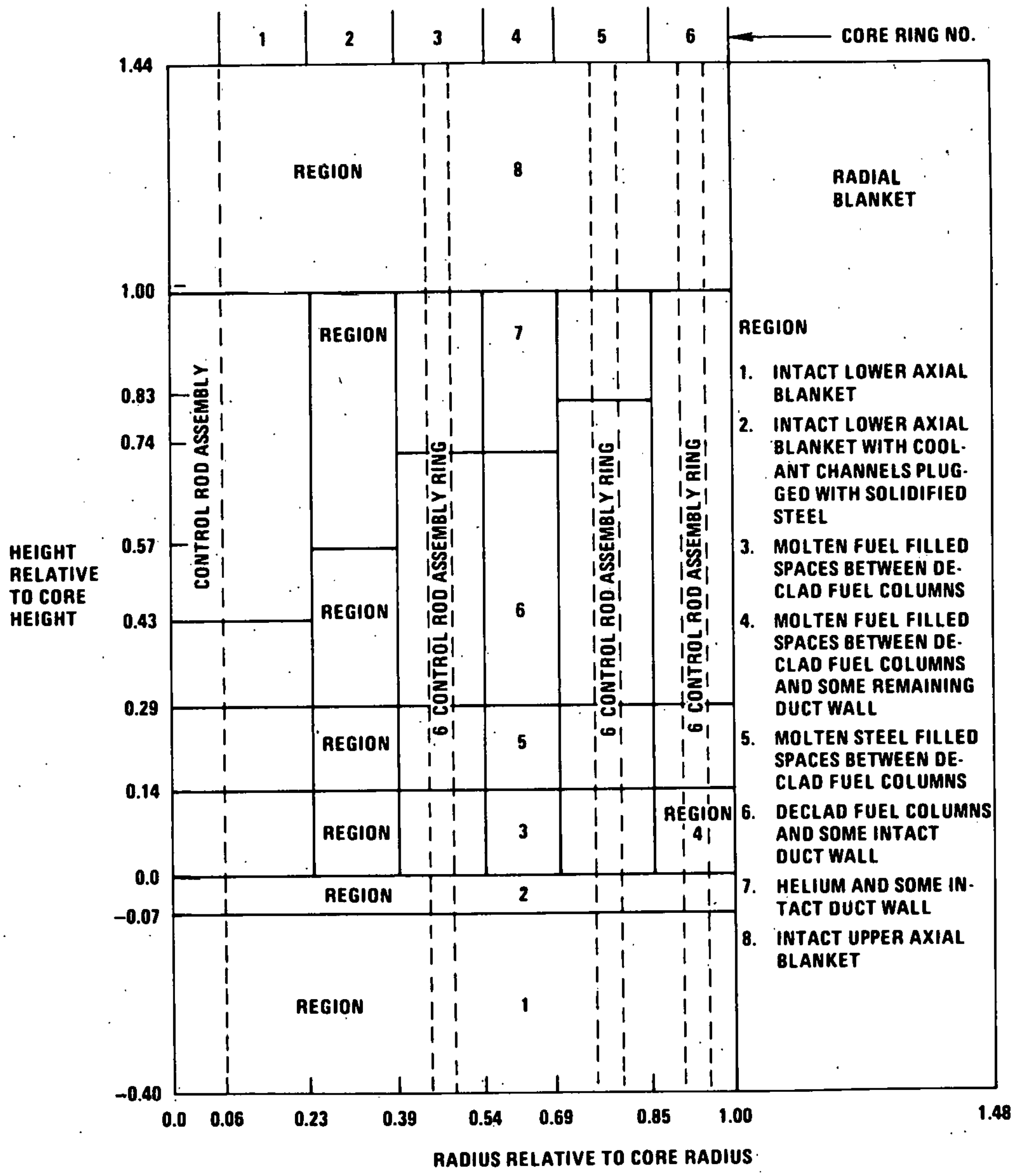

Fig. 4. LOSC critical core configuration

GENERAL ATOMIC COMPANY
P. O. BOX 81608
SAN DIEGO, CALIFORNIA 92138