Paper submitted for presentation at the 1987 Eastern Computer Simulation Conference, Orlando, FLA, April 6-9, 1987.

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CONF-870472--3

DE87 011524

* Work supported by the U.S. Department of Energy, Breeder Reactor Programs under Contract W-31-109-Eng-38.

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ABSTRACT

To ensure that the public health and safety are protected under any accident conditions in a Liquid Metal Fast Breeder Reactor (LMFBR), many accidents are analyzed for their potential consequences. The SAS4A code system, described in this paper, provides such an analysis capability, including the ability to analyze low probability events such as the Hypothetical Core Disruptive Accidents (HCDAs).

The SAS4A code system [1] has been designed to simulate all the events that occur in a LMFBR core during the initiating phase of a Hypothetical Core Disruptive Accident. During such postulated accident scenarios as the Loss-of-Flow and Transient Overpower events, a large number of interrelated physical phenomena occur during a relatively short time. These phenomena include transient heat transfer and hydrodynamic events, coolant boiling and fuel and cladding melting and relocation. Due to the strong neutronic feedback present in a nuclear reactor, these events can significantly influence the reactor power.

The SAS4A code system is used in the safety analysis of nuclear reactors, in order to estimate the energetic potential of very low probability accidents. The results of SAS4A simulations are also used by reactor designers in order to build safer reactors and eliminate the possibility of any accident which could endanger the public safety.

INTRODUCTION

The liquid metal cooled fast breeder reactor (LMFBR) has been recognized as a safe and practically unlimited source for the nation's long term energy requirements. In addition to the capabilities for breeding its own fuel and operating at high thermal efficiencies, the fundamental neutronic and thermal-hydraulic responses to potential accident conditions can provide an inherently safe power system. These inherent safety characteristics are due to several

factors such as operation of the system at low temperature with a large heat rejection capability which allows significant time for operator intervention, the utilization of a low pressure coolant system precluding the rapid expulsion of the reactor coolant, and the prompt negative feedback provided by the Doppler effect.

Despite these characteristics, significant attention has been directed toward low probability severe accidents which could lead to substantial core disruption and pose a threat to public health and safety. While proper design makes such severe accidents very improbably events, they have received attention because their consequences could be significant. Principal concerns include the facts that the LMFBR core is not in its most reactive configuration, there is a large fission product and plutonium inventory, and there are large amounts of liquid sodium coolant present. Since current design efforts have identified and are incorporating additional inherent mechanisms which would preclude these severe accidents, their residual probability of occurrence is viewed now as even lower. Nonetheless, to provide a comprehensive assessment of risk to public health and safety, such accidents are examined, often within the context of a probabilistic risk assessment. These analyses are performed with phenomenological and integrated analysis computational tools, validated against prototypic experimental information, which can simulate the sequence of events occurring during a postulated accident situation.

The SAS system of accident analysis codes developed at Argonne National Laboratory, has played an important part in the computer simulation and assessment of energetics potential for core disruptive accidents. Combined with prototypic in-pile and out-of-pile experimental information and detailed phenomenological analyses, the SAS codes are able to provide a realistic and defensible simulation of severe accident events and an assessment of their consequences.

Although originally focused on the simulation of hypothetical core disruptive accidents in a reference oxide fuel design with a loop-type heat transport system and a liquid metal coolant, the analytical capability has proven to be remarkably robust in performing analyses for other reactor designs, such as pool LMFBR designs and even gas-cooled fast reactors. Over the last several years advanced modeling capabilities were developed and embodied in the first version of the SAS4A code, released for use in the US fast

reactor community in February, 1984. Since its release, the code has undergone extensive testing and application, which has resulted in both refinements to existing models and methodology and additions to phenomenological capability. The SAS4A version of the SAS system is the subject of this paper, in which we summarize the major modeling capability of the integrated phenomenological models.

The SAS4A code is providing an integrated and quantitative framework for examining the behavior of recent innovative design liquid metal reactors under unprotected accident conditions. Preliminary investigations indicate that important mechanisms which introduce negative reactivity in these accidents, such as fuel extrusion and in-pin fuel relocation in metal fuels, structural feedback through thermal-mechanical-neutronic effects and natural circulation heat removal capability can play a significant role in mitigating concern even for coolant boiling, much less an energetic excursion. The SAS4A code, in conjunction with the SASSYS systems analysis [2] code with which it is fully compatible, is among the primary analytical tools used in these investigations.

SCOPE OF SIMULATION

In a Liquid Metal Fast Breeder Reactor (LMFBR) nuclear power plant the thermal energy is produced in the reactor core (Fig. 1), via a nuclear chain reaction. This heat is removed by the flow of primary liquid sodium, which heats up as it moves through the reactor core. The primary sodium then transfers the heat to the secondary sodium circuit in the primary heat exchanger and is sent back through the reactor core by the primary pump. The secondary sodium circuit transfers the heat acquired in the primary heat exchanger to the water circuit via the secondary heat exchanger. The resulting water vapor drives the turbine which turns the electric generator and produces the electricity we use. The vapor leaving the turbine is sent to a condenser and then is recirculated through the secondary heat exchanger.

The SAS4A code has been designed to simulate in detail the behavior of the primary loop. Simpler models are used to describe the response of the "balance-of-plant", only, because during the severe accidents considered a simplified treatment of the "balance-of-plant" system is satisfactory. If a more detailed representation of the plant response is desired, SAS4A can work

together with the system code SASSYS to provide a complete simulation of the plant response. Inside the primary sodium loop the most important and complex element is the reactor core itself. Changes in the flow, temperatures and core reactivity are tightly interdependent. Any change in the material density due to sodium boiling or fuel and cladding heatup lead to changes in the core reactivity and can accelerate or decelerate the chain reaction, leading to further changes. This very tight feedback loop, via the core reactivity, is the most important element in the simulation of reactor behavior and requires detailed models describing the changes in material densities throughout the core. Because changes in the chain reaction can cause very rapid power changes and thus dramatically alter the time scale of events, a sophisticated system of time management, coordinating the various SAS4A models is essential.

OVERVIEW OF CODE STRUCTURE

SAS4A simulates the events taking place in a LMFBR core during the transient following an accident event such as a Transient Overpower (TOP) or Loss-of-Flow (LOF). The reactor core is made of a large number of hexagonal fuel assemblies, each assembly containing a large number of fuel pins. The fuel pins consist of uranium pellets enclosed in a steel tube, and are cooled by the surrounding liquid sodium, as illustrated schematically in Fig. 2.

In order to simplify the simulation and reduce the computational costs the reactor core is subdivided into channels, each channel containing a number of fuel assemblies. All the fuel assemblies in a channel are assumed to behave in an identical manner. Furthermore, all the pins in an assembly are assumed to behavior identically. Thus, a single fuel pin, its cladding and an associated amount of coolant and structure can be taken to be representative of all the pins assigned to a particular channel (Fig. 3).

The organization and structure of SAS4A are depicted in Fig. 4. The root segment consists of three modules: DRIVER, DATSER, and PROMAT. These modules provide logic path control, data management, and properties of materials.

The DATAIN module provides all data input and interpretation services for SAS4A. The DEFORM steady-state segment treats the dynamic response of the pins in the various channels to pre-transient irradiation, while the SSHTR module computes the steady-state fuel pin and coolant temperatures and coolant flow rates at each irradiation time step.

Nine modules interact during a transient calculation. The time-dependent reactivity feedback and flux amplitude (power level) are computed in TSPK. The transient thermal and hydraulic behavior of the primary and secondary coolant loops is provided by PRIMAR-4.

The thermal-hydraulic response of the sodium coolant and the fuel pins in the core is provided by the TSCLO module prior to sodium boiling while the DEFORM module describes the mechanical fuel response. After the initiation of sodium boiling, the thermal-hydraulic behavior of the core coolant and fuel pins is described by the TSBOIL module, which replaces TSCLO. The PINACLE module describes the in-pin molten fuel relocation prior to pin failure, while CLAP describes the relocation of molten cladding prior to pin failure.

When the pin failure is predicted to occur in a channel, either the PLUTO2 or LEVITATE modules are initiated. Only the TSPK neutronic module and the PRIMAR-4 module remain operational, as PLUTO2 or LEVITATE describe all the events occurring in the core in the post-pin-failure period.

The calculation in each channel is advanced until the end of a primary time step is reached. At any given time the calculation in a channel will be performed by the module required by the accident sequence. Thus, in a high power channel where the sodium has boiled and the fuel pin was disrupted, the calculation may be performed by the LEVITATE model, while in lower power channels where the liquid sodium is still present, the calculation might be performed by PLUTO if the fuel pin has failed. At the end of the primary time step the reactivity effects in each channel are integrated and the TSPK module performs the calculation of the reactivity feedback and reactor power using first order perturbation theory and point kinetics. The response of the hydraulic circuit external to the core is calculated by the PRIMAR-4 model. The important features of the basic phenomenological modules presented in Fig. 4 as well as recent validation activities are described below.

DESCRIPTION OF THE MAIN SAS4A PHENOMENOLOGICAL MODULES

The interaction between the different components present in the channel, i.e., mass, energy, and momentum transfer, is largely determined by the local configuration which, in turn, is determined by the flow regime used. The continuous flow regimes modeled in LEVITATE are: a bubbly fuel flow regime, a partial annular fuel flow regime, a partial annular steel flow regime and a bubbly steel flow regime.

At the axial locations were solid fuel pins are still present, the coolant channel is separated from the pin cavity by the cladding and the remaining solid fuel. The temperature field in the cladding and fuel is calculated by a transient heat-transfer model, using the temperatures in the channel and cavity as boundary conditions. Continuous melting occurs at the fuel pin cavity boundary, leading to an increase in cavity diameter and addition of molten fuel and fission gas to the moving components in the cavity. The situation is more complicated at the channel boundary.

The fuel-freezing model used in LEVITATE allows for the formation of a partial fuel crust when the temperature of the fuel in the channel drops below an input freezing temperature. This input temperature is always between the liquidus and solidus temperatures.

When the dominant component in the channel is molten steel, steel freezing can occur, leading to the formation of steel plugs.

The temperature of the fuel crust, at any given location, is calculated by the heat-transfer model. Depending on its temperature and other local conditions, which will be described in detail later, the fuel crust can continue to grow, can start to remelt or can break up when the underlying cladding begins to melt.

LEVITATE is the last module in the sequence of SAS4A active models in the accident simulation. The dispersal of the molten and solid fuel in the coolant channel causes a rapid reactivity and power decrease and causes the neutronic shutdown of the reactor.

Loop Thermo-hydraulics-PRIMAR-4

The PRIMAR-4 module [2] computes coolant pressures, flow rates, and temperatures in the primary and intermediate heat transport loops. This module is designed for analysis of a wide range of transients, from fast unprotected LOF or TOP cases to slow operational transients or natural circulation shutdown heat-removal cases. Also, an arbitrary arrangement of components in either a loop-type or a pool-type system can be treated. Semi-implicit and fully implicit numerical schemes have been developed to handle the full range of transients efficiently. A schematic representation of the primary coolant loop is shown in Fig. 5

The detailed multi-loop PRIMAR-4 treatment models heat transfer and coolant flow in the inlet and outlet coolant plenums, the pipes, pumps, and valves in the primary and intermediate loops, the intermediate heat exchangers, the steam generators, and the pool in a pool system. It utilizes a modular approach. The user specifies the properties of various components and arranges them in an arbitrary manner. Each type of component is treated in a separate section of the code. Components can be added or existing component treatments can be modified without impacting the rest of the code.

Fuel pin heat transfer

The core assembly thermal hydraulics treatment in SAS4A includes the calculation of fuel, cladding, coolant, and structure temperatures, as well as coolant flow rates. This treatment includes melting of the fuel and cladding.

Figure 6 shows the node structure used for temperature calculations. The whole length of a subassembly is represented, although more detail is used in the core and axial blankets than in the rest of the subassembly.

Although SAS4A is mainly a transient code, both steady-state and transient temperatures and coolant pressures are calculated. The steady-state temperatures are obtained rapidly from a direct solution based on conservation of energy which uses the same spatial finite differencing used in the transient.

The thermal hydraulics calculations are carried out in a number of separate modules, each module being designed for a specific situation. A steady-state thermal hydraulics module provides the initial conditions for the transient. The transient temperatures are calculated in a pre-voiding module (TSHTRN) until the onset of boiling or the failure of the fuel pin. TSHTRN calculates the fuel, cladding, coolant, and structure temperatures for an axial node simultaneously using a Crank-Nicholson finite differencing scheme that is stable for large time step sizes. After the onset of boiling, the fuel-pin temperatures are calculated in a separate module (TSHTRV) that couples with the boiling module. After the initiation of the PINACLE module, the temperatures are calculated in the PNHTR module, which provides the coupling with PINACLE at the pin cavity boundary and the coupling with the coolant hydrodynamic module at the cladding coolant interface. After fuel-pin disruption initiates PLUTO2 or LEVITATE, fuel-pin temperatures in the intact

parts of the pin are calculated in PLHTR, which provides the interface with the in-pin fuel motion model at the fuel-cavity interface and with the channel hydrodynamic model at the cladding-coolant interface.

The TSBOIL, PLUTO2 or LEVITATE, modules supply the heat flux at the cladding outer surface to TSHTRV, PNHTR or PLHTR. Also, at axial positions where the fuel is partly molten, PINACLE, PLUTO2 or LEVITATE calculate the temperature of the molten fuel in the inner cavity inside the pin and supply the heat flux at the cavity wall to PLHTR THE PNHTR or modules.

BOILING MODEL

The sodium voiding model [3] in SAS4A is a multiple-bubble finite difference slug ejection model capable of handling flow area changes and non-uniform axial nodes. The main purposes of this model are to predict the rate and extent of voiding for the voiding reactivity calculations, to predict the heat removal from the cladding surface after the onset of voiding for the fuel and cladding temperature calculations, and to predict the vapor flow rates that drive the cladding motion.

Figure 7 illustrates the voiding model. Each channel in SAS4A represents a fuel pin and its associated coolant and structure. Voiding is assumed to result in the formation of bubbles that fill the whole cross section of the coolant channel except for a film of liquid sodium that is left on the cladding and structure. Up to nine bubbles, separated by liquid slugs, are allowed in the channel at any time.

Currently, the film is treated as a static film of a thickness which changes due to vaporization or condensation. A dynamic film treatment in which film motion is determined by the combined effects of gravity and the shear force of streaming vapor will be added to a future version of the code.

The extent of voiding is determined mainly by liquid slug motion. The liquid slugs are driven by the bubble pressures at the bubble-slug interfaces. Therefore, the voiding calculation couples vapor pressure calculations for the bubbles with momentum equations for the liquid slugs. If a bubble is small, it is assumed that the vapor pressure within the bubble is constant throughout the bubble, and the bubble pressure is computed using a uniform vapor pressure model. For larger bubbles, the vapor pressure is calculated from a pressure gradient model.

The voiding model portrayed in Fig. 7 has been developed and extensively tested throughout the evolution of the SAS family of codes. The choice of a multi-bubble slug ejection model was dictated by a considerable body of experimental information [4]. The multiple bubble, slug flow model has been compared with results from a variety of out-of-pile and in-pile experiments, including tests at Argonne National Laboratory with the OPERA, TREAT, and SLSF facilities, experiments conducted at KfK - West Germany [5], and the ORNL Sodium Boiling Tests [6]. These comparisons have consistently shown that the SAS4A voiding model agrees well with experimental data that are prototypic of reactor conditions.

The relationship of the voiding model to other major modules in SAS4A is diagrammed in Fig. 8. This drawing shows that the voiding model picks up its initial information from the cladding motion (CLAP) and transient heat-transfer modules, supplies information to the point kinetics module (which, in turn, feeds data to the transient heat-transfer module), and provides initiating values to the fuel relocation models LEVITATE and PLUTO2. Thus, the voiding model has a direct impact on most of the major modules in SAS4A.

FUEL PIN BEHAVIOR - DEFORM-4

The DEFORM-4 module [7] simulates the mechanical fuel pin response during the pre-transient and transient periods. This response requires the modeling of a number of complex phenomena, such as fuel swelling, pin axial expansion, fuel-cladding interaction, fission gas formation and release and molten cavity pressurization. The axial mesh used in the DEFORM-4 module is shown in Fig. 9. Illustrated are the three fuel-cladding gap conditions considered: (1) no contact between the fuel and cladding, (2) the fuel elastically straining the cladding, and (3) the fuel plastically straining the cladding. Also illustrated is a central cavity that formed in the hotter regions of the driver fuel.

The fuel in an axial segment is divided into a series of radial cells, each radial cell being assigned to a radial zone. The fuel pin in an axial segment is divided into 6 radial zones, (Fig. 10) not all of which need exist. These are (1) the central void, (2) the molten fuel zone, (3) the solid, continuous fuel zone, (4) the cracked fuel zone, (5) the fuel-cladding gap, and (6) the fuel-pin cladding. The zones are illustrated in Fig. 8. Each zone may consist of one or more cells.

A number of phenomena are treated in the pre-transient irradiation calculation, which covers periods varying from several days to several years. These include porosity migration and central void formation, grain growth, fission-gas release and fuel and cladding swelling. Since the transient calculation covers only periods ranging from several seconds to several minutes, only the fission product induced fuel swelling is simulated during the transient.

The thermoelastic mechanical calculations for the fuel and cladding are identical in both the pre-transient and transient. The cladding is treated as elastic/perfectly-plastic material. In addition, the cladding is allowed to creep in response to temperature and stress conditions. Axial and radial deformations result from thermal expansion and mechanical interactions. The effects of fuel-cladding interaction are also considered in the fuel swelling calculation.

The fuel is allowed to crack radially whenever the circumferential stress exceeds a temperature-dependent fracture strength. The crack volume varies due to thermal and swelling effects. In the transient, the volume associated with the cracks, the fission gas, and the remaining as-fabricated porosity can be important in accommodating the thermal expansion on melting and determining the molten cavity pressure. The difference between the pin cavity and the coolant channel, together with information about the cladding temperature, is used to determine the time and location of cladding failure.

In-Pin Fuel Relocation - PINACLE

During both the LOF and TOP postulated accidents, the mismatch between the energy generated in the fuel pin and the energy removed by the coolant leads to the overheating of the fuel pin. As the accident proceeds, the inside of the fuel pin begins to melt, leading to the formation of an internal cavity Fig. 11. This cavity is filled with a mixture of molten fuel and fission gas and extends continuously, both radially and axially, due to continued fuel melting. The fuel-gas mixture in the cavity is pressurized due to the presence of fission gas and can move under the influence of the local pressure gradients. As the cavity walls continue to melt there is a competition between two effects (Fig. 12).

a. The axial extension of the cavity, which can cause the cavity to reach the top of the fuel pin. When this happens the pressurized molten fuel in the cavity is connected to the lower pressure upper plenum and can relocate suddenly, leading to a large insertion of negative reactivity and possible shutdown of the core.

b. The radial extension of the cavity and cladding melting which can cause fuel pin failure. When pin failure occurs the inner cavity is connected to the coolant channel which is at a significantly lower pressure and the molten fuel inside the pin is accelerated rapidly toward the pin failure location. This initial in-pin fuel relocation can have either a negative or positive reactivity contribution, depending on the failure location and axial failure propagation. Molten fuel is ejected into the coolant channel where it is dispersed axially. This fuel dispersal leads to a large insertion of negative reactivity and eventual neutronic shutdown.

The new PINACLE code [8] which has been implemented in SAS4A provides the capability to model the dynamic relocation of the in-pin molten fuel prior to cladding failure. PINACLE is an Eulerian two-phase transient hydrodynamic model describing the axial fuel relocation in a variable area geometry. PINACLE has been constructed using the same computational variables and method of solution as LEVITATE or PLUTO. The compatibility of PINACLE with these two models allows SAS4A to provide a consistent treatment of the in-pin fuel relocation from melting to the end of the initiating phase. The components tracked by PINACLE are the molten fuel and two types of fission gas. The fission gas can exist either in the form of small bubbles, constrained by surface tension, which generally have only a limited contribution to the cavity pressure or as free gas which pressurizes the surrounding molten fuel. The small bubbles coalesce in time and gradually become part of the free gas field. To advance the numerical solution PINACLE uses a staggered mesh, with the dependent variables density and enthalpy defined at the center of each cell and the velocities defined at the cell boundaries. The geometry modelled by PINACLE is shown in Fig. 13.

The pre-failure in-pin fuel motion can play a particularly significant role in metal fuel cores and in oxide fuel cores subjected to a slow ramp

transient overpower (TOP) accident. In these cases the molten fuel cavity can extend all the way to the top of the pin and allow significant in-pin molten fuel relocation prior to cladding failure. The ejection of the molten fuel into the gas plenum space can provide an important source of negative reactivity, which in turn will cause a rapid power decrease and prevent the cladding failure and molten fuel ejection into the coolant channel.

The PINACLE Model is fully integrated within the SAS4A Whole Core Accident Analysis Code. PINACLE is initiated when the accident sequence, as modeled by other modules, leads to the internal melting of the fuel pins in some of the subassemblies. During its calculations PINACLE exchanges information with other SAS4A Models such as DEFORM-4 or the Point Kinetics model, which describe other phenomena affecting the same computational channel. Finally when the cladding failure occurs in a computational channel PINACLE will transfer control to other models such as PLUTO2 or LEVITATE, which will continue the calculations in that channel.

Fuel Relocation in Unvoided Channels - PLUTO2

When a cladding failure occurs (Fig. 12) the molten fuel inside the pin cavity is ejected into the coolant channel. If the coolant channel is still largely filled with liquid sodium coolant, as is the case during Transient Overpower Accidents (TOP), the physical events following the pin failure are described by the PLUTO2 model [9].

PLUTO2 is the SAS4A module for treating the post-pin-failure fuel motion inside the pin, and coolant voiding and fuel motion in the coolant channel in subassemblies which remain unvoided or largely unvoided at the time of pin failure. The geometry described by PLUTO2 is shown in Fig. 14. PLUTO2 can only treat the coolant voiding and fuel motion until molten cladding motion begins or fuel pin breakup occurs. Beyond this time the LEVITATE module takes over the calculation because it can treat molten cladding motion, cladding ablation by molten fuel, and fuel pin breakup.

PLUTO2 has an in-pin fuel motion model which treats the flow of the fuel/fission-gas mixture as a compressible, one-dimensional flow with variable flow cross-section. A transition interface to this model from the DEFORM-4 pre-failure pin behavior module is provided, so that a smooth transition can be made from the DEFORM-4 cavity calculation to the PLUTO2 in-pin hydrodynamic

calculation. The fuel and fission gas ejection through cladding ruptures is based on the assumption of pressure equilibrium between the in-pin fuel/fission-gas mixture and the fuel/ coolant/ fission-gas mixture in the channel at rupture locations.

In the coolant channel, a one-dimensional two-fluid approach is used to treat the flows of the heavy component (fuel) and the light component (comprised of liquid sodium, sodium vapor and fission gas released from fuel moving together). In the coolant channel, PLUTO2 also has separate mass conservation equations for the molten fuel, sodium, fission gas dissolved in fuel (exerting no pressure) and for the fission gas released from fuel (free to exert pressure). The fuel can be in a particulate, partially or fully annular, or a bubbly flow regime. The particulate flow regime is used when significant amounts of liquid sodium and molten fuel are present at the same location, leading to the fragmentation of the molten fuel ejected in the channel. When the molten fuel is ejected in a voided region of the channel, the continuous fuel flow regimes, annular or bubbly, are used (12). The PLUTO2 sequence of events leads to the initial predominance of the particulate flow regime. As the sodium voiding proceeds, the continuous flow regimes become important. Eventually, when cladding melting begins, control of the calculation is transferred to LEVITATE, where the continuous flow regimes are predominant.

Plate-out of frozen fuel and frozen fuel crust release upon melting of the underlying cladding are treated and axial pin failure propagation is also modeled.

PLUTO2 is coupled to the PRIMAR-4 primary loop module via the inlet and outlet coolant pressures, temperatures and flows, as well as the energy contained in the fuel moving into the lower and upper coolant plena.

Fuel Relocation in Voided Channels - LEVITATE

If, at the time of cladding failure the coolant channel is largely voided, as is the case during Loss-of-Flow Accidents (LOF), the physical events following the pin failure are simulated by the LEVITATE model [11]. The lack of coolant leads to a more rapid loss of the original geometry and regimes the modeling of events which do not occur as long as the liquid sodium is present, such as cladding melting, oblation and relocation and fuel pin

disruption. These events are thus not modeled in the PLUTO2 model, but if they are predicted to occur during a TOP event, after the PLUTO2 initiation, SAS4A will transfer control to LEVITATE, via the PLUTO2-LEVITATE interface.

The LEVITATE model describes the physical process that occur in a subassembly during a loss-of-flow (LOF) accident. LEVITATE models the fuel assembly in a one-dimensional geometry, assuming that all the pins in the subassembly behave coherently. Three basic thermal-hydraulic models are used for each subassembly:

(1) The hydrodynamic model describing the cavities inside the fuel pins, which initially contain liquid fuel and gas,

(2) The hydrodynamic model describing the coolant channel, bounded by the outside cladding surface and the hexcan wall,

(3) The heat transfer and melting/freezing model describing the solid fuel-pin stubs, which separate the coolant channel from the pin cavity.

A typical LEVITATE configuration illustrating some of the recently introduced models is presented in Fig 15.

LEVITATE has been designed to simulate a large spectrum of physical phenomena, describing both the high-power and the near-nominal power conditions in voided assemblies. This means that cladding and fuel motion can be treated in a combined or sequential fashion. The LEVITATE model also treats several relevant phenomena not considered in the earlier models. The most important of these are several pin-disruption modes, continuous fuel-steel flow regimes and fuel-steel crust and plug formation, and a tight coupling with the sodium dynamics [12]. LEVITATE has also been designed to incorporate a fuel-chunk model, describing the motion of the solid fuel chunks present in the coolant channel. Since two-phase sodium which is generated by the chugging of the lower sodium slug may penetrate the disrupted region, fuel may be pushed upwards or "levitated," prompting the name of this model.

When the fuel-pin failure occurs, the inner cavity is connected to the coolant channel which is at a significantly lower pressure, and the molten

fuel inside the pin is accelerated rapidly toward the pin failure location. This motion is modeled by the in-pin hydrodynamic model. An ejection model transfers molten fuel and fission gas from the pin cavity to the coolant channel, thus connecting the two main hydrodynamic models.

Before the molten fuel-fission gas mixture is ejected from the pin cavities, the coolant channel contains only sodium and perhaps molten steel As the fuel and fission gas begin to interact with these original components, a very complex situation develops, involving a large number of components that have to be tracked separately. The moving components in the channel are solid and liquid fuel, solid and liquid steel, fission gas, and vapors of fuel, steel and sodium. The material motion is described by a multi-component, multi-phase, nonequilibrium hydrodynamic model. The region described by this model is bounded axially by the liquid sodium slugs, and is generally referred to as "the interaction region". This region can increase or decrease, depending on the dynamics of the liquid slugs which is described by a simple incompressible model. The dependent variables in the interaction region are the density, velocity and enthalpy. A separate mass and energy equation is solved for each component, but only three coupled momentum equations for three velocity fields are solved. The components treated together in a velocity fields are : (a) liquid fuel and liquid steel, (b) fission gas, fuel vapor, steel vapor and two-phase sodium and (c) solid fuel chunks and solid steel chunks.

SAS4A Verification and Validation

The validation of SAS4A Is an ongoing process, complimentary to the model development effort. It is of crucial importance in verifying the phenomenological models and establishing the credibility of the code results. The validation and verification of the individual models and of the code system is achieved through the analysis of out-of-pile experiments isolating specific phenomena of interest, the analysis of in-pile integral experiments prototypic of the actual accident conditions and through inter-code comparative calculations.

In the out-of-pile experiments, such as the CAMEL loop experimental series [13], the fuel is molten via an exotermic, non-nuclear reaction and then injected in a voided or unvoided channel with a geometry similar to the

actual subassembly. These experiments have been used to gain valuable information about fuel and steel relocation and freezing fuel-coolant interactions, crust formation and fragmentation, etc. Parallel simulations of these experiments with SAS4A base been used to refine and validate the corresponding phenomenological models.

In the in-pile integral experiments an experimental loop containing a small number of prototypic fuel pins is inserted in an experimental reactor core and subjected to thermal-hydraulic and neutronic transient conditions prototypic of the actual accident conditions [14]. Many parameters, such as temperatures, sodium flow rates and pressures are measured and then compared to the results of the SAS4A computer simulations. One of the most important results of these experiments is the information about the time dependent fuel relocation because it has a considerable effect on the reactor reactivity and power. The special fuel distribution at various times is obtained using a neutronic imagining device known as "HODOSCOPE" [15]. This information, is then integrated in a single quantity, called "fuel worth", which reflects the changes in the core reactivity. The history of the observed fuel worth can be used as a good integral description of the accident sequence of events, and is the quantity most often compared with the results of SAS4A computer simulations.

Figure 16 illustrates the results of the fuel dispersal calculations performed with SAS4A/PLUTO2 for the analysis of the LO3 TOP experiment (16). LO3 was a slow ramp (10¢/sec) TOP and the initial pin- failure occurred at 80% of core height. The calculated results indicate a dispersive fuel motion following pin failure, in agreement with the experimental observations. Figure 17 illustrates the results of fuel dispersal calculations performed with SAS4A/ LEVITATE for the analysis of the LO7 LOF experiment (17). LO7 was a high power LOF, with the maximum power reaching 40 times the nominal power level. The fuel pin failure occurs near midplane leading to an initial increase in reactivity due to the fuel acceleration toward the failure location. However, the rapid cladding rip propogation and fuel dispersal in the coolant channel causes the subsequent fuel motion to exhibit a strong dispersive character, in good agreement with the experimental data. Results from these and many other similar simulations support the phenomenological models incorporated in the SAS4A modules, PRIMAR-4, DEFORM-4, PLUTO and

LEVITATE modules as well as the interfacing between modules and give confidence in the application of SAS4A code system to reactor calculations.

Other validation efforts currently under way are centered on the pre-failure in-pin fuel relocation which can terminate a power excursion even before pin failure. This relocation modeled with the new SAS4A module PINACLE, appears to be characteristic of metal fuel pins and has also been observed in oxide fuel pins during slow ramp TOP events (7).

CONCLUSIONS

The computer simulation of hypothetical core disruptive accidents plays an important role in estimating the outcomes of such severe accidents and can serve as a guide in the design of inherently safe reactors. These simulations require the development of large integrated computer models which can model a large spectrum of physical phenomena. SAS4A is the latest such model in the SAS family of codes developed at Argonne National Laboratory. It includes advanced models such as PLUTO2, LEVITATE, DEFORM4 and PINACLE which allow the mechanistic description of the entire sequence of events occurring during the initiating phase of a hypothetical accident. The extensive use of the integrated code for experiment analyses and whole core calculations has lead to an increased reliability of the code and has increased the confidence of the user community in the SAS4A modeling.

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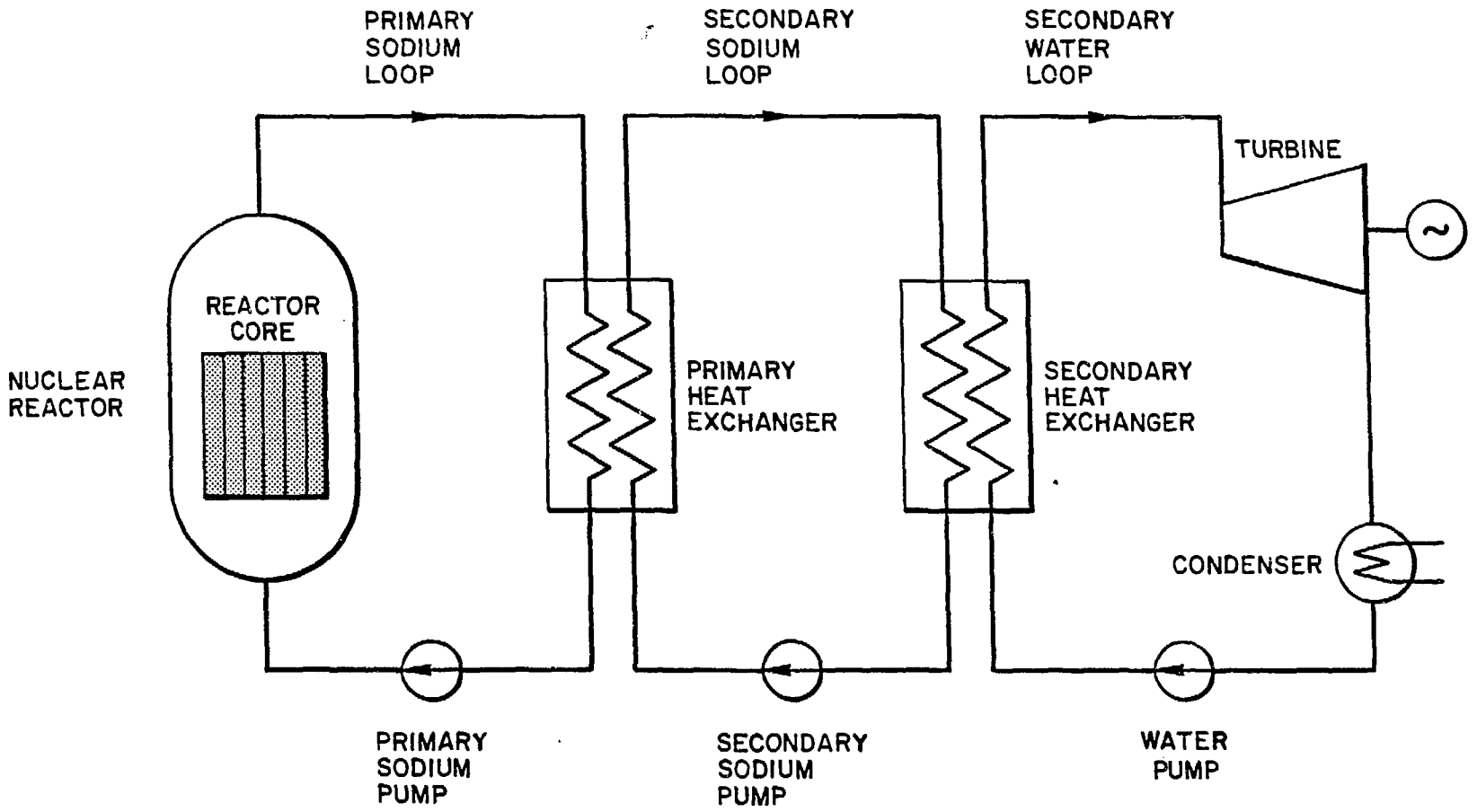
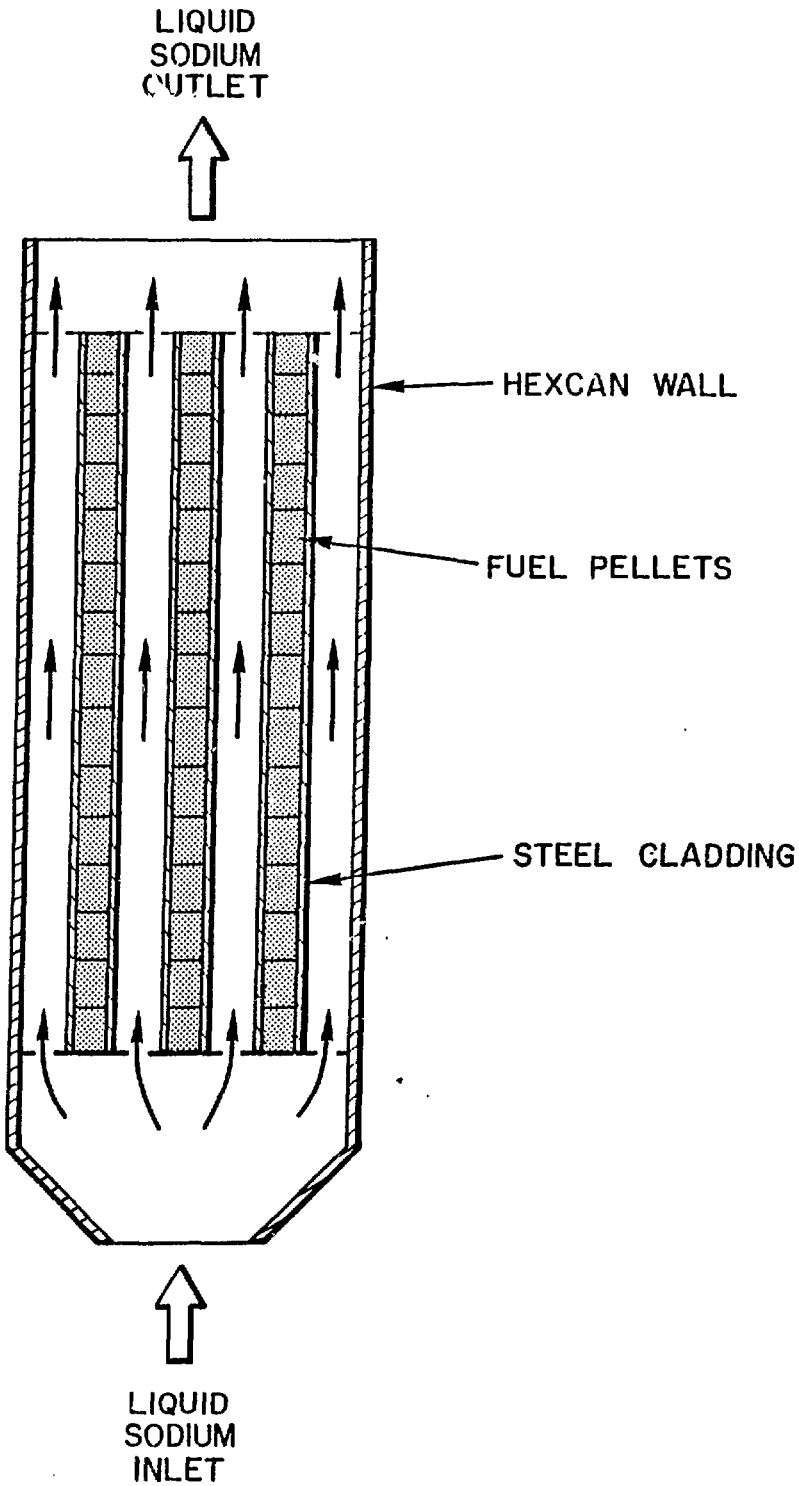

PRIMARY
SODIUM
LOOP
SECONDARY
SODIUM
LOOP
SECONDARY
WATER
LOOP
TURBINE
REACTOR
CORE
NUCLEAR
REACTOR
PRIMARY
HEAT
EXCHANGER
SECONDARY
HEAT
EXCHANGER
CONDENSER
PRIMARY
SODIUM
PUMP
SECONDARY
SODIUM
PUMP
WATER
PUMP

FIG. 1


LIQUID
SODIUM
OUTLET
HEXCAN WALL
FUEL PELLETS
STEEL CLADDING
LIQUID
SODIUM
INLET

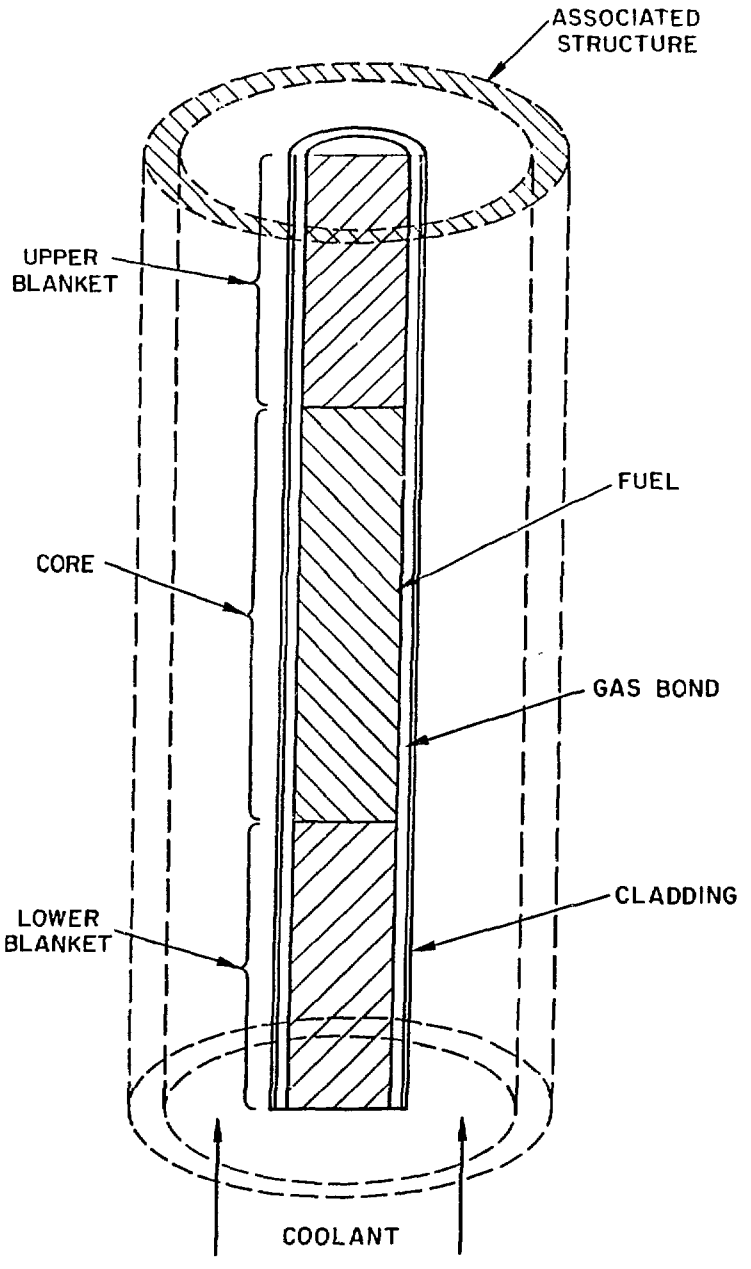

ASSOCIATED STRUCTURE
UPPER BLANKET
FUEL
CORE
GAS BOND
CLADDING
LOWER BLANKET
COOLANT

FIG. 3

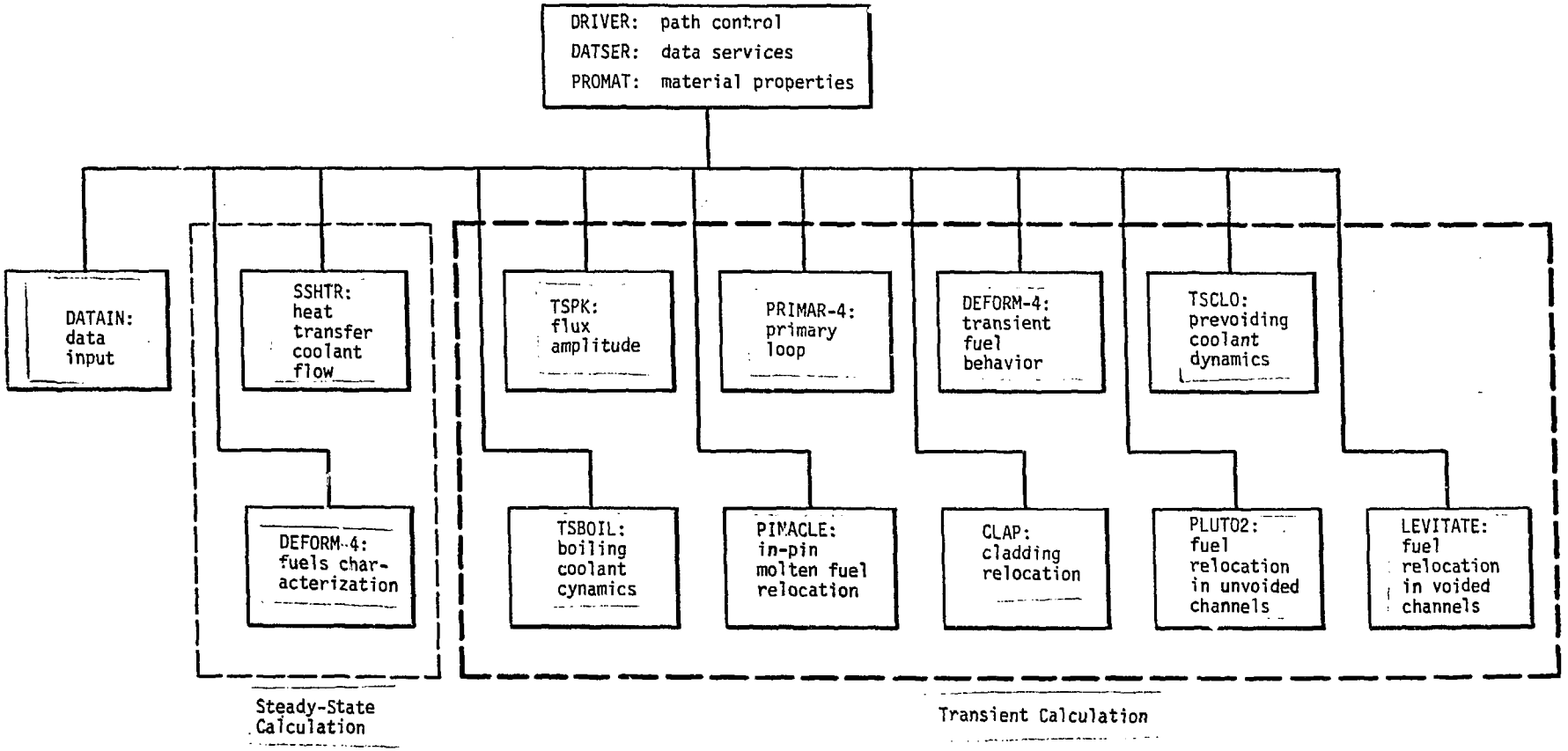

DRIVER: path control
DATSER: data services
PROMAT: material properties
DATAIN: data input
SSHTR: heat transfer coolant flow
TSPK: flux amplitude
PRIMAR-4: primary loop
DEFORM-4: transient fuel behavior
TSCLO: prevoiding coolant dynamics
DEFORM-4: fuels characterization
TSBOIL: boiling coolant cynamics
PIMACLE: in-pin molten fuel relocation
CLAP: cladding relocation
PLUTO2: fuel relocation in unvoided channels
LEVITATE: fuel relocation in voided channels
Steady-State Calculation
Transient Calculation

Fig 4

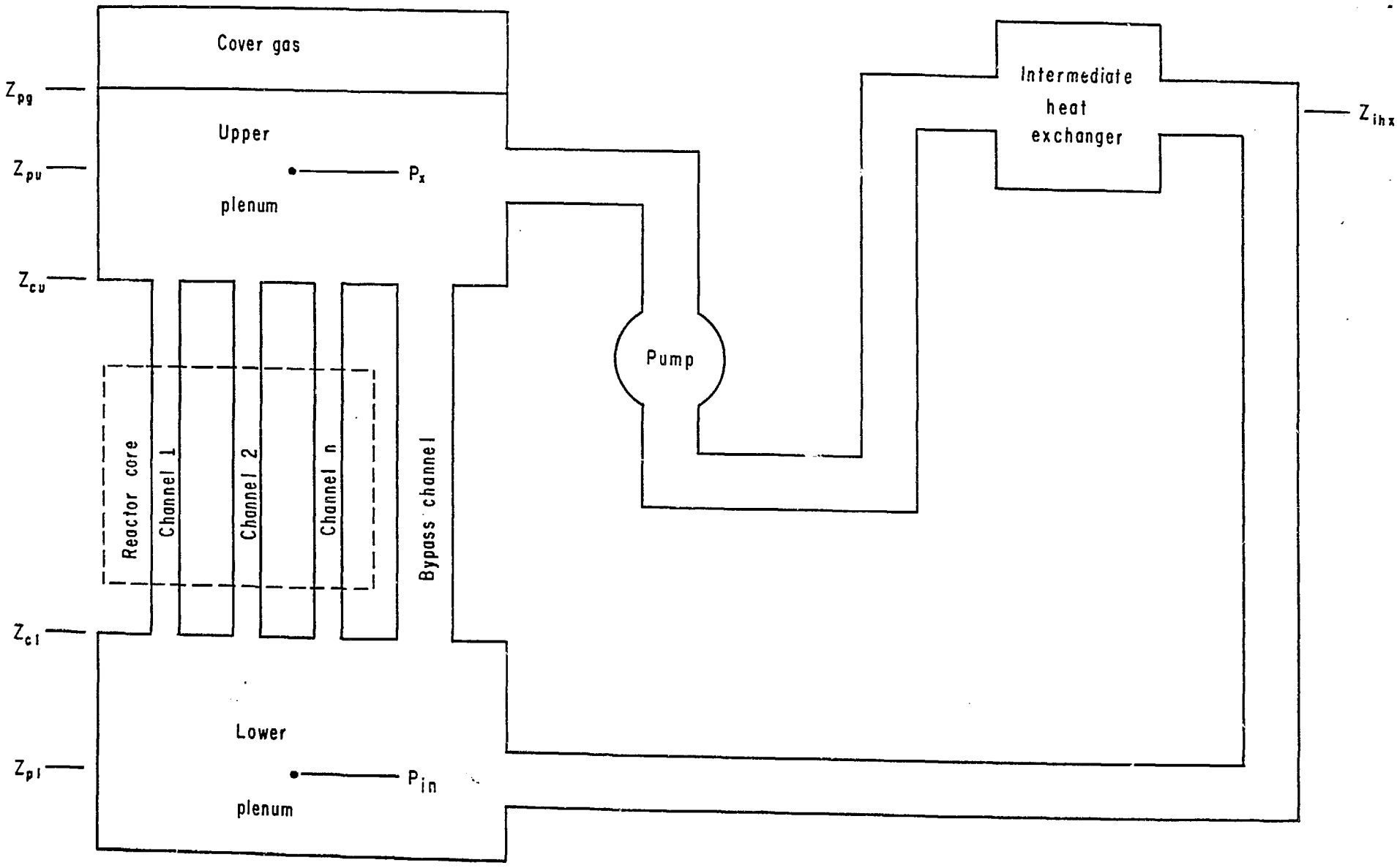

Cover gas
Z_{pg}
Upper
Z_{pu}
P_x
plenum
Z_{cu}
Reactor core
Channel 1
Channel 2
Channel n
Bypass channel
Pump
Intermediate
heat
exchanger
Z_{ihx}
Z_{cl}
Lower
Z_{pl}
P_{in}
plenum

FIG. 5

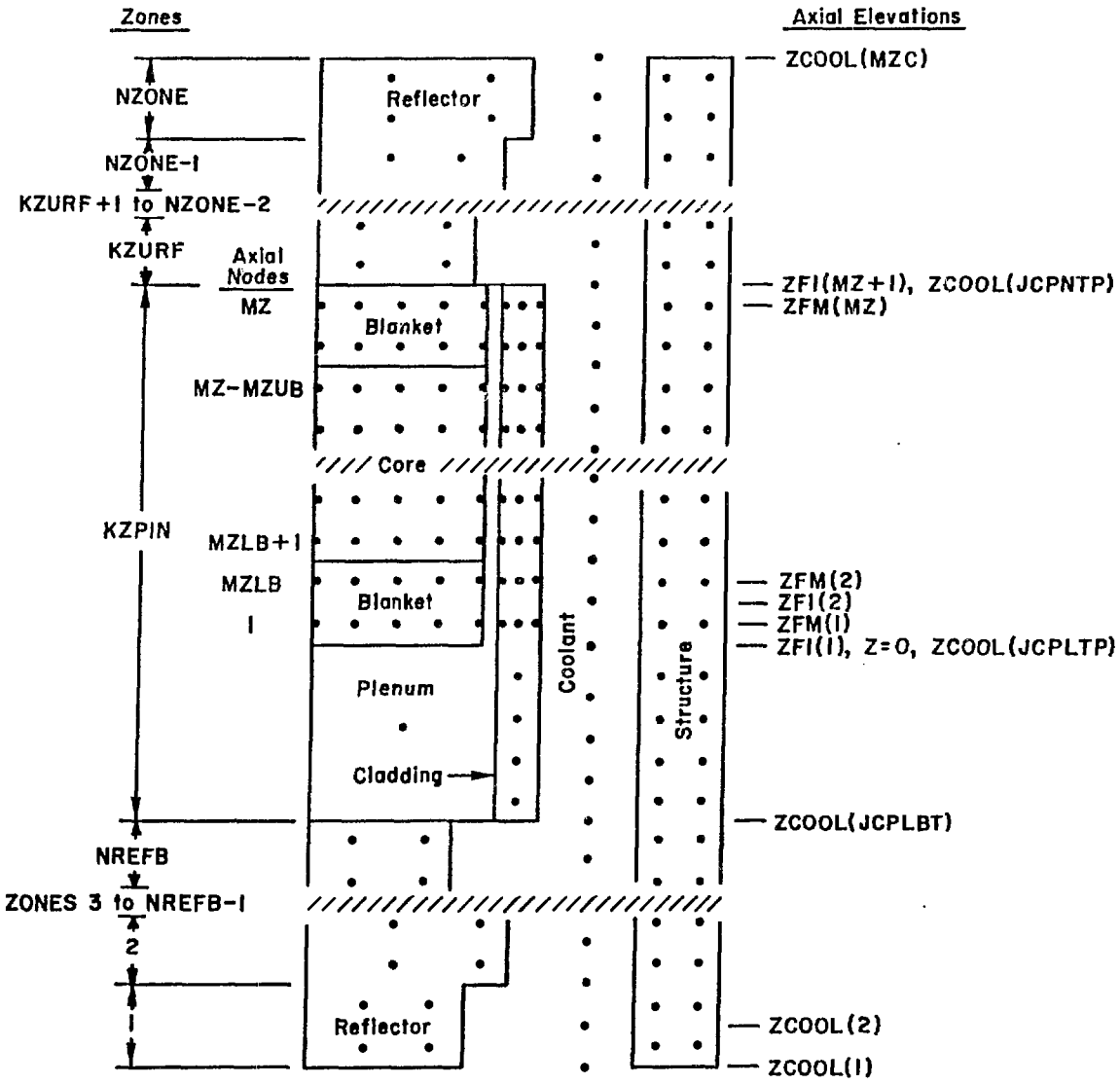

Zones
Axial Elevations
NZONE
NZONE-1
KZURF+1 to NZONE-2
KZURF
Axial Nodes
MZ
MZ-MZUB
KZPIN
MZLB+1
MZLB
1
NREFB
ZONES 3 to NREFB-1
2
1
Reflector
Blanket
Core
Blanket
Plenum
Cladding
Coolant
Structure
Reflector
ZCOOL(MZC)
ZFI(MZ+1), ZCOOL(JCPNTP)
ZFM(MZ)
ZFM(2)
ZFI(2)
ZFM(1)
ZFI(1), Z=0, ZCOOL(JCPLTP)
ZCOOL(JCPLBT)
ZCOOL(2)
ZCOOL(1)

FIG. 6

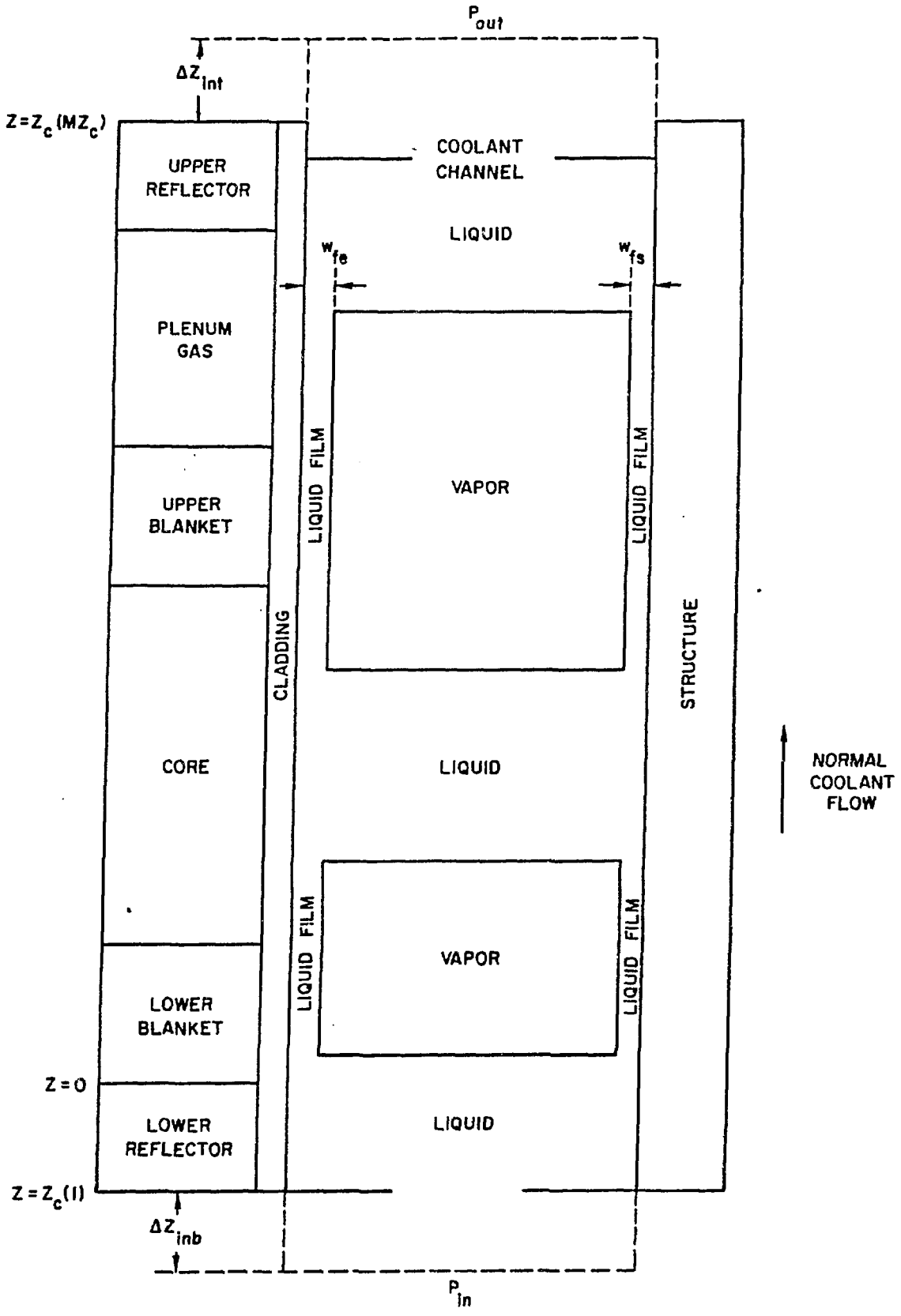

P_{out}
ΔZ_{int}
$Z=Z_c(MZ_c)$
UPPER REFLECTOR
COOLANT CHANNEL
LIQUID
w_{fe}
w_{fs}
PLENUM GAS
LIQUID FILM
VAPOR
LIQUID FILM
UPPER BLANKET
CLADDING
STRUCTURE
CORE
LIQUID
NORMAL COOLANT FLOW
LIQUID FILM
VAPOR
LIQUID FILM
LOWER BLANKET
Z = 0
LOWER REFLECTOR
LIQUID
$Z=Z_c(1)$
ΔZ_{inb}
P_{in}

FIG 7

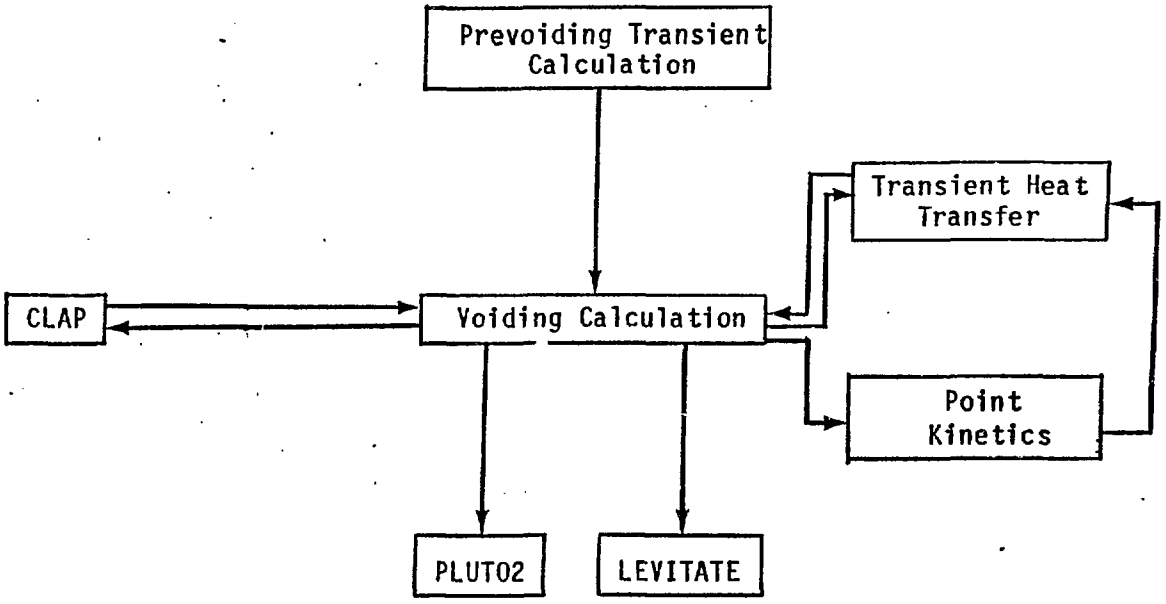


Fig 8 Schematic Drawing of the Relationship of the Voiding Model to Other SAS4A Models

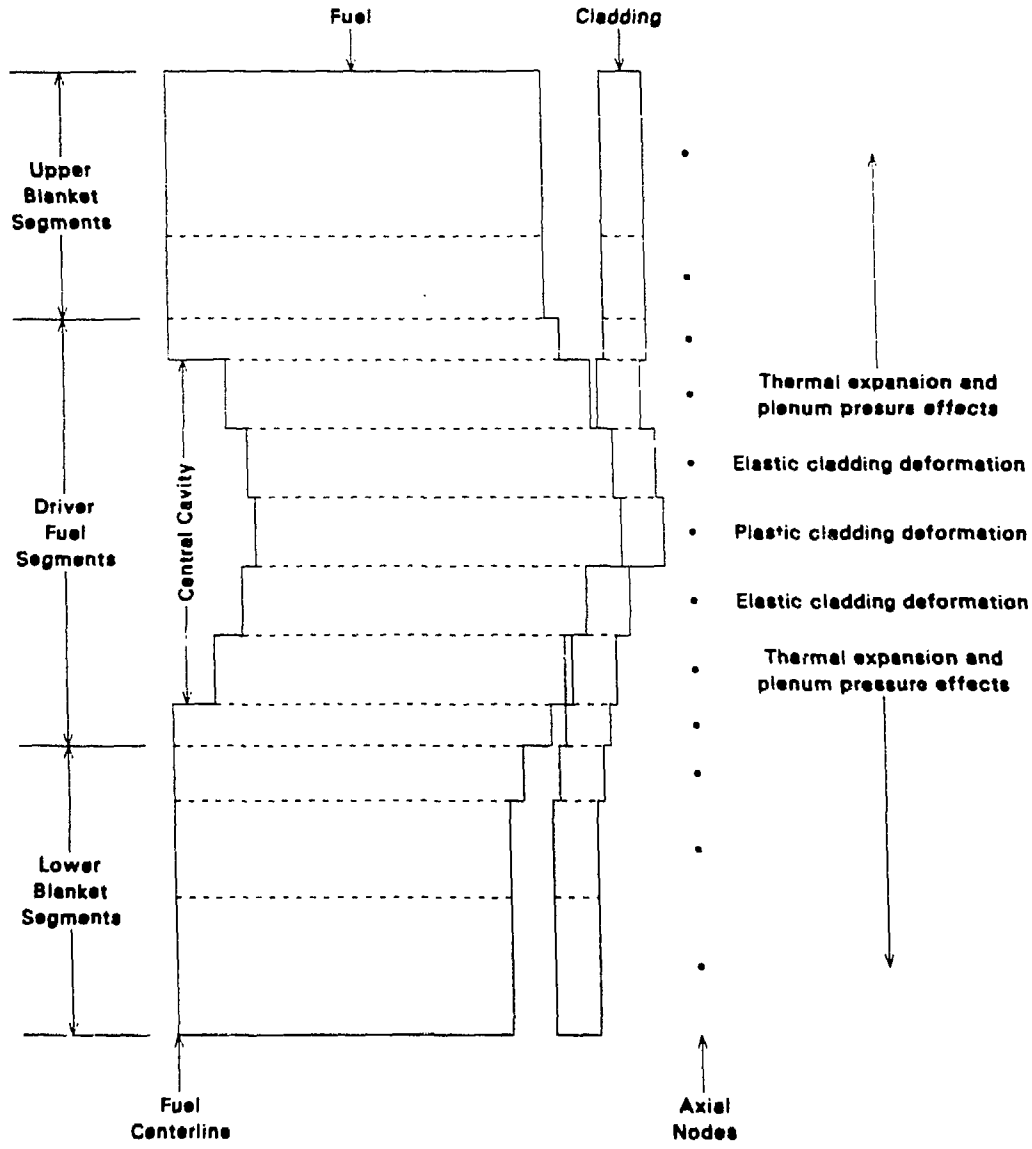

Fuel
Cladding
Upper Blanket Segments
Driver Fuel Segments
Lower Blanket Segments
Central Cavity
Thermal expansion and plenum presure effects
Elastic cladding deformation
Plastic cladding deformation
Elastic cladding deformation
Thermal expansion and plenum pressure effects
Fuel Centerline
Axial Nodes

Fig. 9

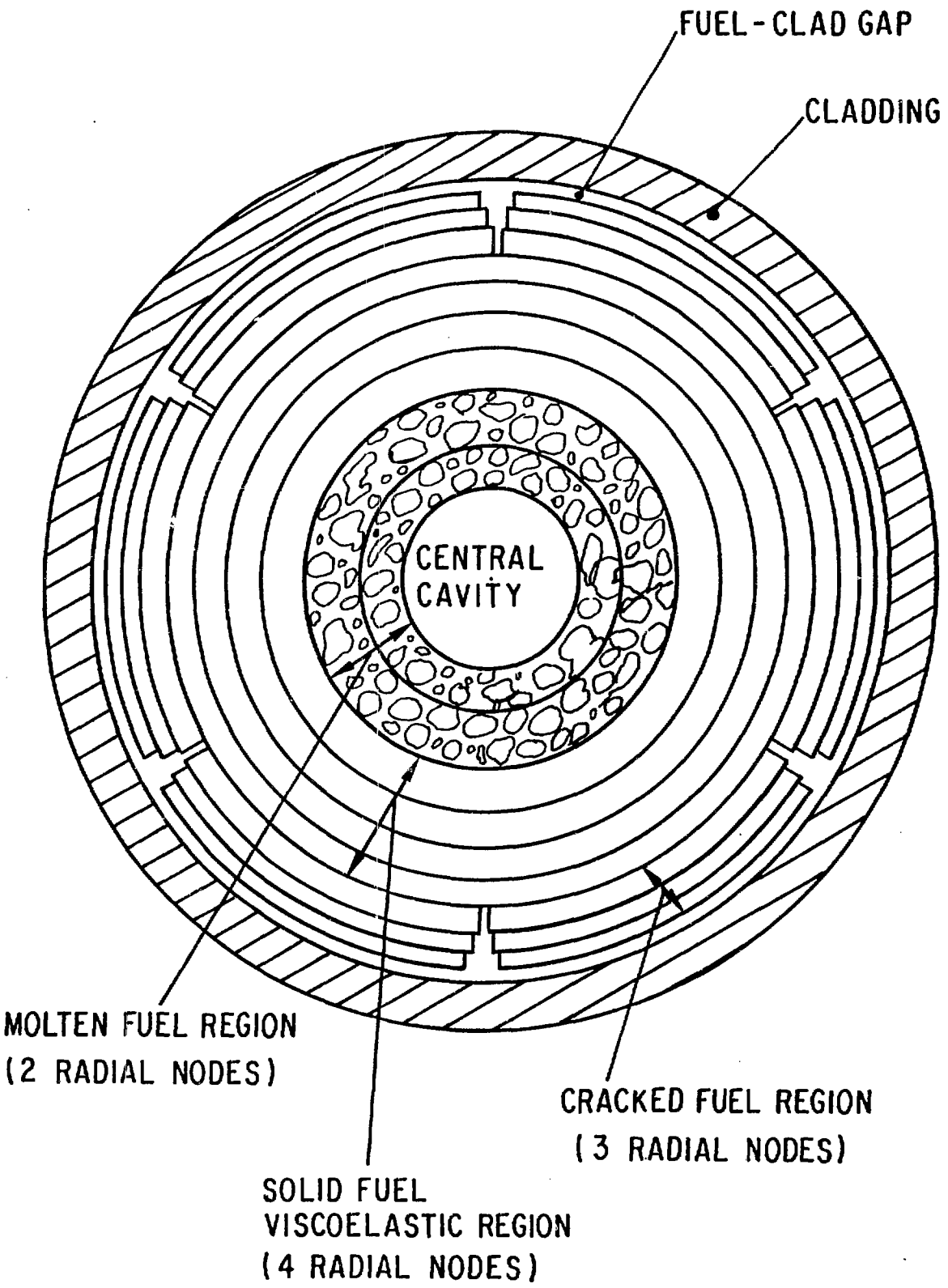

FUEL-CLAD GAP
CLADDING
CENTRAL CAVITY
MOLTEN FUEL REGION
(2 RADIAL NODES)
CRACKED FUEL REGION
(3 RADIAL NODES)
SOLID FUEL
VISCOELASTIC REGION
(4 RADIAL NODES)

FIG. 10

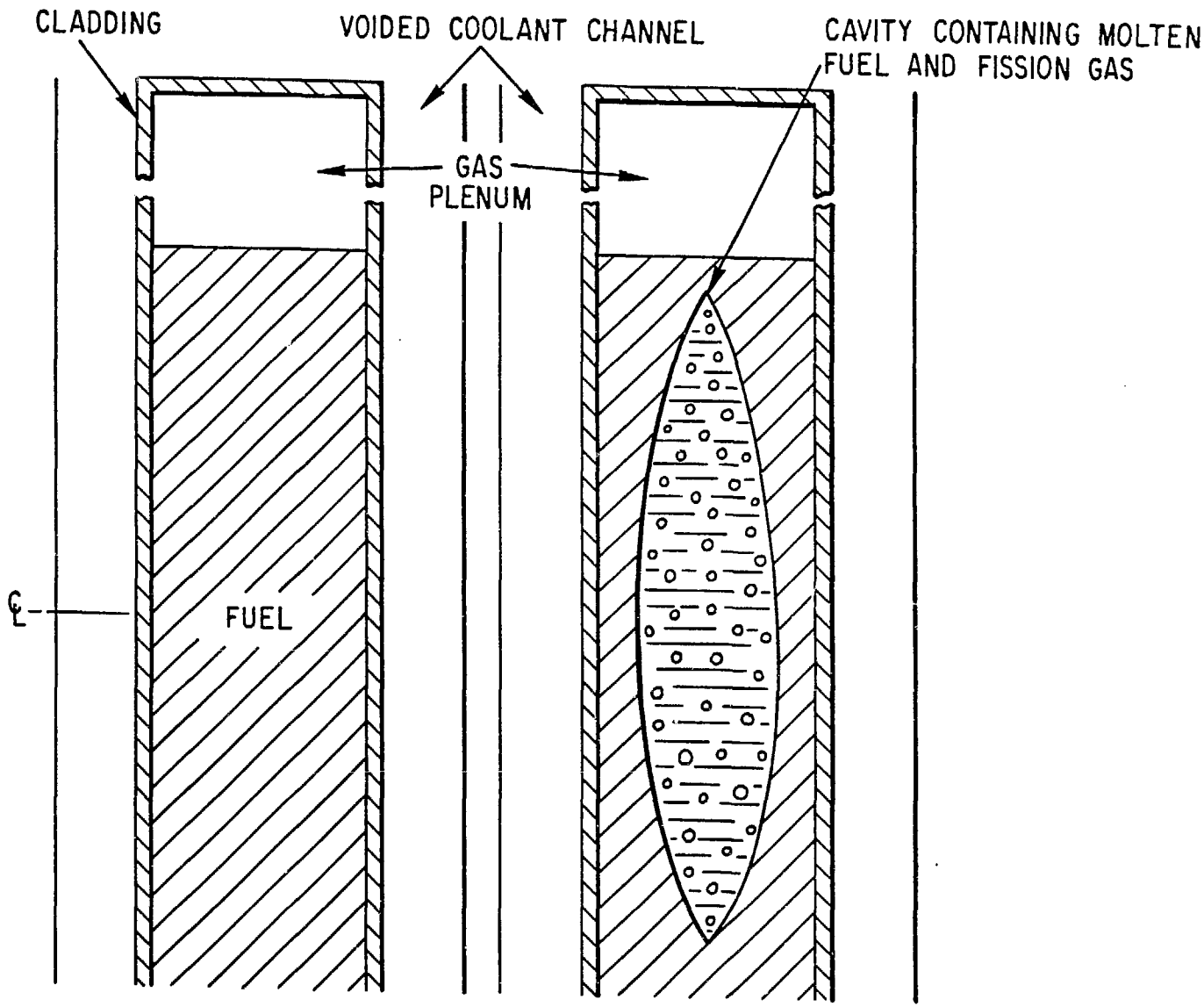
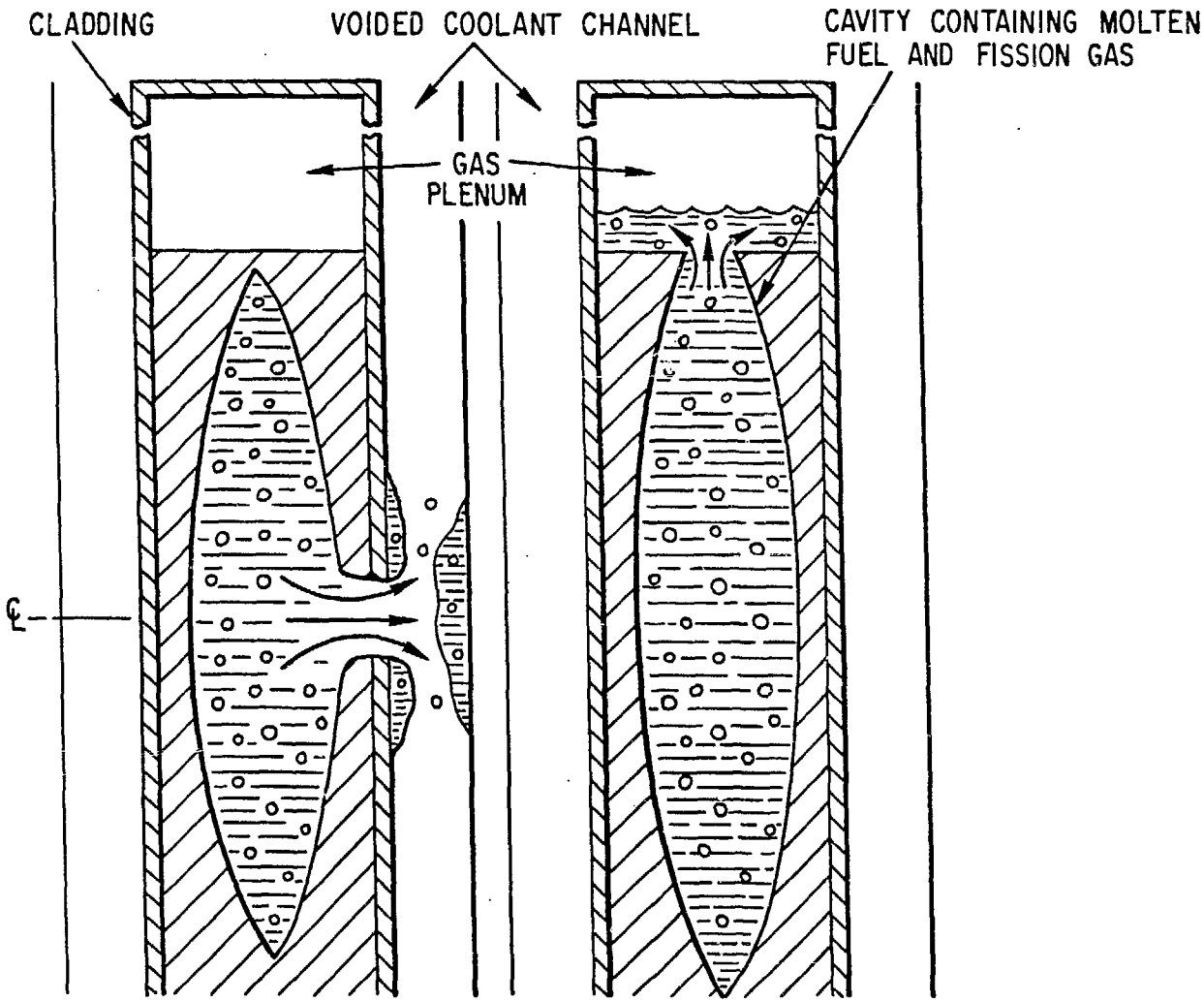

CLADDING
VOIDED COOLANT CHANNEL
CAVITY CONTAINING MOLTEN FUEL AND FISSION GAS
GAS PLENUM
FUEL
a. INTACT PIN
b. PIN CAVITY FORMATION

Fig 11



c. ONSET OF IN-PIN FUEL MOTION DUE TO CLADDING FAILURE

d. ONSET OF IN-PIN FUEL MOTION DUE TO CLADDING FAILURE REACHING THE TOP OF THE FUEL PIN

Fig. 12

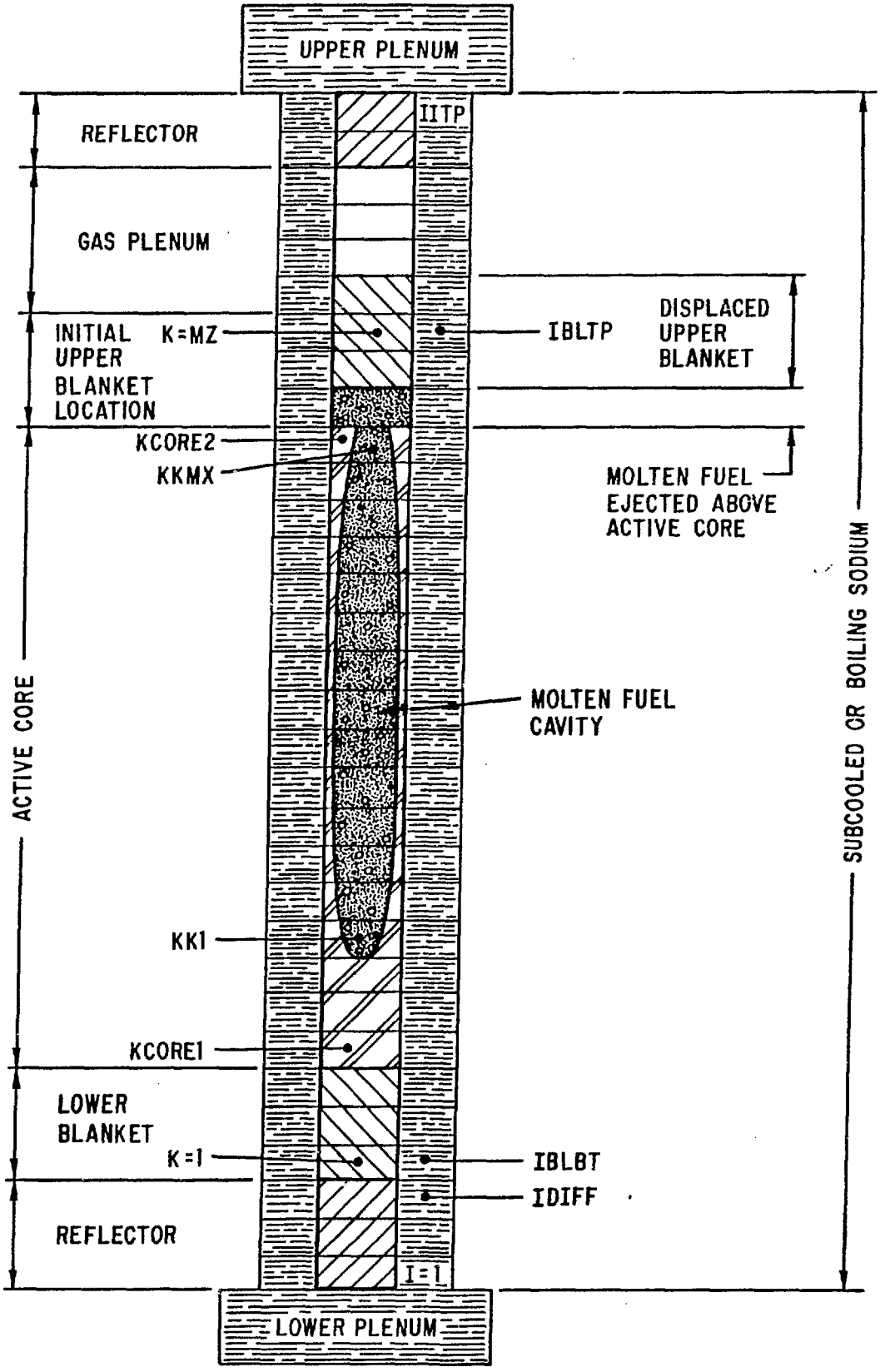

UPPER PLENUM
REFLECTOR
IITP
GAS PLENUM
INITIAL UPPER BLANKET LOCATION
K=MZ
IBLTP
DISPLACED UPPER BLANKET
KCORE2
KKMX
MOLTEN FUEL EJECTED ABOVE ACTIVE CORE
ACTIVE CORE
MOLTEN FUEL CAVITY
SUBCOOLED OR BOILING SODIUM
KK1
KCORE1
LOWER BLANKET
K=1
IBLBT
IDIFF
REFLECTOR
I=1
LOWER PLENUM

FIG. 13

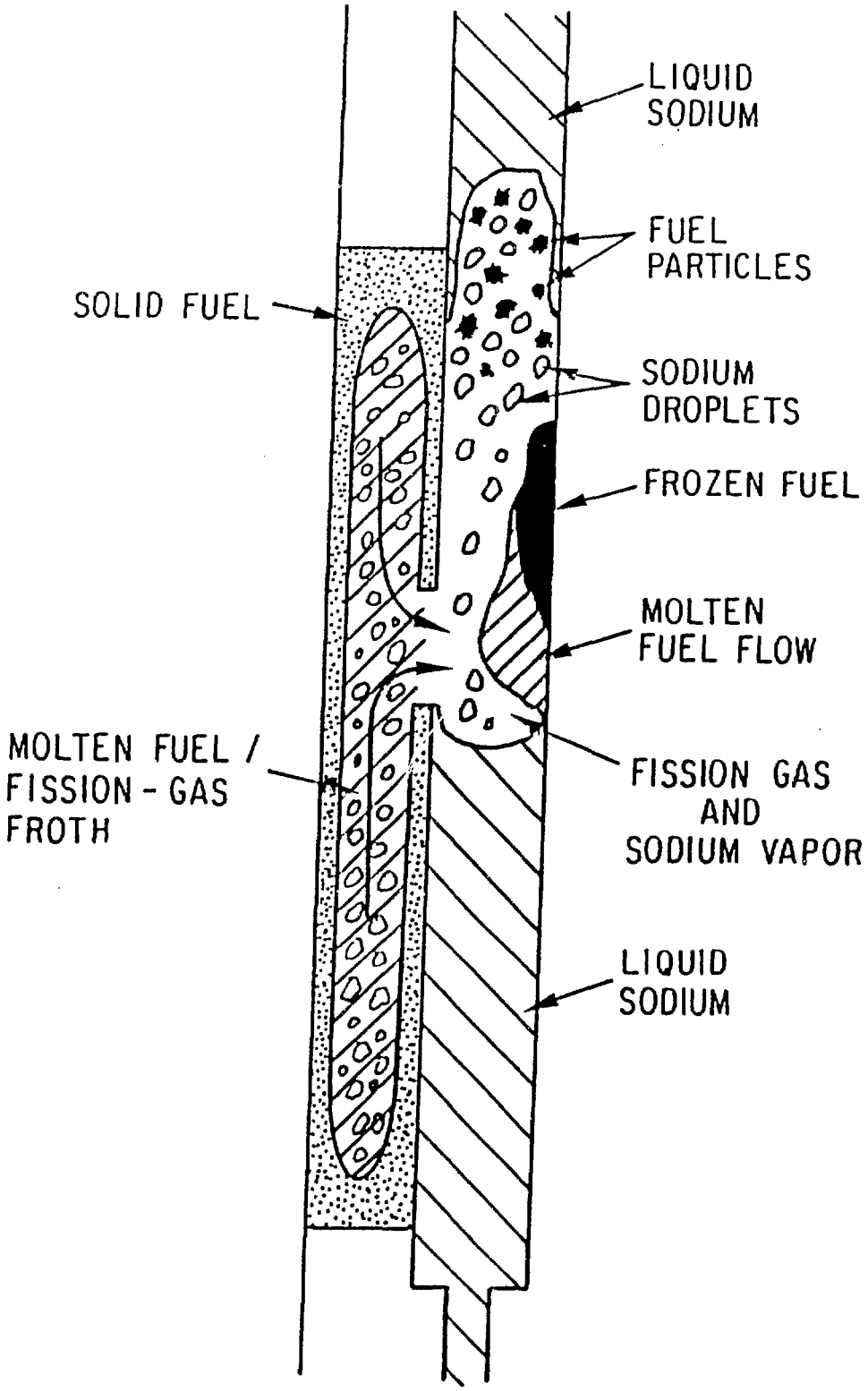

LIQUID SODIUM
FUEL PARTICLES
SOLID FUEL
SODIUM DROPLETS
FROZEN FUEL
MOLTEN FUEL FLOW
MOLTEN FUEL / FISSION - GAS FROTH
FISSION GAS AND SODIUM VAPOR
LIQUID SODIUM

Fig. 14

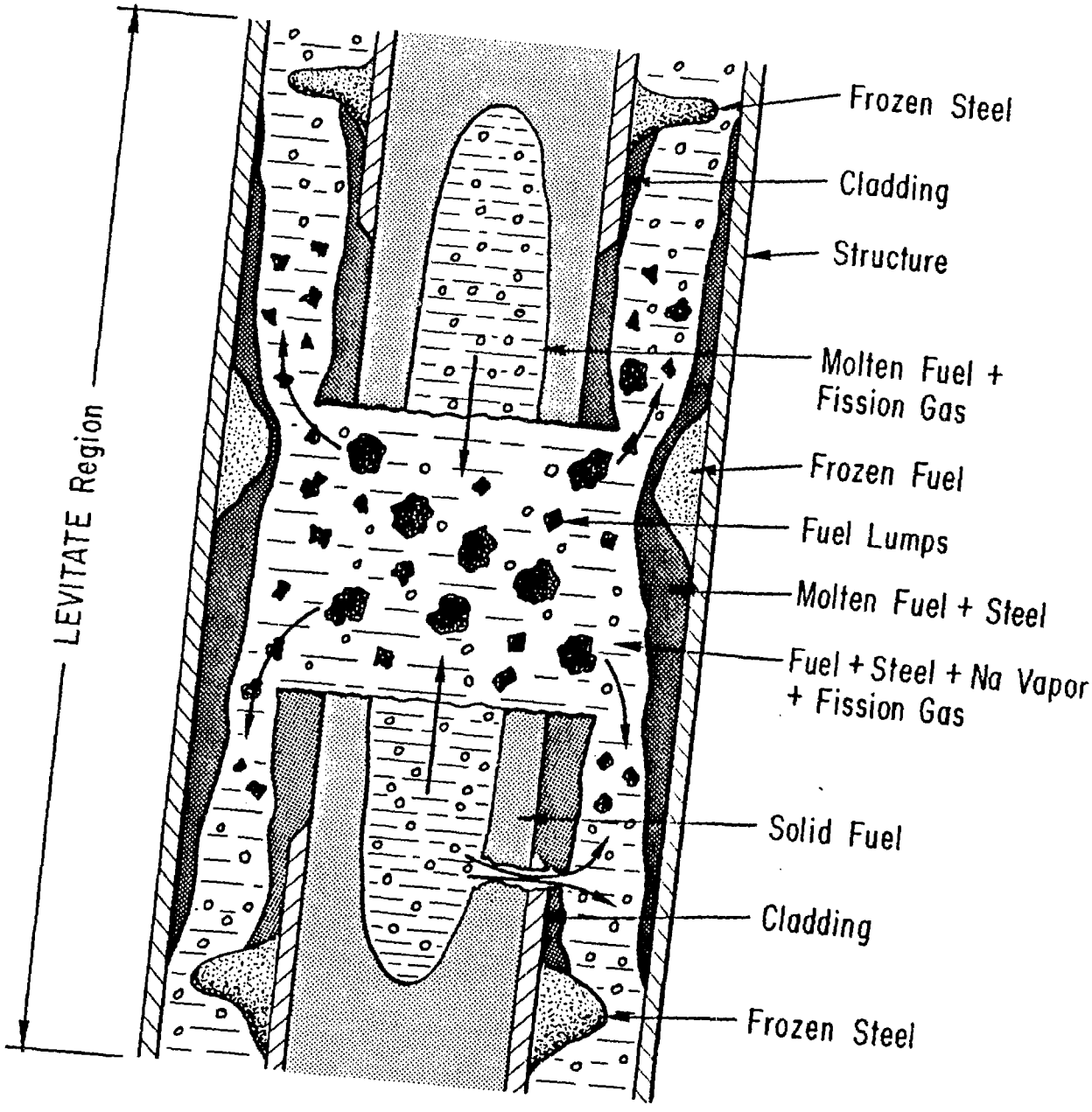

LEVITATE Region
Frozen Steel
Cladding
Structure
Molten Fuel + Fission Gas
Frozen Fuel
Fuel Lumps
Molten Fuel + Steel
Fuel + Steel + Na Vapor + Fission Gas
Solid Fuel
Cladding
Frozen Steel

Fig 15

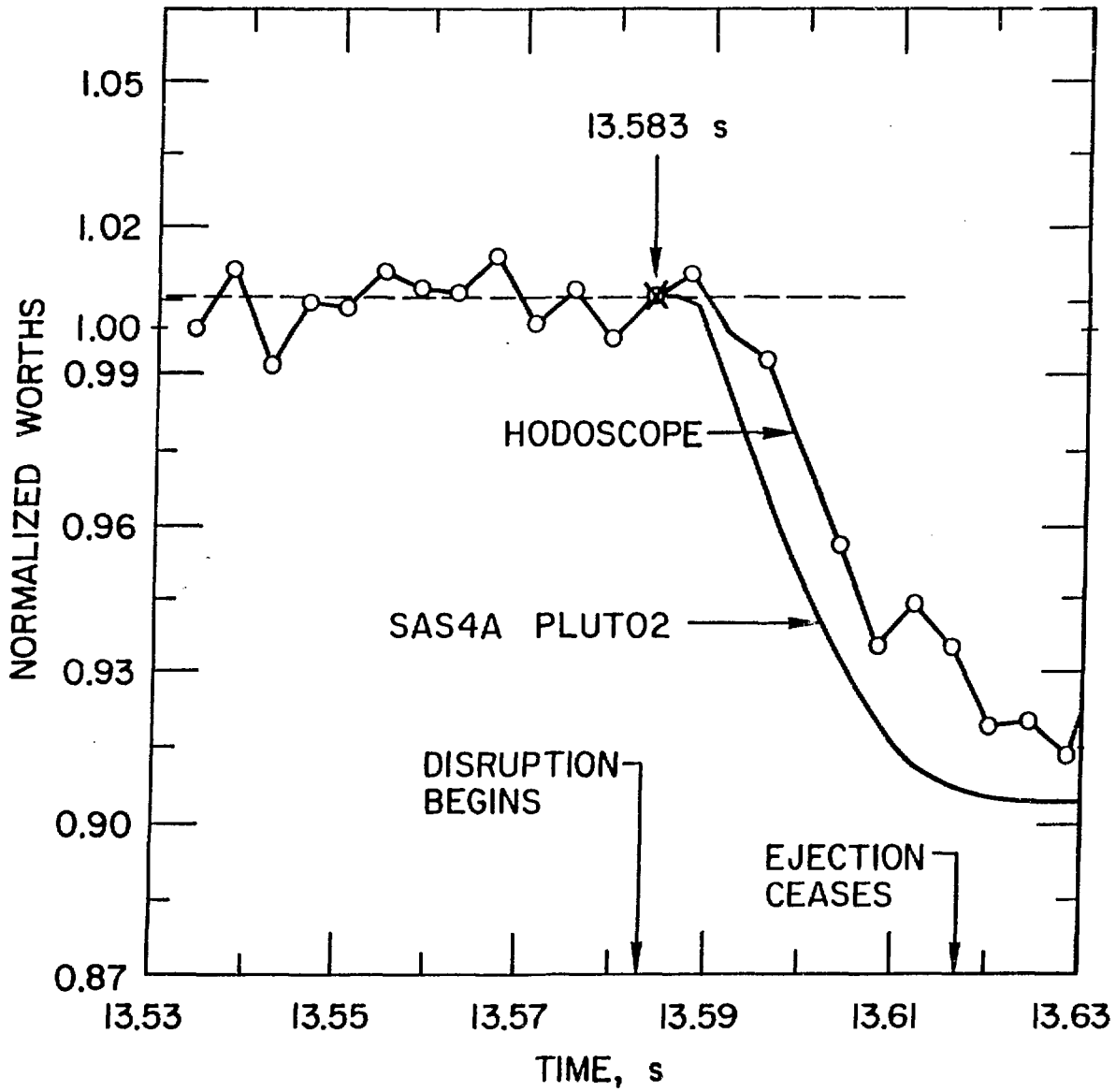

1.05
1.02
1.00
0.99
0.96
0.93
0.90
0.87
NORMALIZED WORTHS
13.583 s
HODOSCOPE
SAS4A PLUTO2
DISRUPTION BEGINS
EJECTION CEASES
13.53
13.55
13.57
13.59
13.61
13.63
TIME, s

FIG 16

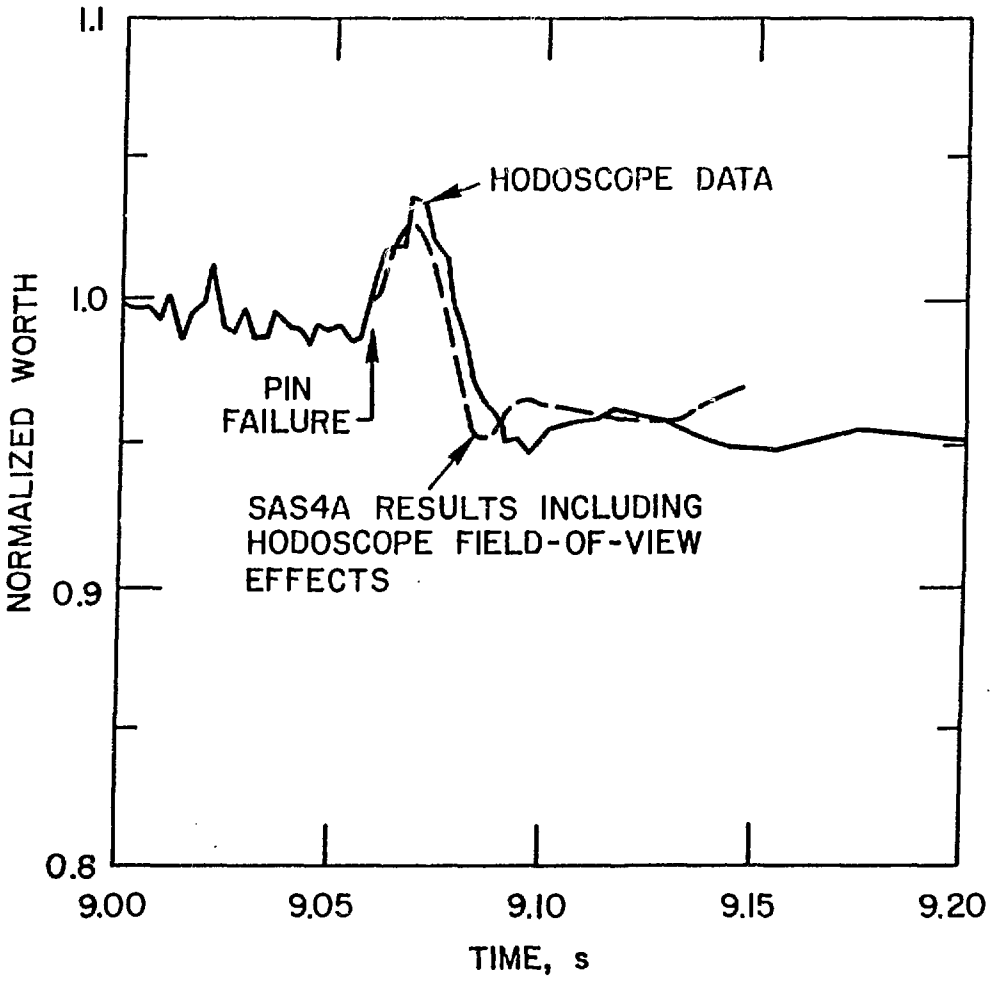

1.1
1.0
0.9
0.8
NORMALIZED WORTH
HODOSCOPE DATA
PIN
FAILURE
SAS4A RESULTS INCLUDING
HODOSCOPE FIELD-OF-VIEW
EFFECTS
9.00
9.05
9.10
9.15
9.20
TIME, s

FIG 17