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ABSTRACT

The SAS4A and SASSYS computer codes are being developed at Argonne National Laboratory for transient analysis of liquid metal cooled reactors. The SAS4A code is designed to analyse severe loss-of-coolant flow and overpower accidents involving coolant boiling, cladding failures, and fuel melting and relocation. Recent SAS4A modeling developments include extension of the coolant boiling model to treat sudden fission gas release upon pin failure, expansion of the DEFORM fuel behavior model to handle advanced cladding materials and metallic fuel, and addition of metallic fuel modeling capability to the PINACLE and LEVITATE fuel relocation models. The SASSYS code is intended for the analysis of operational and beyond-design-basis transients, and provides a detailed transient thermal and hydraulic simulation of the core, the primary and secondary coolant circuits, and the balance-of-plant, in addition to a detailed model of the plant control and protection systems. Recent SASSYS modeling developments have resulted in detailed representations of the balance of plant piping network and components, including steam generators, feedwater heaters and pumps, and the turbine.

INTRODUCTION

The SAS4A (1) and SASSYS (2) computer codes are being developed at Argonne National Laboratory for transient analysis of liquid metal cooled reactors (LMRs). The SAS4A code is being developed to analyze severe, core disruptive accidents resulting from undercooling or overpower initiating conditions. SAS4A contains detailed, mechanistic models of transient thermal, hydraulic, neutronic, and mechanical phenomena to describe the response of the reactor core, its coolant, fuel elements, and structural members to accident conditions. The core models in SAS4A provide the capability to analyze the initial phase of core disruptive accidents, through coolant heatup and boiling, fuel element failure, cladding melting and relocation, and fuel melting and relocation. Originally developed to analyse oxide fuel clad with stainless steel, the models in SAS4A are now being extended and specialized to metallic fuel with advanced, low-swelling cladding alloys.

The SASSYS code, originally developed to address the consequences of loss of decay heat removal accidents, has evolved into a tool to analyze passive safety response mechanisms in anticipated transients without scram

(ATWS) and as a margin assessment tool for Design Basis Accidents (DBAs). To fulfill this role, the SASSYS code contains the same models as SAS4A for fuel element heat transfer and single and two-phase coolant hydraulics. In addition, SASSYS has the capability to provide a detailed thermal-hydraulic simulation of the primary and secondary sodium coolant circuits, in order to simulate the longer-term transients considered in ATWS and DBA events. Recently, a Blanace-of-Plant (BOP) modeling capability has been added to SASSYS, extending its transient simulation capability to the feedwater/steam circuit with its heaters, pumps, steam generators, and turbine.

This paper provides an overview of recent modeling developments in the SAS4A and SASSYS computer codes. It focuses on coolant dynamics, fuel behavior, and molten fuel relocation models for SAS4A and the new BOP models in SASSYS.

SAS4A MODEL DEVELOPMENTS

Coolant Boiling Model

To simulate the potential impact of fuel element failures at high burnup conditions with advanced cladding alloys, the coolant boiling model used in both SAS4A and SASSYS has been modified to simulate the effect of sudden gas release from failure of high burnup fuel elements. The time and location of the failure is predicted with either the DEFORM-4 (oxide fuel) or DEFORM-5 (metal fuel) fuel behavior models. The gas release provides a localized source of noncondensible vapor to the coolant dynamics model. An adjustable cladding rip area and orifice coefficient determine the rate at which gas is released from the failed elements. The internal pin pressure is reduced as the fission gas flows out of the cladding rip. In the coolant channel, the gas mixes with coolant vapor, if present, reducing the condensation coefficient and modifying the vapor friction factor. As the gas bubbles out of the top of the subassembly, a smooth transition is made to normal coolant flow or coolant boiling, depending on the coolant channel thermal conditions. Within a subassembly, multiple fuel element failure groups are provided to account for intra-subassembly incoherence in cladding failure timing and location. Each failure group represents a fraction of the total number of fuel elements in the subassembly and may have its own plenum gas pressure, temperature, and gas release flow rate through the cladding rupture.

The new gas release model developed for SAS4A and SASSYS has been applied to analysis of the consequences of cladding rupture failures of high-burnup metal fuel elements in EBR-II (3). These analyses indicate that sudden gas releases from one or a number of fuel elements has the potential to temporarily stop and reverse liquid coolant flow, and even void the fuel subassembly briefly, prior to resumption of coolant flow. At power and with coolant pumps operating, voiding is sustained for only a fraction of a second, while gas release during a pump coastdown accident at a reduced power level would void the subassembly for up to two seconds. In either case, the temperature rise in the fuel element due to loss of heat removal is in the neighborhood of 40°C to 50°C, which presents little additional safety margin degradation in accident conditions and is well within allowable margins during normal operation.

Metal Fuel Performance

Recent SAS4A fuel behavior model development has focused on simulation of metal fuel performance in off-normal (accident) situations. The DEFORM-5 metal fuel behavior model is being developed to provide the capability to describe the response of metallic fuel and advanced cladding materials in power and flow transients. Development of DEFORM-5 has centered on phenomena related to failure of metal fuel elements, including fission gas generation and release, internal element pressure loading and cladding strain, and fuel-cladding chemical interaction with cladding thinning due to eutectic formation. In DEFORM-5, modeling of these phenomena is integrated with the SAS4A fuel element heat transfer and coolant dynamics models to provide the capability to predict cladding failure. The DEFORM-5 model has been used to analyze a number of metal fuel element transient tests conducted in TREAT, and excellent agreement between code calculatons and test results has been obtained (4).

This focus on prediction of metal fuel failure timing and location is continuing. Initially aimed at providing a quantitative measure of safety margins to fuel element in failures in ATWS events, the DEFORM-5 model is being extended to provide initial conditions for the SAS4A fuel relocation models. To this end, the capability to treat advanced cladding alloys in combination with binary (U-Zr) and ternary (U-Pu-Zr) metal fuel alloys has been implemented and tested, with confirmatory analyses of recent TREAT fuel testing underway. To this capability, modeling will be added in the fueled region to treat irradiation induced fuel swelling; fission gas generation, release, and pin pressurization; zirconium migration and the impact on fuel properties; fuel-cladding contact and cladding strain; fuel-cladding chemical interaction and cladding thinning; and high rate cladding strain and failure. These modeling additions will be verified and validated with in-pile test data from TREAT testing and comparison to the detailed modeling in the FPIN code.

Metal Fuel Disruption

In severe undercooling and overpower transients, metal fuel can become sufficiently hot to lose strength so that the pressurization due to fission gas trapped in the fuel matrix can provide a mechanism to relocate molten fuel within the cladding prior to cladding failure. This in-pin fuel motion can provide a significant negative reactivity effect that acts as a self-limiting accident mitigation feature. In SAS4A, this phenomenon is modeled with the PINACLE in-pin fuel relocation model. PINACLE provides a detailed transient fuel and fission gas motion calculation that includes treatments of fuel melting, molten cavity formation and pressurization by fission gas, gas expansion and fuel motion, and fuel ejection inside the cladding above the original fuel column. Continued heating of the fuel element may result in cladding failure, as predicted by DEFORM-5, and ejection of molten fuel into the coolant channel. The LEVITATE model provides a detailed calculation of fuel element depressurization and coolant channel pressurization, molten fuel ejection, and fuel/fission gas motion and heat transfer in the coolant channel. The application of DEFORM-5, PINACLE, and LEVITATE to a recent overpower test on metal fuel in TREAT is detailed in another paper submitted to this meeting (5).

SASSYS MODEL DEVELOPMENT

Past usage of the LMR system transient analysis code SASSYS has mainly been in the area of engineering simulation and specifically in the analysis of design basis accidents relevant to system design evaluation (6). In the recent past the focus of the application of the code has appreciably widened to include not only those transients considered as plant operational upsets, but also those traditionally considered as beyond design basis accidents (BDBA); in particular the class of anticipated transients without scram (ATWS). In addition, the area of application of SASSYS has changed to include analysis with artificial intelligence (AI) knowledge-based expert systems for online reactor diagnostics and control where a system simulation code such as SASSYS is used as a simulation engine. In both of these new areas of SASSYS application, the role of the water side part of the plant becomes significantly more important than in the classical DBAs.

To address this need, a balance-of-plant (BOP) model has been developed for use within the SASSYS liquid metal reactor systems analysis code. This model expands the scope of SASSYS so that the code can explicitly model the water side components of a nuclear power plant; previously, only the water side of the steam generators could be modeled, with the remainder of the water side represented by boundary conditions on the steam generator. The new model represents the balance of plant as a set of flow paths and path junctions. The various water side component models are specialized types of energy or momentum cells, as appropriate. The balance-of-plant model is coupled to the sodium side of the plant through the water side of the steam generator. The steam generator is modeled separately and is explicitly coupled to the balance-of-plant model. A number of modifications to the existing steam generator model and solution algorithm were implemented. Several types of components, interacting with one another, are involved in the complicated thermal hydraulic network simulating a BOP system. In the work presented, the attention was focused on two generic types of components; heat transfer components and rotating machinery.

A number of test problems have been run with the BOP model incorporated into the SASSYS code. These cases range from upsets in the feedwater train, such as simultaneous feedwater pump trips, to transients in the steam system such as the closure of the turbine admission valve. In terms of the plant duty cycle, the events range from mild to moderate upsets. The model has demonstrated reasonable response in these test cases while showing acceptable running times. A future validation program will be implemented to verify the capability of the models to generate results within an acceptable accuracy range.

BOP Network Model

The balance-of-plant network model is patterned after the model used for the sodium side of the plant (7). It will handle subcooled liquid water, superheated steam, and saturated two-phase fluid. With the exception of heated flow paths in heaters, the model assumes adiabatic conditions along flow paths; this assumption simplifies the solution procedure while introducing very little error for a wide range of reactor plant problems. A later section discusses flow through heaters. The balance-of-plant model is explicitly coupled to the steam generator waterside model.

SASSYS represents the balance of plant as a network of one-dimensional flow paths, or segments, which are joined at flow junctions called compressible volumes. Therefore, one-dimensional forms of the mass, momentum, and energy equations can be used to describe the system. The network is a discretization of the balance of plant using a non-uniform spatial mesh. The momentum equation is solved along each flow path, and the mass and energy equations are solved at each flow junction. Flow is assumed uniform throughout each flow path. Components which primarily affect mass flow rate and pressure drop in a flow segment are best described through the momentum equation and are modeled as sections of flow segments; these sections are called flow elements. The cross-sectional area is constant throughout a given flow element. Element types include pipes, valves, check valves, and pumps. Flow segments then become strings of one or more flow elements. Components which join two or more flow segments are best described through the mass and energy equations and are modeled as compressible volumes; these include inlet and outlet plena, piping junctions such as tees, and open heaters. Closed heaters must be described through a combination of flow elements and a compressible volume (8).

The general analytical equations are simplified by making the following assumptions: 1) one-dimensional flow, 2) neglect the work done by viscous forces on a compressible volume, 3) neglect kinetic energy and gravitation energy, and 4) the viscous term in the momentum equation can be expressed in algebraic form. In addition, the internal energy is expressed in terms of the enthalpy. The system is closed by using an equation of state.

The analytical forms of the mass, momentum, and energy equations and the equation of state are discretized over the compressible volumes and flow elements of the balance-of-plant nodalization. The result of the discretization is a set of fully implicit equations which can be solved simultaneously for the changes in pressure, flow, and enthalpy in a timestep. All other quantities (e.g., densities, heat sources) are computed explicitly. The first step is to use the momentum equation to express the change over a timestep in the mass flow rate in each segment as a function of the changes in the segment endpoint pressures. Next, the mass and energy equations and the equation of state can be combined to express the change in pressure within a compressible volume as a function of the changes in the flows of all segments which are attached to the volume. If these two sets of equations are combined by eliminating the change in flow, the resulting matrix equation can be solved for the change in pressure in each compressible volume. The changes in flow, enthalpy, and all explicit variables can then be determined.

The balance-of-plant coding includes a steady-state initialization subroutine which takes user-input data describing the plant geometry and generates a consistent plant steady state. The steady state calculated by the initializer compares very well with the results of null transient calculations run by the transient portion of the coding.

The steam generator is not included as one of the components in the balance-of-plant model; instead, it is a separate model within SASSYS. The two models are coupled in a mathematically explicit fashion. One interface between them is at the steam generator outlet. The other interface is along the steam generator subcooled liquid region. The balance-of-plant treats the subcooled region as one of the flow segments in the plant network, with the steam generator model providing the enthalpy distribution along the region and the pressure at the end of the region, so that the balance-of-plant model computes the flow within the subcooled region and passes the flow value to the steam generator model.

Since the coupling between the balance-of-plant and steam generator models is explicit rather than implicit, some time averaging is required to stabilize the rate of change of the steam generator pressure. For the same reason, the rate of change of the subcooled zone flow must be limited. Neither constraint affects the accuracy of the overall calculation.

Steam Generator Model

A new steam generator model (9) has been developed for SASSYS. It has been incorporated into the new SASSYS balance-of-plant model but it can also function on a stand-alone basis. The steam generator can be used in a once-through mode, or a variant of the model can be used as a separate evaporator and a superheater with a recirculation loop. The new model provides for an exact steady-state solution as well as the transient calculation. There was a need for a faster, more flexible and more detailed model than the old steam generator model. The new model provides more detail and flexibility with its multi-node treatment as opposed to the previous model's one node per region approach. The old model relied on a log-mean temperature difference to calculate the transient heat flux. The new model makes a more accurate estimate of the heat flux with local nodewise temperatures. Numerical instability problems which were the result of cell-centered spatial differencing, fully explicit time differencing and the moving boundary treatment of the boiling crisis point in the boiling region have been reduced or eliminated in the new model. The new model uses donor-cell differencing, implicit time differencing and a greatly improved and much more stable method of determining the boiling crisis point. This leads to an incease in the speed of the calculation as larger time steps (at least a factor of ten or more) can now be taken. The actual difference in time for the two codes will vary depending on how many nodes are used in the new mode. The new model is an improvement in many respects.

On the water side, the steam generator is divided into three regions at most: a subcooled liquid, a saturated boiling and a super-heated steam region. A subcooled region is always assumed to exist but the disappearance and reappearance of the other two regions is calculated. Thus a liquid-filled steam generator can be characterized but dry-out can be calculated only to the extent a small liquid region remains. The boundaries of the subcooled region are defined as the inlet of the steam generator and the point where saturated liquid enthalpy is attained or the top of the steam generator. The boiling zone is bounded by the point of saturated liquid enthalpy and the point of saturated vapor enthalpy or the top of the steam generator. The superheated region is, of course, above the point of saturated vapor enthalpy.

The subcooled region is treated as incompressible and therefore the inlet flow is constant throughout the subcooled region and provides a lower flow boundary condition for the boiling zone. Saturation conditions and a no-slip condition between phases are assumed at all times in the boiling zone. Pressure boundary conditions are provided from an external calculation at the inlet and outlet of the steam generator and an average of this is curently used for calculating properties. The subcooled and superheated regions each have one heat transfer regime and the boiling zone has two regimes separated at the boiling crisis point.

There is no momentum equation used in an integrated fashion to produce nodal velocities. The inlet water flow is assumed to be a driving function of the equation set and only mass and energy conservation equations are used to solve for mass flows, enthalpies, etc. for the compressible regions on the water side. A momentum equation is, however, explicitly coupled to the calculation. It is used to calculate the pressure drop across the steam generator in order to link the steam generator with the balance-of-plant and calculate the liquid mass flow at the steam generator inlet.

Each of the three regions is divided into a fixed number of cells which are thus a constant fraction of the varying region length. The volumetric heat source and the wall temperature are calculated at the cell center. All other parameters are calculated at the cell edge. The heat flux is always explicit in time but other parameters have varying degrees of implicitness in time. Donor-cell differencing is used for numerical stability on both the sodium and water sides. The wall temperature calculation is central differenced, however. The sodium side, always being in the liquid state, is treated as incompressible flow.

BOP Component Models

Models (10) of power plant heat transfer components and rotating machinery have been added to the balance-of-plant model in the SASSYS code. These models extend the scope of the balance-of-plant model to handle non-adiabatic conditions and two-phase conditions along flow paths. The models for the various types of components rely on simple conservation balances and extensive component data in the form of correlations. While the mass and momentum equations remain the same as in the network model, the energy equation now contains a heat source term due to energy transfer across the flow boundary or to work done through a shaft. The heat source term is treated fully explicitly. To handle two-phase conditions, the equation of state is rewritten in terms of the quality and separate parameters for each phase. The models are simple enough to run quickly, yet include sufficient detail of dominant plant component characteristics to provide reasonable results.

Tables I and II list the various types of heat transfer and rotating machinery components. The seven types of heaters and the turbine model will be discussed below; the feedwater pump model is addressed in Ref. 8.

TABLE I
HEAT TRANSFER COMPONENTS

Open heater:	Deaerator
Closed heater:	Condenser
	Reheater
	Flashed heater
	Drain cooler
	Desuperheating heater
	Desuperheater/Drain Cooler

TABLE II
ROTATING MACHINERY COMPONENTS

Feedwater Pump
Turbine

Heaters fall into two classifications: open heaters and closed heaters. The term "open heater" refers to the fact that there is no distinction between tube and shell sides, so that hot fluid and cold fluid entering the heater mix together. An open heater is actually a closed volume containing liquid and vapor at saturation conditions. The term "closed heater" indicates that hot and cold fluids are separated between a tube side and a shell side. Heat transfer occurs across the tube between hot and cold fluids. Closed heaters consist of a closed volume, or shell side, and a tube bundle, or tube side. Flow is carried into and out of the tube bundle by pipes which lie outside the heater boundary.

The following assumptions are made in all seven heater models. Flow is incompressible on both shell and tube sides. Any two-phase fluid entering on the shell side instantaneously separates into liquid and vapor, and a new thermodynamic equilibrium is reached immediately. The two-phase interface serves as the reference point for the saturation pressure. The momentum equation governing flow entering and exiting the shell side accounts for elevation pressure differences as gravity heads. The two phases are at a common saturation temperature, and each phase is assumed to be at a uniform enthalpy. The tube bundle is modeled as a single tube. Mass flux and pressure drop in the tube are the same as in the tube bundle, and the mass of the metal tubing is also conserved. These constraints do not allow tube length or surface area to be conserved, and so the tube surface heat transfer area is corrected to simulate the bundle heat transfer area through the use of calibration factors which provide an effective thermal resistance for conduction heat transfer.

A turbine is composed of many stages driving one rotor which extracts work from the flow. A series of volumes is used to model the various stages in the turbine. The stages are connected by nozzles which permit both nonchoked and choked flow. Compressible flow is very important in describing the flow behavior in the nozzles. Separate correlations based on thermodynamic conditions at the inlet are used for the nozzle flow depending on whether the flow is choked or not and whether the fluid is single phase or two phase. Turbine efficiency is based on losses to isentropic expansion and shaft work is then calculated using quasi-empirical correlations for stage efficiency. Stage efficiency is affected by many loss factors like rotation loss and moisture loss. Steam at the extraction ports is treated as incompressible flow. In general, the turbine model is similar to the ones in RETRAN (11) and TRAC (12).

The component models are integrated into the existing solution scheme of the balance-of-plant coding, so that volume pressures and segment flows in the heaters and turbine are computed simultaneously with the pressures and flows in the remaining balance-of-plant components. The primary purpose of these models is to generate the energy equation source term, which is treated explicitly. Some of the models, such as the drain cooler and desuperheating heater, also contribute to the calculation of the enthalpy of fluid entering or leaving a compressible volume.

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