

## **Coupling the System Analysis Module with SAS4A/SASSYS-1**

---

**Nuclear Engineering Division**

### **About Argonne National Laboratory**

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see [www.anl.gov](http://www.anl.gov).

### **DOCUMENT AVAILABILITY**

**Online Access:** U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via DOE's SciTech Connect (<http://www.osti.gov/scitech/>)

### **Reports not in digital format may be purchased by the public from the National Technical Information Service (NTIS):**

U.S. Department of Commerce  
National Technical Information Service  
5301 Shawnee Rd Alexandria,  
VA 22312 [www.ntis.gov](http://www.ntis.gov)  
Phone: (800) 553-NTIS (6847) or (703) 605-6000  
Fax: (703) 605-6900  
Email: [orders@ntis.gov](mailto:orders@ntis.gov)

### **Reports not in digital format are available to DOE and DOE contractors from the Office of Scientific and Technical Information (OSTI):**

U.S. Department of Energy  
Office of Scientific and Technical Information  
P.O. Box 62  
Oak Ridge, TN 37831-0062  
[www.osti.gov](http://www.osti.gov)  
Phone: (865) 576-8401  
Fax: (865) 576-5728  
Email: [reports@osti.gov](mailto:reports@osti.gov)

### **Disclaimer**

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

**ANL/NE-16/22  
(ANL-ART-74)**

## **Coupling the System Analysis Module with SAS4A/SASSYS-1**

---

prepared by  
T. H. Fanning and R. Hu  
Nuclear Engineering Division, Argonne National Laboratory

September 30, 2016



## ABSTRACT

SAS4A/SASSYS-1 is a simulation tool used to perform deterministic analysis of anticipated events as well as design basis and beyond design basis accidents for advanced reactors, with an emphasis on sodium fast reactors. SAS4A/SASSYS-1 has been under development and in active use for nearly forty-five years and is currently maintained by the U.S. Department of Energy under the Office of Advanced Reactor Technology. Although SAS4A/SASSYS-1 contains a very capable primary and intermediate system modeling component, PRIMAR-4, it also has some shortcomings: outdated data management and code structure makes extension of the PRIMAR-4 module somewhat difficult. The user input format for PRIMAR-4 also limits the number of volumes and segments that can be used to describe a given system.

The System Analysis Module (SAM) is a fairly new code development effort being carried out under the U.S. DOE Nuclear Energy Advanced Modeling and Simulation (NEAMS) program. SAM is being developed with advanced physical models, numerical methods, and software engineering practices, however it is currently somewhat limited in the system components and phenomena that can be represented. For example, component models for electromagnetic pumps and multi-layer stratified volumes have not yet been developed. Nor is there support for a balance of plant model. Similarly, system-level phenomena such as control-rod driveline expansion and vessel elongation are not represented.

This report documents fiscal year 2016 work that was carried out to couple the transient safety analysis capabilities of SAS4A/SASSYS-1 with the system modeling capabilities of SAM under the joint support of the ART and NEAMS programs. The coupling effort was successful and is demonstrated by evaluating an unprotected loss of flow transient for the Advanced Burner Test Reactor (ABTR) design. There are differences between the stand-alone SAS4A/SASSYS-1 simulations and the coupled SAS/SAM simulations, but these are mainly attributed to the limited maturity of the SAM development effort.

The severe accident modeling capabilities in SAS4A/SASSYS-1 (sodium boiling, fuel melting and relocation) will continue to play a vital role for a long time. Therefore, the SAS4A/SASSYS-1 modernization effort should remain a high priority task under the ART program to ensure continued participation in domestic and international SFR safety collaborations and design optimizations. On the other hand, SAM provides an advanced system analysis tool, with improved numerical solution schemes, data management, code flexibility, and accuracy. SAM is still in early stages of development and will require continued support from NEAMS to fulfill its potential and to mature into a production tool for advanced reactor safety analysis. The effort to couple SAS4A/SASSYS-1 and SAM is the first step on the integration of these modeling capabilities.



## TABLE OF CONTENTS

Abstract .....	i
Table of Contents.....	iii
List of Figures.....	iv
List of Tables .....	iv
1 Introduction .....	5
2 SAS/SAM Coupling .....	6
2.1 Strategy .....	6
2.2 Data Exchange Requirements .....	8
3 Code Modifications.....	9
3.1 SAS Code Modifications.....	9
3.2 SAM Code Modifications .....	13
4 Coupling Results.....	17
4.1 ABTR Reference Model .....	17
4.2 SAM System Model.....	22
4.3 Verification of Coupling Interface.....	23
4.4 Unprotected Loss of Flow Transient Sequence .....	25
4.5 Transient Simulation Results of Unprotected Loss of Flow .....	25
5 Path Forward .....	32
6 References.....	33

## LIST OF FIGURES

Figure 1: Tight Coupling Scheme for a Generic Time Step .....	7
Figure 2: SAS4A/SASSYS Time Step Hierarchy .....	7
Figure 3: Sequential Two-Way Coupling Scheme during a Transient.....	8
Figure 4: Relationship between PRIMAR-4 and the SAS4A/SASSYS-1 Thermal-Hydraulics Solvers.....	10
Figure 5: Summary of SAS4A/SASSYS-1 Input Required for SAS/SAM Coupling .....	12
Figure 6: Example of SAS4toSAM.dat file for SAS/SAM Coupling.....	15
Figure 7: Example of SAMtoSAS.dat file for SAS/SAM Coupling.....	16
Figure 8: Execution Process Flow Chart of CoupledSASSteady Executioner .....	16
Figure 9: Execution Process Flow Chart of CoupledSASTransient Executioner .....	17
Figure 10: Reference ABTR Core Configuration .....	18
Figure 11: Channel Assignments for the SAS4A/SASSYS-1 Core Model. ....	19
Figure 12: Elevation view of the ABTR Primary System.....	20
Figure 13: PRIMAR-4 Representation of the Primary, Intermediate, and Decay Heat Coolant Systems.....	21
Figure 14: Schematics of the ABTR model for coupled SAS/SAM simulations .....	23
Figure 15: Coupled SAS/SAM simulation results of ABTR null transient.....	24
Figure 16: Normalized power and core flow during the ABTR ULOF transient.....	27
Figure 17: Pool temperatures during the transient.....	27
Figure 18: Transient temperatures for Channel 5.....	28
Figure 19: Core channel flow velocities during the transient.....	28
Figure 20: Total core flow differences between SAM surrogate model and SAS4A/SASSYS-1 core channel simulation results.....	29
Figure 21: Transient reactivity feedback.....	29
Figure 22: Normalized power and core flow, comparison between stand- alone SAS and coupled SAS/SAM simulation results.....	31
Figure 23: Transient temperatures for Channel 5, stand-alone SAS simulation .....	31
Figure 24: Transient reactivity feedback, stand-alone SAS simulation.....	32

## LIST OF TABLES

Table 1: Data exchange flow for SAS/SAM coupling at the coupling interface .....	9
--	---

## 1 Introduction

SAS4A/SASSYS-1 is a simulation tool used to perform deterministic analysis of anticipated events as well as design basis and beyond design basis accidents for advanced liquid-metal-cooled nuclear reactors.[1] With its origin as SAS1A in the late 1960s, the SAS series of codes has been under continuous use and development for over forty-five years and represents a critical investment in safety analysis capabilities for the U.S. Department of Energy. In contrast, the US DOE Nuclear Energy Advanced Modeling and Simulation Program (NEAMS) has made recent investments to explore new systems modeling capabilities in a software tool referred to as the System Analysis Module (SAM).[2] This report documents fiscal year 2016 activities that were carried out to couple the transient safety analysis capabilities of SAS4A/SASSYS-1 with the system modeling capabilities of SAM under the joint support of the Advanced Reactor Technology (ART) and NEAMS programs.

SAS4A/SASSYS-1 contains a capable primary and intermediate system modeling component, PRIMAR-4. PRIMAR-4 can represent complex arrangements of coolant system components including pumps, piping, valves, intermediate heat exchangers, air dump heat exchangers, steam generators, etc. SAS4A/SASSYS-1 also contains a control system module that can dynamically interact with PRIMAR-4 based on user-defined logic and controls. Control signals can affect certain plant state parameters such as scram reactivity, pump speed, and valve actuation.

In addition to its capabilities, PRIMAR-4 has some shortcomings. The most significant shortcomings are in the form of data management, code structure, and user input limitations. Outdated data management and code structure makes extension of the PRIMAR-4 module difficult. Adding new component models requires knowledge of unrelated code in order to avoid introducing bugs. Lack of modularity means that unit testing to validate individual models is not possible. The user input format for PRIMAR-4 limits the number of volumes and segments that can be used to describe a given system. Coupling with SAM will provide an alternative to PRIMAR-4 for primary, secondary, and decay heat coolant system modeling capabilities that are more flexible and extensible.

SAM development aims for the advances in physical modeling, numerical methods, and software engineering to enhance its user experience and usability. To facilitate the code development, SAM utilizes an object-oriented application framework (MOOSE), and its underlying meshing and finite-element library (libMesh) and linear and non-linear solvers (PETSc), to leverage modern software environments and numerical methods. As a new code development, the initial effort has been focused on the modeling and simulation capabilities of heat transfer and single-phase fluid dynamics responses in the advanced reactor systems.

Despite the advanced software architecture of SAM, it is currently somewhat limited in the system components and phenomena that can be represented. For example, component models for electromagnetic pumps and multi-layer stratified volumes have not yet been developed. Nor is there support for a balance of plant model. Similarly, system-level phenomena such as control-rod driveline expansion and vessel elongation are not

represented. Nevertheless, the modern software design of SAM should facilitate rapid development of models, and continued investment by NEAMS would eliminate these gaps.

Until SAM matures to provide the same range of components and phenomena that PRIMAR-4 provides, PRIMAR-4 will be the preferred module for primary and intermediate coolant systems modeling. By completing the coupling, however, a path forward will be available to support enhanced modeling capabilities that are not currently possible.

## **2 SAS/SAM Coupling**

### **2.1 Strategy**

To combine the advantages of SAS4A/SASSYS-1 and SAM, an initial coupling strategy has been defined that retains the full complement of core (in the reactor sense) modeling capabilities of SAS4A/SASSYS-1 — coolant channel and sub-channel thermal hydraulics, sodium boiling, fuel restructuring and relocation, in-pin fuel melting, cladding failure, and fuel and clad melting and relocation — and adds the option to use SAM for the primary, intermediate, and decay heat coolant systems. In this approach, the modeling capabilities of PRIMAR-4 will be retained to maintain continuity of simulation capabilities.

In all multi-code coupling applications, careful control of data exchange and time synchronization are essential for a numerically stable and physically valid simulation. When using a tight coupling scheme, an interface consistency, or convergence, check is needed to make sure the results are consistent at the coupling interface between the two codes, as shown in Figure 1. If this scheme were adopted, each time step is repeated in both SAM and SAS4A/SASSYS-1 until the desired convergence is achieved. Tight coupling in this manner usually does not require significant modifications to the underlying solution schemes of the two codes.

However, this approach often requires the modification of the time stepping control and data management in the two codes, which is not always a trivial task. For example, Figure 2 shows that SAS4A/SASSYS-1 uses a multi-level time-step hierarchy to ensure stability of the many different accident models available. PRIMAR-4 itself uses a theta-weighted, semi-implicit solution scheme with time-step cut-back controls to avoid expensive iterations. Therefore, a tight coupling scheme that requires iteration is not appropriate.

Instead, a sequential two-way coupling scheme is used for coupling SAM with SAS4A/SASSYS-1. This approach is shown in Figure 3. In this scheme, each of the two codes drives its own portion of the simulation and coupling interface data is exchanged at well-defined points. For steady-state initialization, SAS4A/SASSYS-1 will determine core inlet and outlet boundary conditions based on model input. Those conditions will provide the initial steady-state conditions for SAM. During the transient, the roles will be reversed. SAM will determine coolant system dynamic changes, such as loss of flow or loss of heat sink, and will define the interface conditions for the core channel models in SAS4A/SASSYS-1.

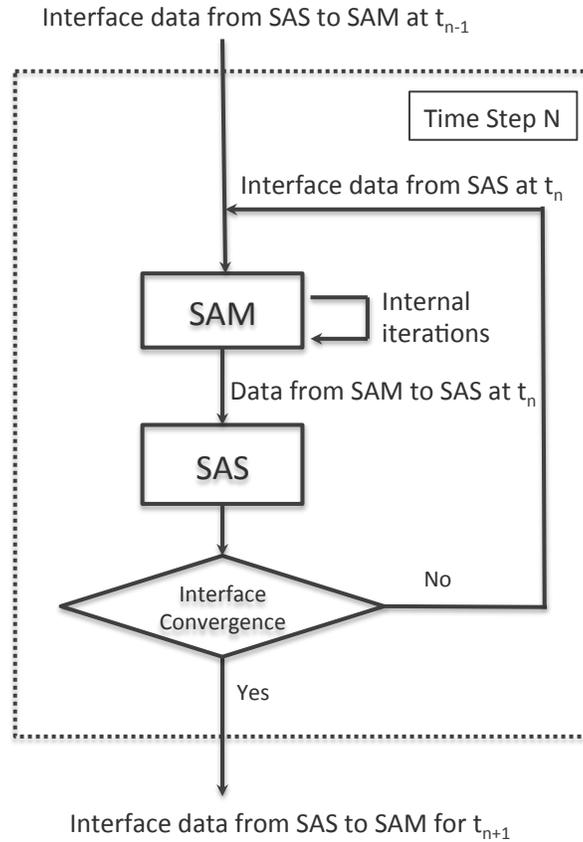


Figure 1: Tight Coupling Scheme for a Generic Time Step

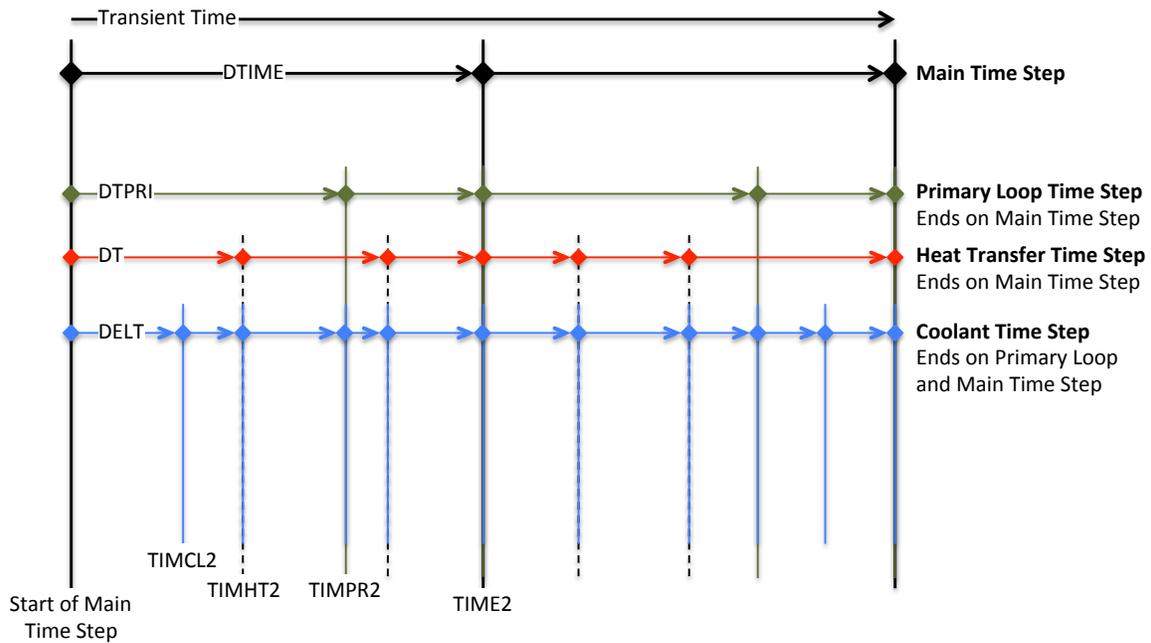


Figure 2: SAS4A/SASSYS Time Step Hierarchy

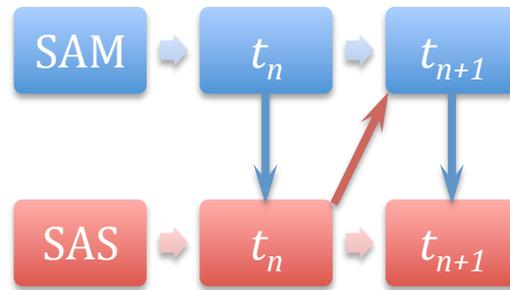


Figure 3: Sequential Two-Way Coupling Scheme during a Transient

This approach is similar to the proven approach used between the SAS4A/SASSYS-1 core channel models and PRIMAR-4. In PRIMAR-4, a surrogate core channel model is used to estimate the rate of change in the mass flow rate for each channel. Additionally, the differences between the estimated channel flows and computed channel flows are considered in the adjustments of the plenum coupling parameters. In this way, the numerical stability of the coupled code is assured, while the modifications to SAS4A/SASSYS-1 are minimized.

## 2.2 Data Exchange Requirements

In SAS4A/SASSYS-1, the multi-channel core model is coupled with PRIMAR-4 at the inlet and outlet plena. When the core-channel thermal hydraulics modules in SAS4A/SASSYS-1 complete a time step for the core simulation portion of the transient, they also defines *surrogate* models for each channel. The surrogate models are used during the PRIMAR-4 time step to estimate changes in core channel flow rates during the next primary coolant system time step.

The surrogate models are defined based on the following equation that relates changes in the core channel flow rates to changes in the plenum pressures:

$$\frac{dw}{dt} = C_0 - C_1 p_{in} + C_2 p_{out} + C_3 w|w| \quad (1)$$

The coefficients  $C_0$  through  $C_3$  are provided by the core channel model to PRIMAR-4, while the pressure ( $p_{in}$  and  $p_{out}$ ) and flow ( $w$ ) variables are solved by PRIMAR-4 during the primary coolant time step. Solutions for pressure and flow are estimates because they are based on the surrogate model.

For transients in which the core channel coolant remains single phase, these estimates will be quite accurate. If boiling initiates, the process of void formation and coolant expulsion introduce rapid, non-linear changes that require significant reductions in time-step sizes in order to maintain accuracy. Also, PRIMAR-4 will need to adjust plenum mass, pressure, temperature, and cover-gas interface elevations to account for differences between the estimated channel flows based on the linear surrogate model and the actual flows computed by the coolant dynamics models.

Following completion of a time step for the primary and intermediate coolant loops, PRIMAR-4 provides the following information back to the core channel coolant dynamics routines in SAS4A/SASSYS-1:

$p_{in}(t_n)$  = inlet plenum pressure at the beginning of the PRIMAR-4 time step

$p_{out}(t_n)$  = outlet plenum pressure at the beginning of the PRIMAR-4 time step

$\frac{dp_{in}}{dt}, \frac{dp_{out}}{dt}$  = time derivatives of the inlet and outlet plenum pressures

$T_{in}, T_{out}$  = inlet and outlet plenum temperatures

These parameters provide the boundary conditions needed to update the core channel solution.

A similar coupling method is used to couple SAS4A/SASSYS-1 with SAM. The data exchange between the two codes at each coupling interface (core channel/plenum) is summarized in Table 1.

Table 1: Data exchange flow for SAS/SAM coupling at the coupling interface

SAS → SAM (at the beginning of SAM time step)	For every channel: $C_0, C_1, C_2,$ and $C_3$ Inlet and Outlet Mass Flow Rate Inlet and Outlet Temperature
SAM → SAS (at the end of SAM time step)	For every plenum: Pressure Pressure derivatives Temperature

### 3 Code Modifications

#### 3.1 SAS Code Modifications

In SAS4A/SASSYS-1, the PRIMAR-4 module traditionally carries out the simulation of the primary and intermediate coolant loops. The goal of this work is to develop a capability to use the NEAMS System Analysis Module (SAM) as an alternative to PRIMAR-4. It is fortunate that the early development of SAS was implemented as two separate codes: SAS1A through SAS4A for severe accidents and SASSYS (including PRIMAR) for system thermal hydraulics. Although the codes have long since merged, there are still discernable boundaries between the core channel models and the PRIMAR system models. The traditional relationship between PRIMAR-4 and the core channel models is illustrated in Figure 4.

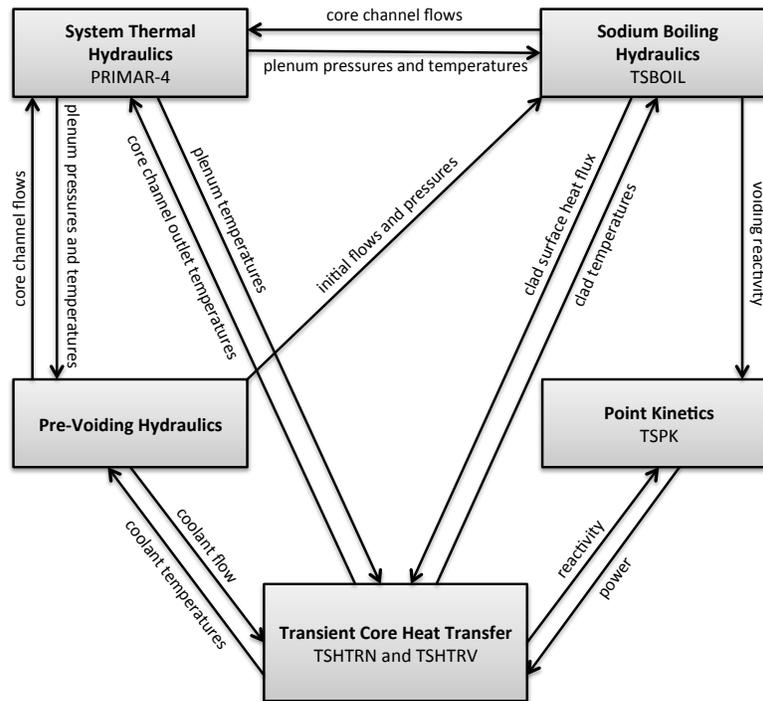


Figure 4: Relationship between PRIMAR-4 and the SAS4A/SASSYS-1 Thermal-Hydraulics Solvers.

Figure 4 suggests that only boundary conditions are passed between PRIMAR-4 and the core channel models. In the absence of object-oriented programming capabilities, decades of development have resulted in mixed code shared between the different models. This was particularly true in the main driver for steady-state initialization. Over time, new features were introduced — such as control-rod driveline expansion, support for multiple inlet and outlet plena, and structural grid-plate expansion — that blurred the distinction between primary coolant system and core channel source code.

To support coupling with SAM, that distinction needed to be reinforced. A new approach was built upon modular object-oriented concepts available in Fortran 2003. A new module, named *CoupleSYS*, was developed that manages all boundary condition information for both the core and the primary coolant loop (see Table 1). For each core channel, the module maintains information about channel flow, inlet and outlet temperatures, surrogate model parameters, and sodium vapor energy discharge. For each plenum, the module maintains elevation, temperature, pressure, and pressure derivative information. The module also maintains a map-type data structure that links any number of core channels to any number of inlet and outlet plena. Although the number and complexity of connections is limited in PRIMAR-4, the *CoupleSYS* module imposes no limitations on the complexity of a SAM model.

In SAS4A/SASSYS-1 terminology, a core segment is composed of one or more channels or channel groups to represent assemblies in the core. A segment also defines

connections to one inlet and one outlet plenum. By combining multiple segments and multiple plena, more complex core designs can be represented. An example would be the high- and low-pressure inlet plena in EBR-II that results in two core segments. User input, either from PRIMAR or for SAM, controls these connections through calls to *LinkGroupToSegmentID* and *LinkSegmentToPlenaID* that are part of the CoupleSYS interface.

The core channel models include not only those in Figure 4 (transient core heat transfer and pre-voiding and boiling hydraulics) but also the fuel melting and relocation models defined by PLUTO and LEVITATE. All of these models were modified to communicate boundary conditions to the CoupleSYS module instead of to PRIMAR. Likewise, the steady-state and transient-state thermal-hydraulics drivers (SSTHRM and TSTHRM respectively) were modified to fetch primary system boundary conditions from CoupleSYS and apply them to every channel.

Significant complications were encountered while updating the steady-state driver, SSTHRM. Unlike many other system codes, SAS4A/SASSYS-1 directly solves the steady-state equations rather than iterate on the transient equations until an equilibrium is found (although that is an option). This simplifies input requirements for the user. In addition to power and flow distributions, the user only has to supply the inlet plenum temperature and the outlet plenum pressure. SSTHRM determines the solution for initial temperature and pressure distributions and automatically adjusts the orifice coefficients for every channel. This approach requires coordination between the core channel models and the system models for the inlet and outlet plena. As a result, the source code for the core channel and system plenum models had blended together in many places, breaking the encapsulation that is needed for object-oriented programming constructs.

To resolve this issue, nearly all of the PRIMAR-related steady-state support routines used by SSTHRM, particularly those that support multiple inlet and outlet plena configurations, had to be rewritten. In addition, SSTHRM can take one of several different paths depending on the type and combination of core channels being used — single-pin (traditional), multiple-pin, and sub-channel — and whether a null transient is needed to initialize assembly-to-assembly heat transfer. Fortunately, the rewrite led to the elimination of specialized code that handled multiple core segments and plena separately from traditional, single segment designs.

To couple with SAM (or any system code that satisfies the requirements defined in Section 0), two additional modules were written. The first is a plug-in addition to the input processor that handles new input for describing segment and plenum connections. The second is a module that handles communications between SAS and SAM.

SAS4A/SASSYS-1 input consists of input *blocks*. A new block, *SAMSYS*, defines the input requirements for coupling with SAM. The *SAMSYS* block allows two types of sub-blocks: *PLENUM* and *SEGMENT*. The *PLENUM* block defines the *z* elevation and either the inlet temperature or outlet pressure for an inlet or outlet plenum, respectively. The *SEGMENT* block defines the association between a core segment and its inlet and outlet plena. Figure 5 illustrates the input required for the *SAMSYS* block.

The SAMSYS input block undergoes extensive input verification. For example, a plenum cannot be defined more than once, nor can it define both an inlet temperature and an outlet pressure. Temperatures and pressures must be positive values, and each segment must connect to valid inlet and outlet plena.

Each SEGMENT must have a unique *id*. The existing channel-dependent input, *NSEGMP*, is used to associate a core channel with a segment based on the ID. If left blank, the segment ID will default to its sequence number in the SAMSYS block (starting with 1), and NSEGMP will default to one (1). This allows the most common case of a single core segment to be defined with minimal input.

The final module, *CoupleSAM*, launches the SAM executable and handles communications between the two codes. It also handles updates to the boundary conditions maintained by the CoupleSYS module. Three key interfaces are defined. *InitWithSurrogate* initializes the CoupleSAM module and passes a reference to the surrogate boundary conditions in CoupleSYS. Near the end of the steady-state initialization in SSTHRM, *SSInit* is called to send the resolved steady-state boundary conditions to SAM for its own steady-state initialization. During each transient time step, *TSSStep* is called to provide updated surrogate channel parameters to SAM and receive updated inlet and outlet boundary conditions for SAS. Additional interfaces are defined to handle job termination or restart situations.

```
SAMSYS "<name>"

    path = "<SAM executable path>"

    ! Define an inlet plenum:
    PLENUM "<name>"
        Zref = Z ! inlet plenum elevation
        Tin  = T ! inlet plenum temperature
    END

    ! Define an outlet plenum:
    PLENUM "<name>"
        Zref = Z ! outlet plenum elevation
        Pout = P ! outlet plenum pressure
    END

    ! Define a core segment
    SEGMENT "<name>"
        id = # ! needed for core channel models
        inlet = "<name of inlet plenum>"
        outlet = "<name of outlet plenum>"
    END

    ! [...]

END
```

Figure 5: Summary of SAS4A/SASSYS-1 Input Required for SAS/SAM Coupling

### 3.2 SAM Code Modifications

Significant code updates have been made for the implementation of the SAS/SAM coupling strategy and data exchange discussed in the above Sections. Major code updates include:

- Implementation of surrogate core-channel flow models in SAM;
- Development of new coupling boundary components, *CoupledVolumeBranch* and *CoupledLiquidVolume*, including additional physics modeling associated with the new Components;
- Data exchange and file I/O;
- Development of Coupled SAS Steady Executioner and steady-state initialization;
- Development of Coupled SAS Transient Executioner.

A surrogate model, as described in Eq. (1), is implemented in SAM to approximate the SAS core channel flow rate based on coefficients  $C_0$  through  $C_3$  provided by SAS, and the state variables in the SAM primary loop.

New components were developed in SAM to model a volume with additional mass sources or sinks, which represent the connecting pipes modeled in the other codes such as SAS4A/SASSYS-1. The governing equations of mass and energy conservation for the *CoupledVolumeBranch* and *CoupledLiquidVolume* Components are

$$-\frac{d(\rho V)}{dt} + \sum_{i=1}^n (\rho u A \vec{n})_i + \sum_{j=1}^m \dot{m}_{\text{coupled}} + \dot{m}_{\text{adj}} = 0 \quad (1)$$

$$-\frac{d(\rho V h)}{dt} + \sum_{i=1}^n (\rho u A h \vec{n})_i + \sum_{j=1}^m \dot{m}_{\text{coupled}} h_{\text{coupled}} + \dot{m}_{\text{adj}} h = 0 \quad (2)$$

where

$\rho$  = density of the volume component

$V$  = volume of the volume component

$t$  = time

$\rho u$  = mass flux at the connecting nodes

$u$  = flow velocity at the connecting nodes

$A$  = flow area of the connecting components

$h$  = fluid enthalpy of the volume component

$\dot{m}_{\text{coupled}}$  = coupled pipe flow rate

$h_{\text{coupled}}$  = coupled pipe flow enthalpy.

When coupled with SAS4A/SASSYS-1, the core channel flow rate calculated from the surrogate model will be used as  $\dot{m}_{\text{coupled}}$  in the coupled volume component model. A mass adjustment term  $\dot{m}_{\text{adj}}$  is also included to account for the differences between the SAM surrogate model and the SAS4A/SASSYS-1 core channel model results.

Because SAM is developed in an object-oriented programming language, most of the terms in the coupled volume governing equations were available from the development of the original *PBVolumeBranch* and *PBLiquidVolume* components. Only the new terms,  $\sum_{j=1}^m \dot{m}_{\text{coupled}}$  and  $\sum_{j=1}^m \dot{m}_{\text{coupled}} h_{\text{coupled}}$ , are implemented as new Nodal Scalar Kernels in SAM.

The data exchange requirements defined in Section 2.2 are currently implemented in both SAS4A/SASSYS-1 and SAM through file inputs and outputs. Direct data exchange through memory could be implemented in the future to improve the coupling interface. The examples of the data transfer files “SAStoSAM.dat” and “SAMtoSAS.dat” are shown in Figure 6 and Figure 7. After the data is exchanged, it will be propagated into all related MOOSE objects in SAM, including *ScalarKernels* and *AuxScalarKernels* to calculate the surrogate core channel flow rates and the flow rate adjustments.

A special MOOSE Executioner, *CoupledSASSteady*, was developed to implement the coupling strategy between SAM and SAS for steady state initialization. It inherits methods from the regular Steady Executioner, but adds simplified models for coupling boundary components and additional processes for communicating with the SAS code. Its process flow chart is depicted in Figure 8, where the regular processes in a Steady Executioner are on the left, and the dashed lines and blocks on the right are additional processes for the coupled code execution.

Special modeling options are also used in the *CoupledVolumeBranch* and *CoupledLiquidVolume* components for steady-state initialization. Instead of using the surrogate model to calculate the core channel flow rates, constant core channel flow rates from SAS are used. Additionally, constant pressure and temperature are assumed for the outlet plenum, while the pressure and temperature of the inlet plenum will be calculated by the code. Once a converged simulation is obtained, the inlet plenum conditions will be checked with SAS results for consistency.

Similarly, a transient Executioner, *CoupledSASTransient*, was developed for coupled SAM/SAS transient simulation. It inherits methods from the regular MOOSE Transient Executioner, but adds additional processes for communicating with the SAS code, as depicted in Figure 9. At each time-step, SAM will read in the SAS simulation results (from the previous time step) and complete its own inner iterations for the time-step. It will also check if the simulation time is synchronized in the two codes. When the SAM time step is converged, SAM will send the results at the coupling interfaces (inlet and outlet plenum) to SAS. This is the same process as depicted in Figure 3.

```

STEP 0.0000000E+00 2.5000000E-01
NSEG 1
ISEG 1 1 2
NCHN 5
ICHN 1 1
DATA
 5.02738439E+02 5.02738439E+02
 6.28150000E+02 7.92070772E+02
-8.98160471E+02 -8.98160471E+02
 3.76658339E-02 3.76658339E-02
-3.76658339E-02 -3.76658339E-02
-5.09810775E-02 -5.09810775E-02
 0.00000000E+00 0.00000000E+00
 0.00000000E+00 0.00000000E+00
ICHN 2 1
DATA
 1.29659670E+02 1.29659670E+02
 6.28150000E+02 7.77447007E+02
-2.34923308E+02 -2.34923308E+02
 9.82586971E-03 9.82586971E-03
-9.82586971E-03 -9.82586971E-03
-1.99906354E-01 -1.99906354E-01
 0.00000000E+00 0.00000000E+00
 0.00000000E+00 0.00000000E+00
ICHN 3 1
DATA
 5.74500990E+02 5.74500990E+02
 6.28150000E+02 7.75603758E+02
-1.17500736E+03 -1.17500736E+03
 4.91293485E-02 4.91293485E-02
-4.91293485E-02 -4.91293485E-02
-5.09113676E-02 -5.09113676E-02
 0.00000000E+00 0.00000000E+00
 0.00000000E+00 0.00000000E+00
ICHN 4 1
DATA
 3.34098683E+01 3.34098683E+01
 6.28150000E+02 7.96439451E+02
-1.22363928E+03 -1.22363928E+03
 5.13559913E-02 5.13559913E-02
-5.13559913E-02 -5.13559913E-02
-1.57402335E+01 -1.57402335E+01
 0.00000000E+00 0.00000000E+00
 0.00000000E+00 0.00000000E+00
ICHN 5 1
DATA
 2.40600920E+01 2.40600920E+01
 6.28150000E+02 8.11907475E+02
-3.89099428E+01 -3.89099428E+01
 1.63764495E-03 1.63764495E-03
-1.63764495E-03 -1.63764495E-03
-9.68009690E-01 -9.68009690E-01
 0.00000000E+00 0.00000000E+00
 0.00000000E+00 0.00000000E+00
NPLN 2
IPLN 1
DATA
-6.00000000E-01 5.48818671E+05 6.28150000E+02 0.00000000E+00
IPLN 2
DATA
 2.30000000E+00 1.62850000E+05 7.83578000E+02 0.00000000E+00
DONE

```

Figure 6: Example of SASToSAM.dat file for SAS/SAM Coupling

```

STEP    999.75    1000
NPLN    2
IPLN    1
DATA
-0.6    194369.17  673.62795  2.5896327
IPLN    2
DATA
 2.3    170465.05  817.25098  2.5916317
    
```

Figure 7: Example of SAMtoSAS.dat file for SAS/SAM Coupling

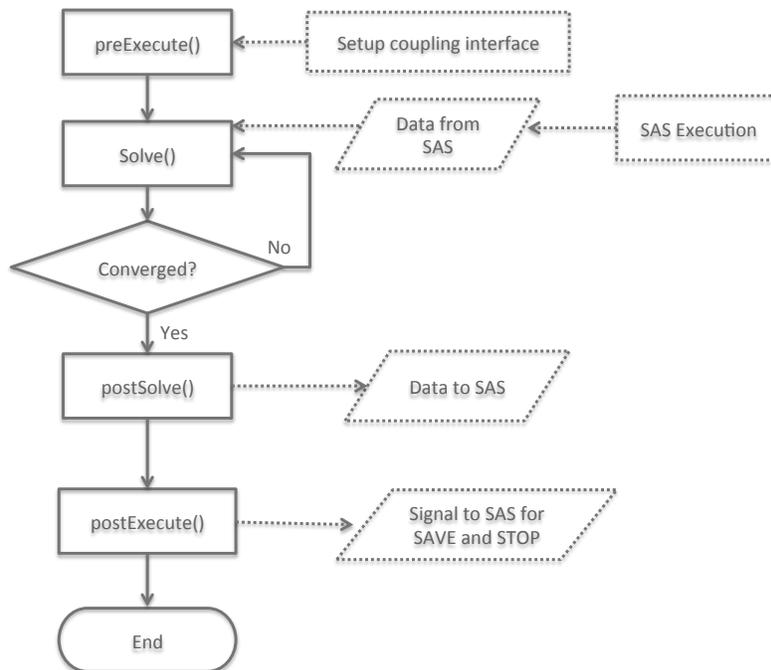


Figure 8: Execution Process Flow Chart of CoupledSASSteady Executioner

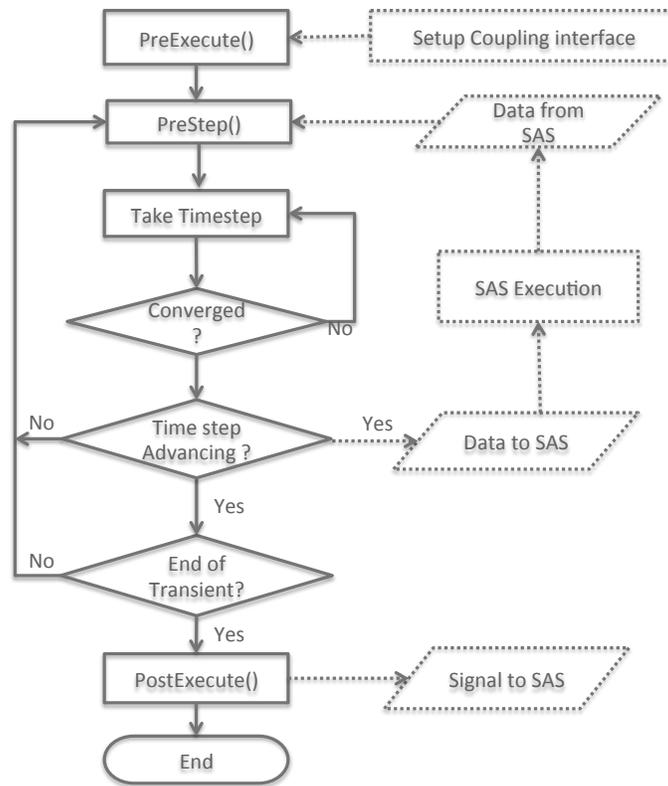


Figure 9: Execution Process Flow Chart of CoupledSASTransient Executioner

## 4 Coupling Results

To test the coupling interface, an existing SAS4A/SASSYS-1 model of the Advanced Burner Test Reactor (ABTR) conceptual design was used. Details of this design are available in Reference 3. In the following sections, a brief summary of the ABTR reference model is provided, including the primary and intermediate system layout. The SAM model is then described. It is this model that replaces the PRIMAR-4 model from the original reference model. Finally, results for an unprotected loss of flow (ULOF) accident sequence are presented. The results show that key features of the ULOF transient are captured by the coupled code, but that some improvements are needed. In particular, control rod driveline expansion and certain options for grid plate expansion are not yet supported. These differences were expected for the initial coupling implementation.

### 4.1 ABTR Reference Model

The ABTR design concept is a 250 MWt pool-type sodium fast reactor with metal alloy fuel. The core consists of 54 driver assemblies, 78 reflector assemblies, 48 shield assemblies, and ten control-rod assemblies. Nine test assembly locations are reserved for material and fuel testing. The core configuration is shown in Figure 10.

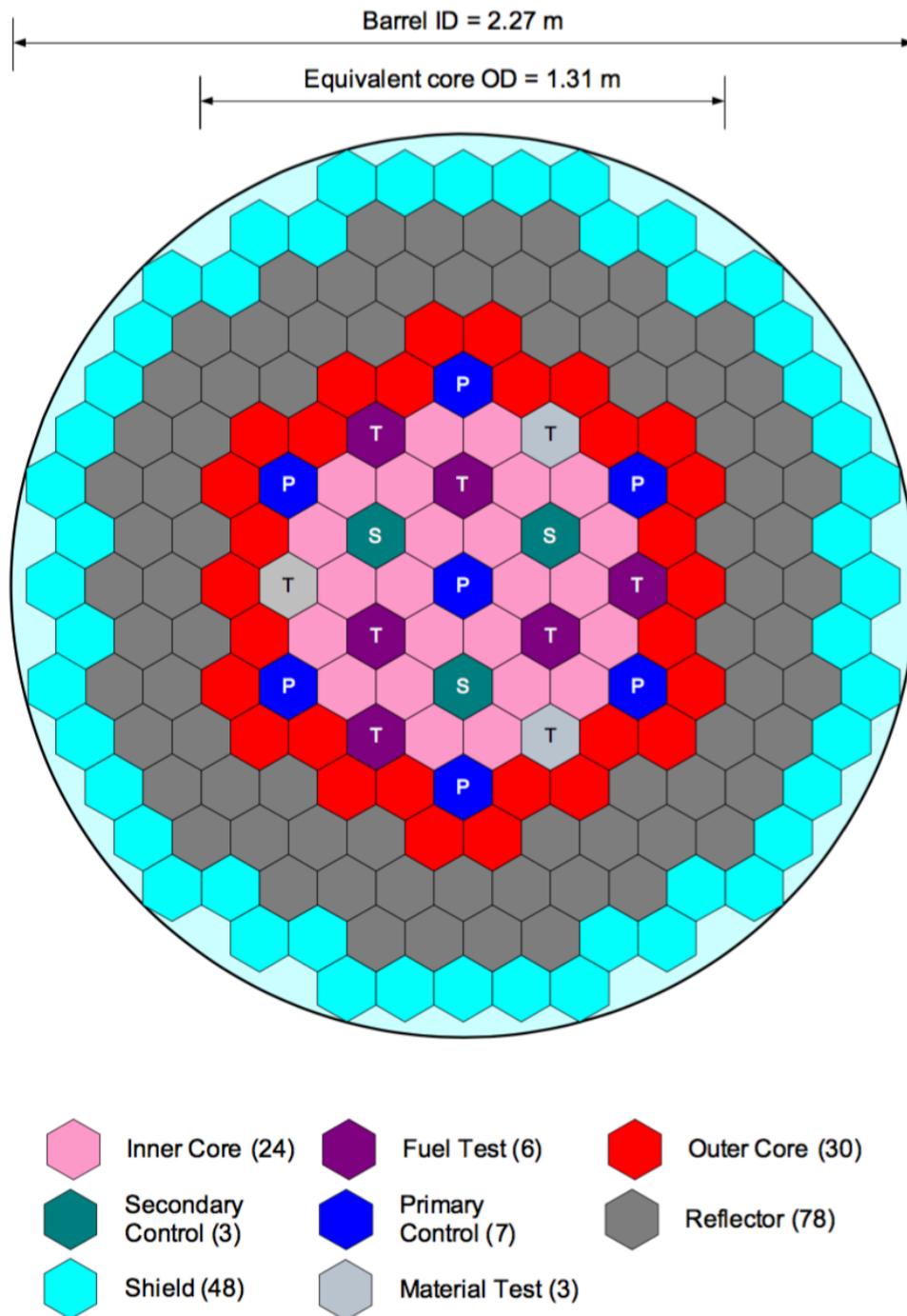


Figure 10: Reference ABTR Core Configuration

Five core channels are used to represent the core assemblies in the reference SAS4A/SASSYS-1 model. Three of the channels are defined based on assembly type and enrichment zone. A fourth channel represents reflector assemblies, and the fifth channel represents a single, inner-core peak assembly. Channel assignments are shown in Figure 11.

The primary vessel configuration is shown in Figure 12 and the PRIMAR-4 model for the primary, intermediate, and decay heat coolant loops is illustrated in Figure 13. Large sodium volumes in the coolant loops are modeled as *compressible volumes* (CVs) in PRIMAR-4. For example, CV1 is the inlet plenum, CV2 is the outlet plenum (hot pool) and CV3 is the cold pool. Compressible volumes are connected by *liquid segments*. In this model, segment one (S1) is the segment representing the core, and it connects the inlet plenum to the outlet plenum. Segment four (S4) includes the primary pump and piping that connects the cold pool to the inlet plenum.

The core segment (S1) is unique because PRIMAR-4 uses the surrogate parameters and Eq. (1) to estimate core channel flows during the primary coolant loop calculations. Once the inlet and outlet plenum conditions are known, the actual core channel flows are determined by the detailed transient core heat transfer and pre-voiding and boiling hydraulics solvers.

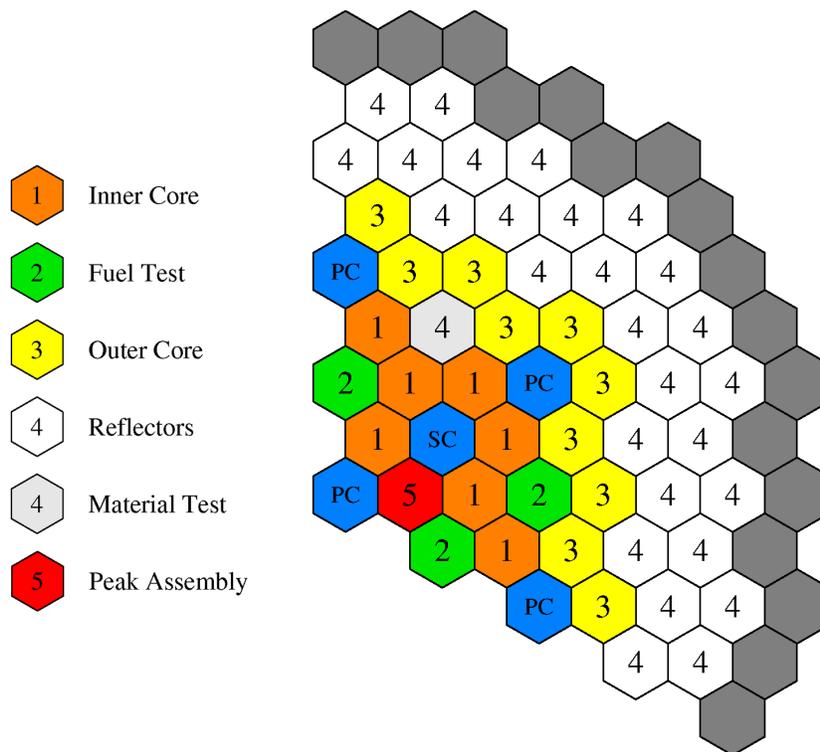


Figure 11: Channel Assignments for the SAS4A/SASSYS-1 Core Model.

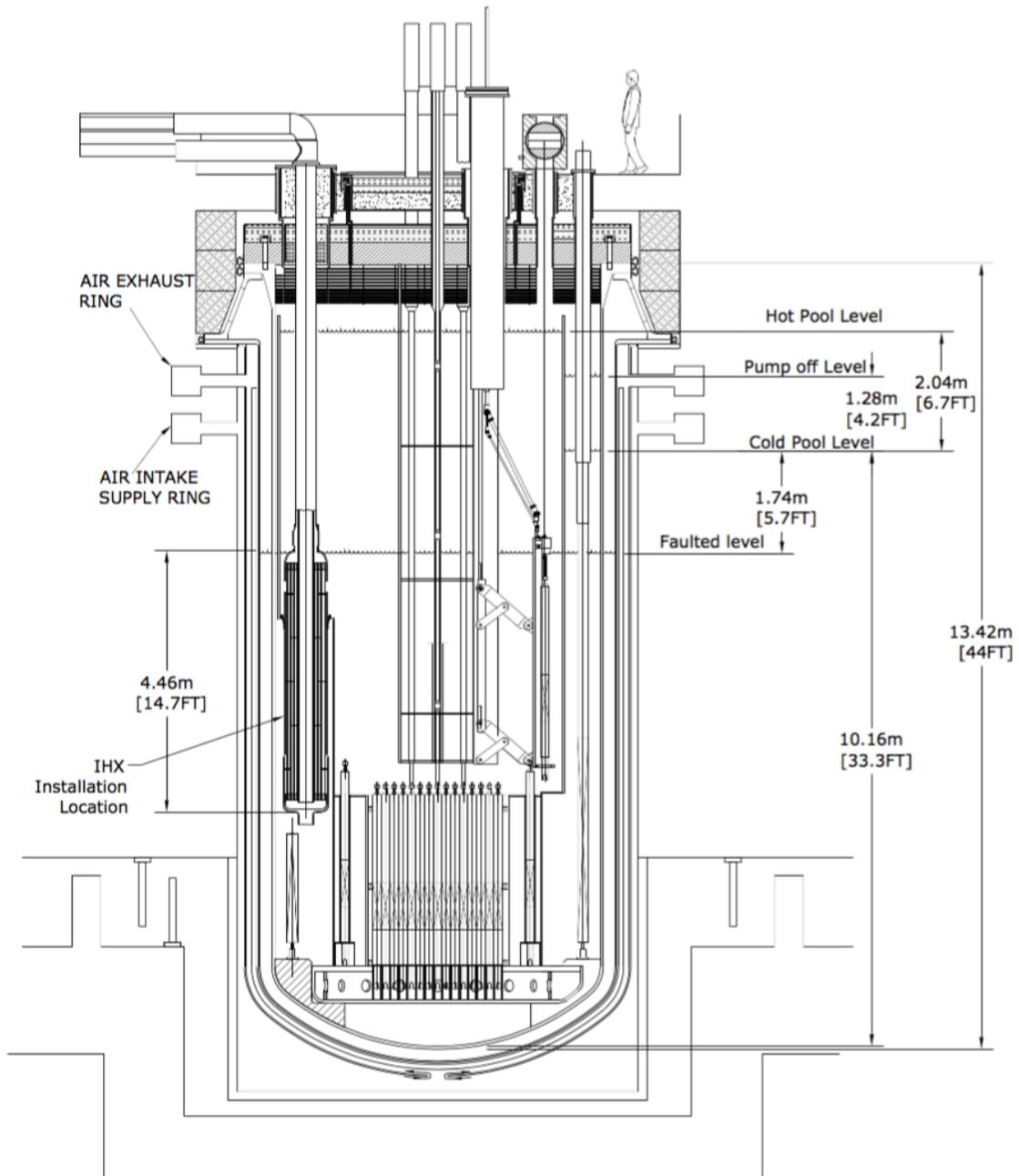


Figure 12: Elevation view of the ABTR Primary System

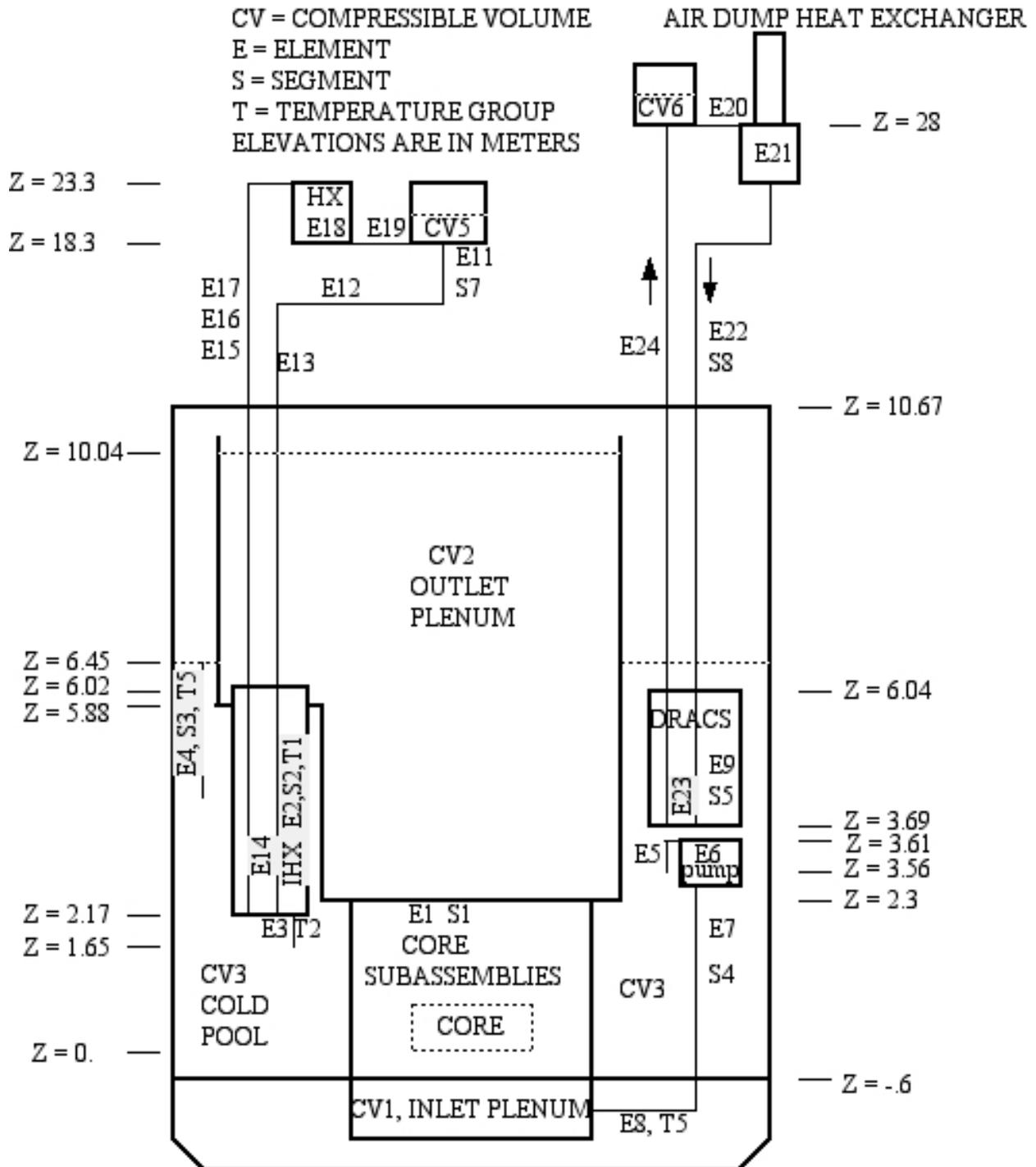


Figure 13: PRIMAR-4 Representation of the Primary, Intermediate, and Decay Heat Coolant Systems.

## 4.2 SAM System Model

In a coupled SAS/SAM simulation, the core segment is still unique. In this case, however, SAM uses the surrogate parameters and Eq. (1) to estimate core channel flows during the primary coolant loop calculations. Once the inlet and outlet plenum conditions are known, the actual core channel flows are determined by the detailed transient core heat transfer and pre-voiding and boiling hydraulics solvers of SAS4A/SASSYS-1.

The changes to the reference SAS4A/SASSYS-1 input are straightforward. All PRIMAR-4 input is deleted, and a SAMSYS input block with the following input is added:

```
SAMSYS "ABTR System Model"

    path = "<executable path>"

    PLENUM "Inlet Plenum"
        Zref = -0.60
        Tin = 628.15
    END

    PLENUM "Outlet Plenum"
        Zref = 2.30
        Pout = 1.6285E+05
    END

    SEGMENT "ABTR Core"
        id = 1
        inlet = "Inlet Plenum"
        outlet = "Outlet Plenum"
    END

END
```

The reference elevations and steady-state inlet temperature and outlet pressure are the same as the values used in the original model.

Figure 14 shows the schematics of the SAM ABTR model for the coupled SAS/SAM simulation. The primary coolant system consists of the inlet piping (pump outlet and pump discharge), the lower plenum, the reactor core model, the outlet plenum, and the intermediate heat exchanger. Five core channels were modeled in SAS to describe the reactor core. *CoupledLiquidVolume* and *CoupledVolumeBranch* components are used to represent the core outlet plenum (hot pool) and the inlet plenum. Both are connected to imaginary mass source and sinks representing the flow from and to the SAS core channels. The intermediate loop, the secondary loop, and the DRACS loop are modeled with great simplicities. Single-phase counter current heat exchanger models are implemented to mimic the function of the intermediate loop heat exchanger (IHX), DRACS heat exchanger (DHX), and secondary loop heat exchanger (SHX) to transfer heat among the primary, intermediate, secondary, and DRACS loops.

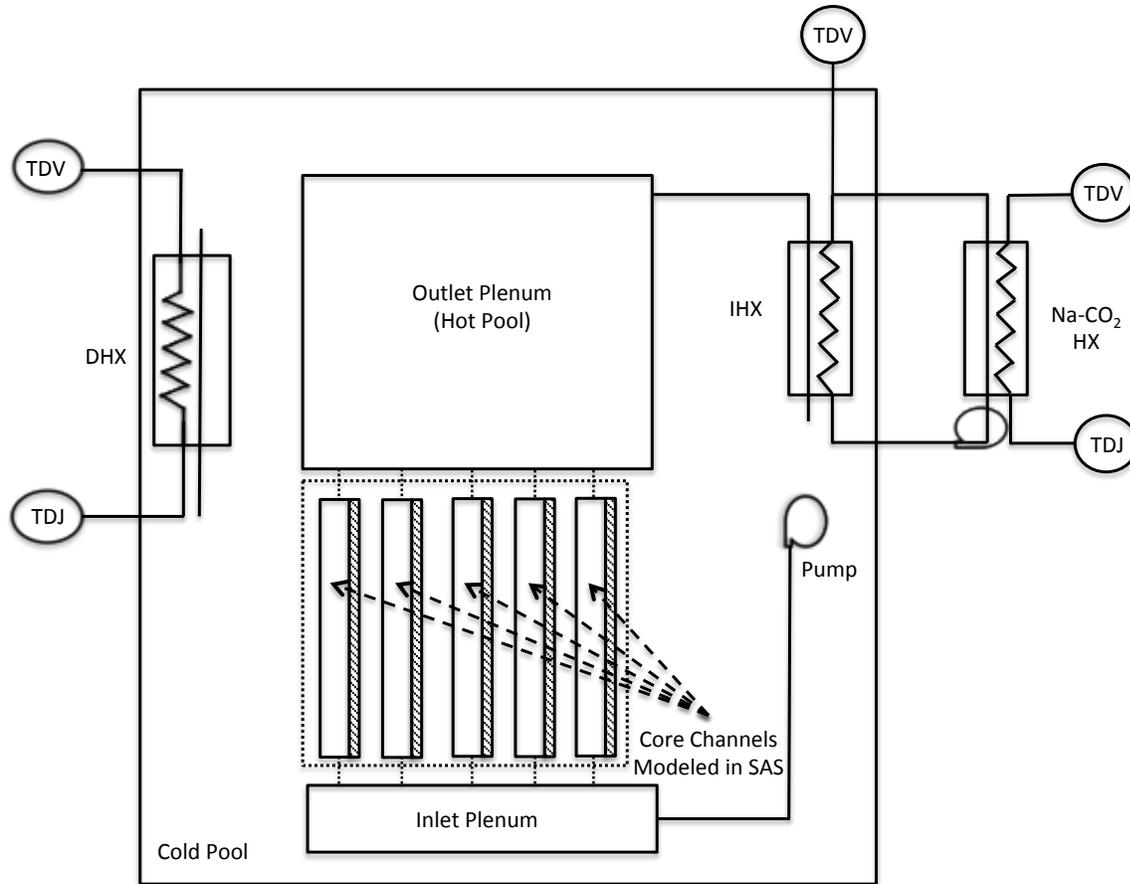
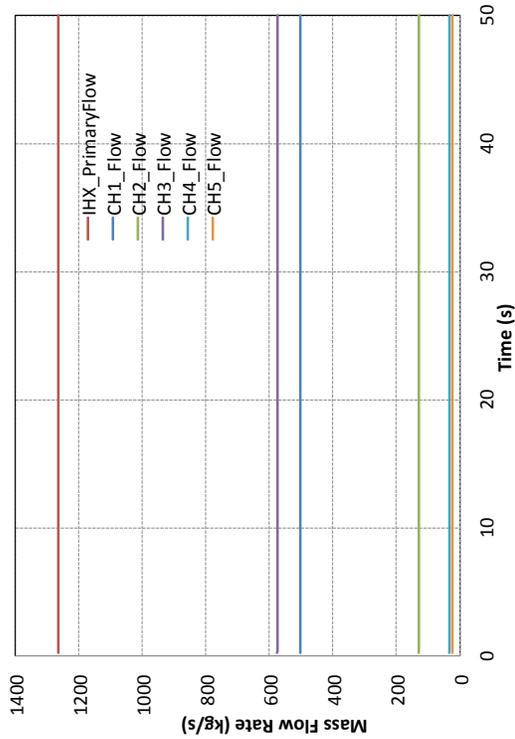


Figure 14: Schematics of the ABTR model for coupled SAS/SAM simulations

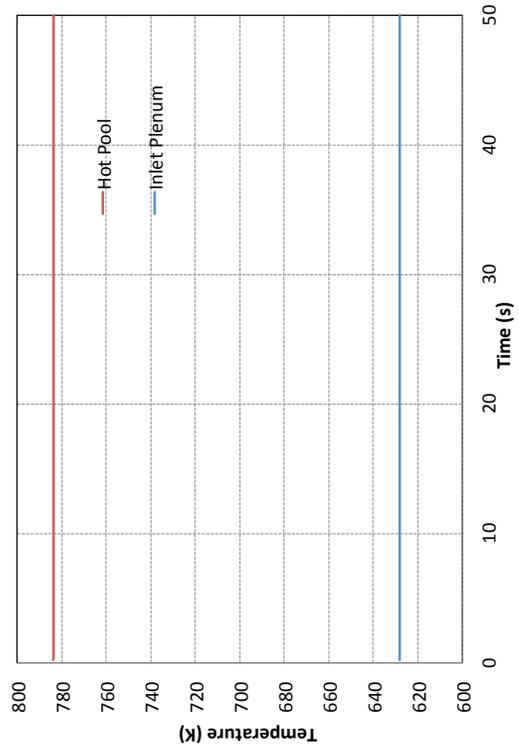
### 4.3 Verification of Coupling Interface

Steady state simulation of the ABTR model was first performed to assure the correct initialization of the operating conditions prior to transient simulation. The primary pump heads at normal conditions are adjusted in the SAM model to match the pressure conditions in the core inlet and outlet plena from SAS4A/SASSYS-1 steady state results. Major ABTR operation parameters were confirmed in the coupled SAS/SAM model.

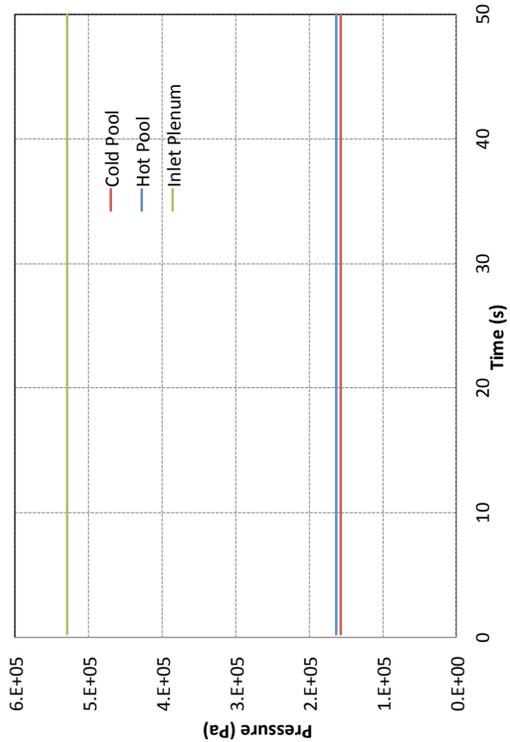
Additionally, a null transient simulation was performed to further verify the functionality of the SAS/SAM coupling interface. The null transient responses of major operation parameters are shown in Figure 15, which shows that the coupled SAS/SAM model holds steady state during the null transient. Identical core channel flow rates are obtained from the SAM surrogate model and SAS core channel calculations, as shown in Figure 15d.



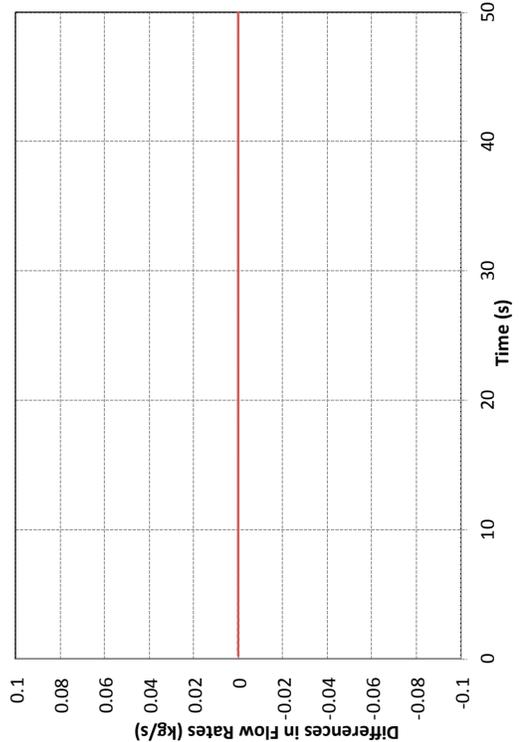
(a) Mass flow rates



(b) Pool temperatures



(c) Pool pressures



(d) Difference in core channel flow rates between SAM surrogate model and SAS calculations

Figure 15: Coupled SAS/SAM simulation results of ABTR null transient

#### **4.4 Unprotected Loss of Flow Transient Sequence**

The basic accident sequence analyzed is the loss of normal power to the reactor and intermediate coolant pumps with failure of the emergency power supplies. The result is a loss of forced flow in the primary and intermediate coolant circuits. In addition, it is assumed that the flow rate in the power cycle loop is reduced to zero immediately following the accident so that the only heat removal path is through the emergency direct reactor auxiliary cooling system (DRACS). It is also assumed that the reactor safety system is not activated, i.e. control rods are not inserted to reduce reactor power immediately. This sequence is an unprotected loss-of-flow (ULOF) accident.

The natural circulation DRACS is modeled as a simple heat exchanger in this demonstration problem. Inlet flow rate, inlet temperature, and outlet pressure are fixed on the secondary side as boundary conditions. The DRACS is designed to remove 0.5% of full power (1250 kW) at normal operating temperatures assuming failure of one DRACS unit. Initial conditions for the accident sequence are normal operations at full power and flow. With the loss of pumping power, flow in the primary circuit coasts down according to the spinning inertia of the pumps and motors. Following flow coast down, natural circulation flow is established. With the loss of power, forced flow in the intermediate coolant system is also lost, and coasts down according to the characteristics of the intermediate pumps, which is assumed to be similar to the primary pumps.

In the ULOF sequence, the reactor safety system fails to scram the reactor, thus the reactor remains at full power initially. Immediately following the accident, reactor temperatures increase as the coolant flow rate decreases, and various reactivity feedback mechanisms reduce the reactor power. As coolant flow continues to decrease, a second temperature peak occurs after the full stop of primary pumps and before full natural circulation is established. Once natural circulation is established in the primary loop, the temperatures continue increasing slowly because the DRACS has insufficient heat removal capacity to overcome both the early decay heat production and the stored heat in the primary coolant system. Eventually, the decay heat falls below the DRACS capacity, and the system temperatures decline.

#### **4.5 Transient Simulation Results of Unprotected Loss of Flow**

Results from analysis of the early part of the ULOF transient, during the pump coast down and transition to natural circulation, are shown in Figure 16–Figure 21. The normalized core power and flow rate are shown in Figure 16. This transient is initiated by a complete loss of forced coolant flow in the primary and intermediate loops. Both the primary and intermediate pumps are designed with sufficient flow inertia and do not cease operation until about 420 seconds after the start of the transient, followed by a transition to natural circulation. The power-to-flow imbalance results in significant transient reactor heating during the first 200 seconds.

The temperatures at the core inlet plenum, outlet plenum, and the cold pool are shown in Figure 17. Shortly after the transient, the only heat removal is through the DRACS. The rapid core flow reduction due to the pump trip leads to a rapid increase of the coolant and fuel rod temperatures in the core and then the outlet plenum. The drop in

reactor power due to inherent reactivity feedback stabilizes the hot pool temperature. Cold pool temperatures continue rising during the whole transient because the hot coolant continues entering the cold pool from the IHX outlet. This will continue until the DRACS heat removal capability becomes equal to the decay heat production, which will occur at about 5 hours. After that, the cold pool temperature will decrease as the whole system cools. The inlet plenum temperature response follows the similar trend of the cold pool temperature response, but with some delay.

Peak fuel, peak clad, and coolant outlet temperatures for channel 5 (inner core peak fuel assembly) are shown in Figure 18. The peak fuel, cladding, and coolant temperatures remain well below the coolant saturation (boiling) temperature, with a minimum margin to coolant boiling of nearly 300°C. This suggests that the core would survive an unprotected loss-of-flow accident without pin failures or fuel damage. Figure 19 shows the mass flow rate in all core channels during the transient. Similar behaviors are found, and the establishments of the natural circulation flows occur at the same time for all channels.

The total core flow differences between the results from the SAM surrogate model and SAS4A/SASSYS-1 core channel model are shown in Figure 20. Differences between the two models are very small throughout the transient and are less than 0.1 kg/s most of the time. This demonstrates that the surrogate model is able to accurately estimate the core channel flow rate, which is crucial for the convergence speed and the consistency in the coupled SAS/SAM simulation using a sequential two-way coupling scheme (as discussed in Section 2).

The reactivity feedbacks during the transient are shown in Figure 21. Axial and Radial expansion are the main contributors to the initial negative reactivity feedback, which causes power and fuel temperatures to decline. Reduced fuel temperatures provide a positive Doppler feedback, although the magnitude is modest due to the high thermal conductivity and relatively low operating temperatures of metallic fuel. Note that the reactivity feedback due to the control-rod driveline expansion are always zero in the coupled SAS/SAM simulation as the control rod driveline expansion is not supported the current coupling. Negative reactivity due to control-rod driveline expansion would be expected as the control-rod drivelines are heated by higher temperature coolant shortly after the onset of the transient.

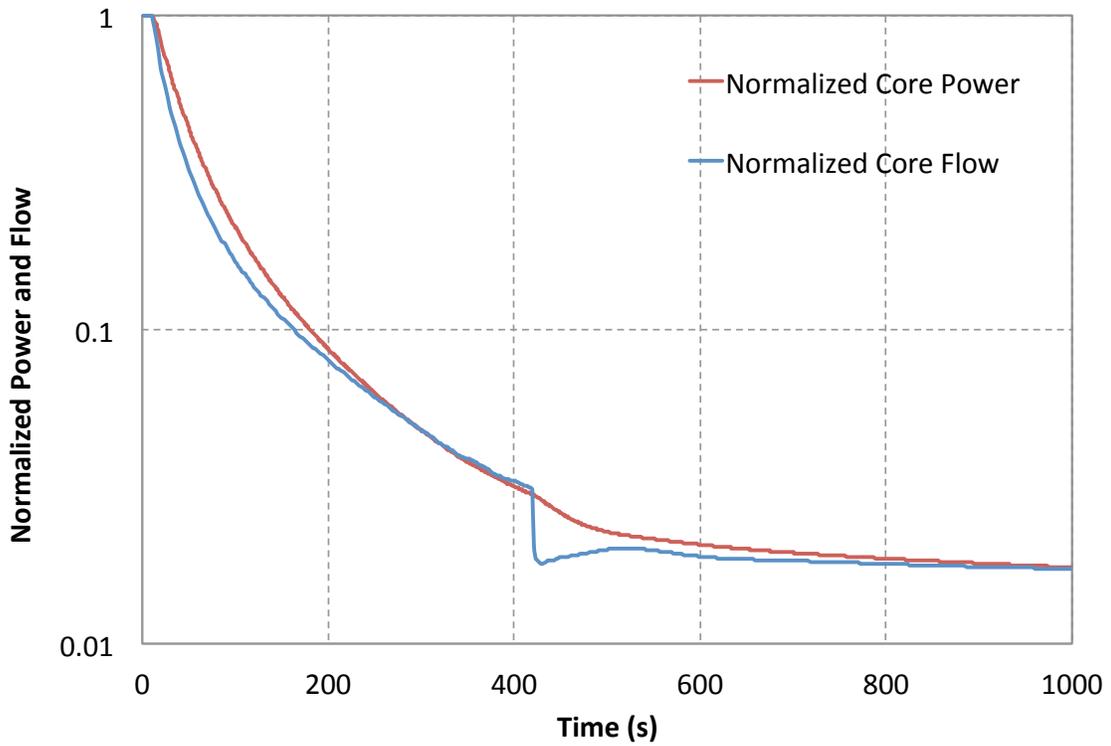


Figure 16: Normalized power and core flow during the ABTR ULOF transient

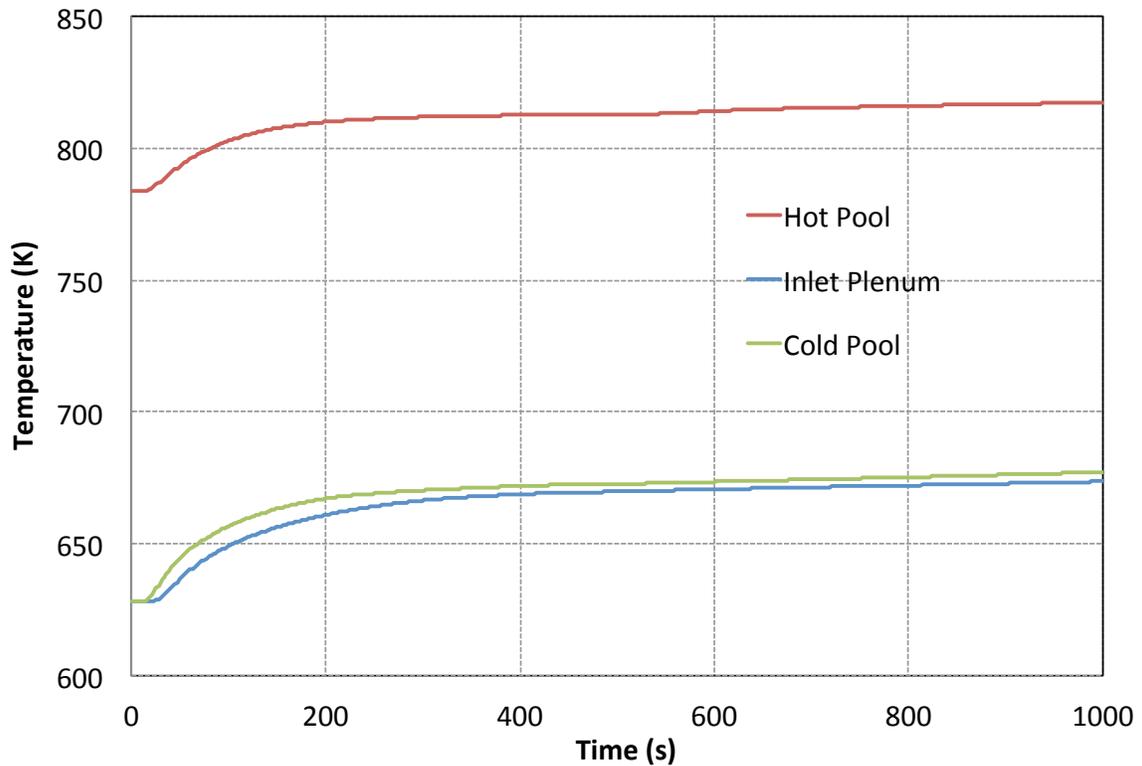


Figure 17: Pool temperatures during the transient

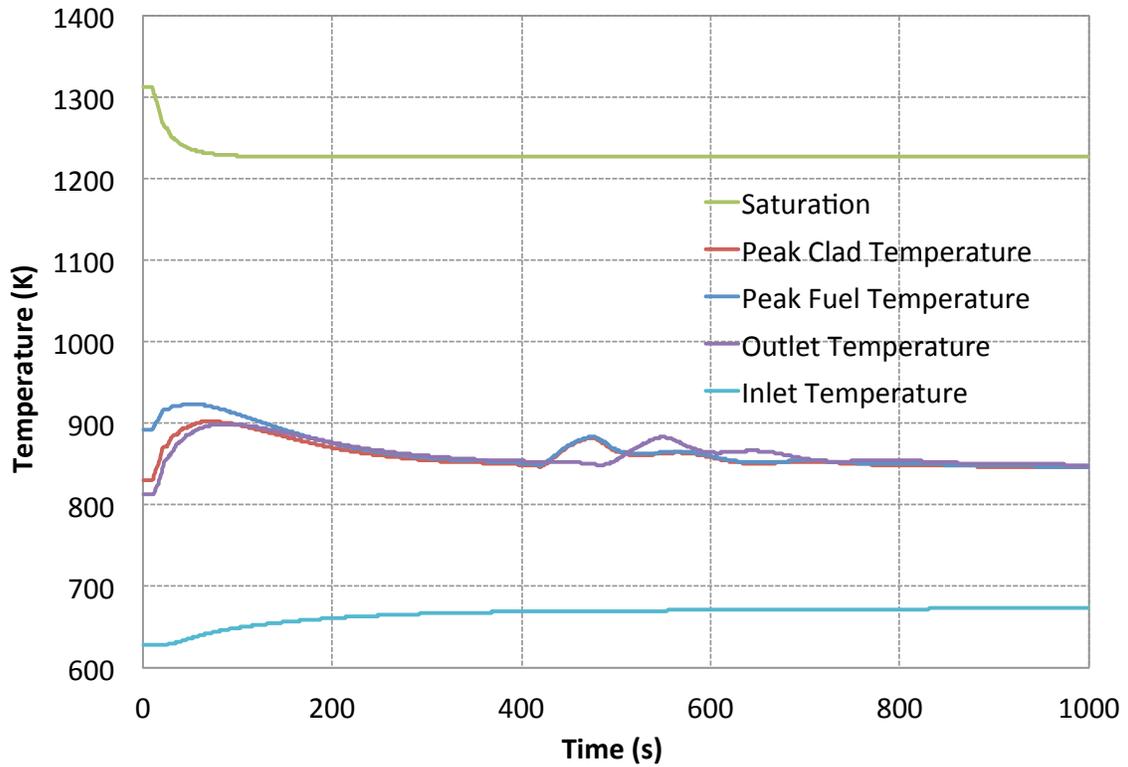


Figure 18: Transient temperatures for Channel 5

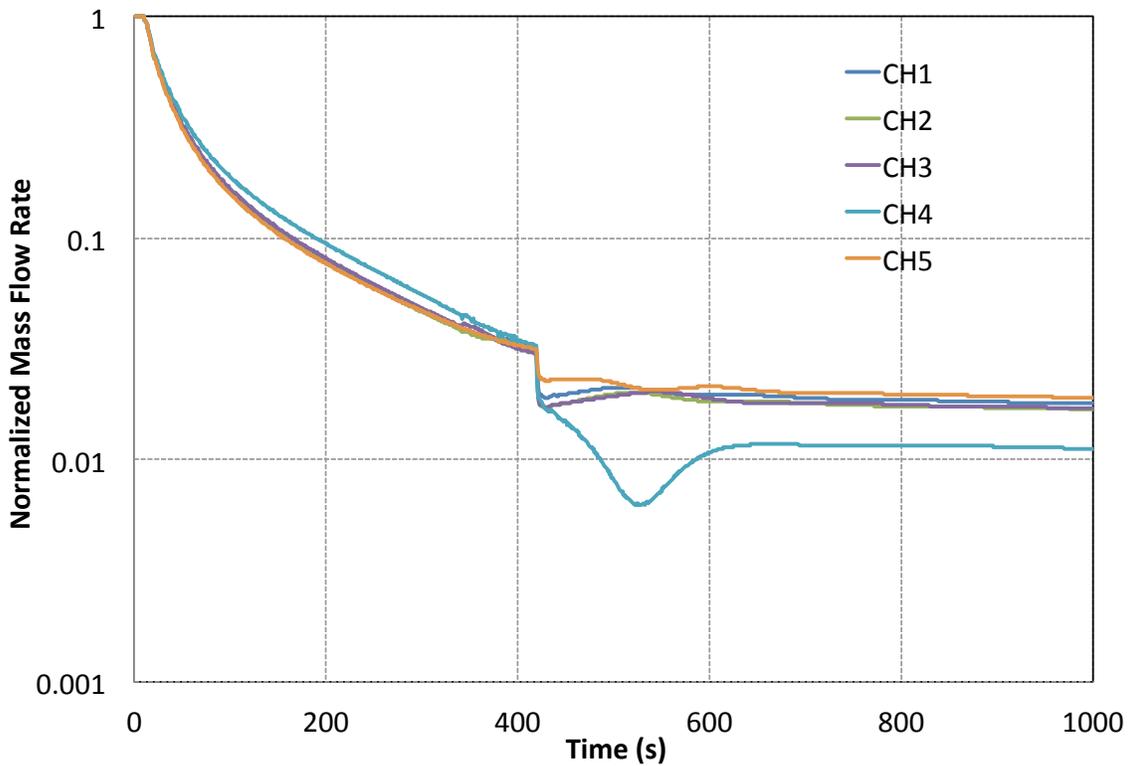


Figure 19: Core channel flow velocities during the transient

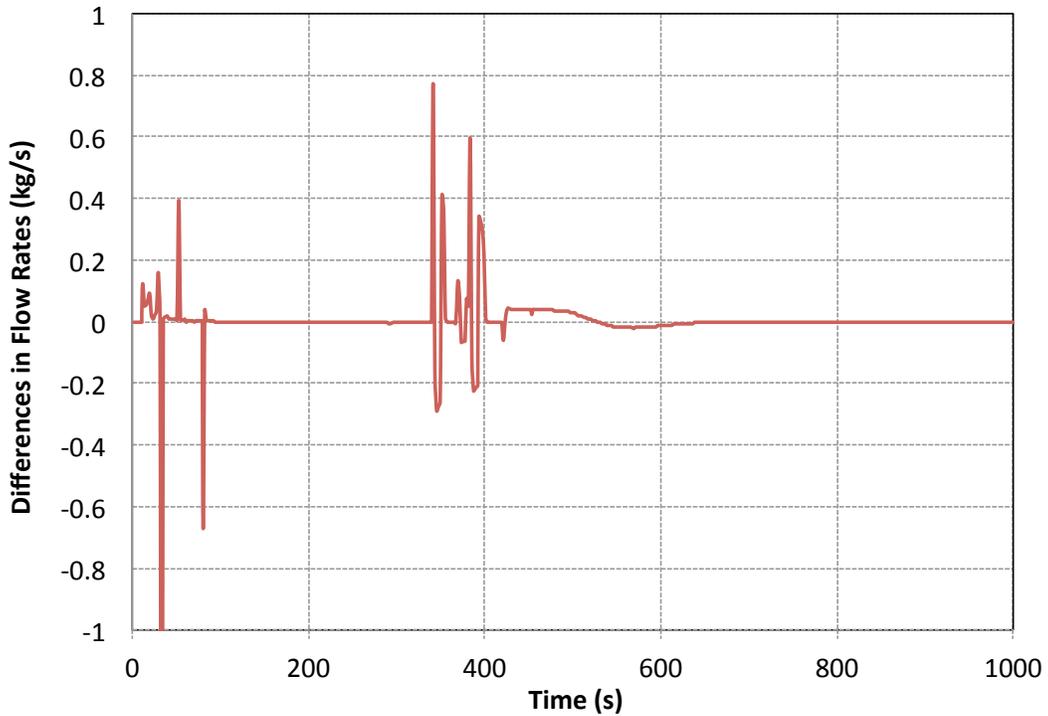


Figure 20: Total core flow differences between SAM surrogate model and SAS4A/SASSYS-1 core channel simulation results

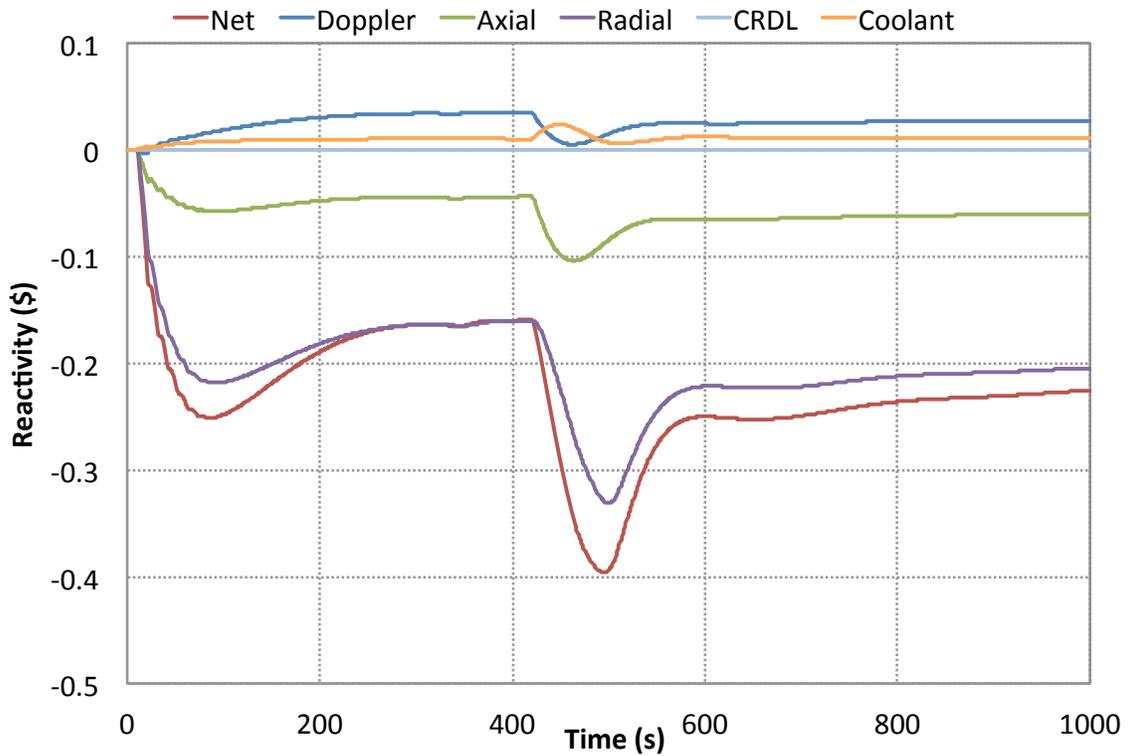


Figure 21: Transient reactivity feedback

The stand-alone SAS4A/SASSYS-1 simulation results of the ABTR ULOF transient are also compared with the coupled SAS/SAM results. For consistency with the SAM primary loop modeling, the perfect mixing pool models are used in the stand-alone SAS4A/SASSYS-1 simulation.

Normalized core power and flow rate are compared in Figure 22. Very similar core powers and flow rates were predicted throughout the transient in the two simulations. Very small differences in reactor power were found in the initial 50s due to differences in reactivity feedback due to control-rod driveline expansion, and between 390 and 410s of the transient due to differences in core flow rates and temperatures. The core flow rates were almost identical for the first 150 seconds, but deviate slightly from each other later due to the differences in pump and loop friction modeling. The larger differences in flow rates between 390 and 410s are attributed to differences in modeling the pump resistance after the full stop of the pump impeller.

Peak fuel, peak clad, and coolant outlet temperatures for channel 5 in the stand-alone SAS4A/SASSYS-1 simulation are shown in Figure 23, and the reactivity feedbacks are shown in Figure 24. Note that the reactivity feedbacks due to control-rod driveline expansion were included in the stand-alone SAS simulation. Comparing these results to the coupled SAS/SAM simulation (Figure 18 and Figure 21), the transient response (both trends and magnitudes) are very similar between the two simulations.

This demonstration simulation focuses on the early stage of the ULOF transient. It shows that major physics phenomena in the primary coolant loop can be captured by the coupled SAS4A/SASSYS-1 and SAM simulations. Some differences were found in the coupled SAS/SAM simulation results. These can be reduced by addressing the known modeling differences between the two simulations.

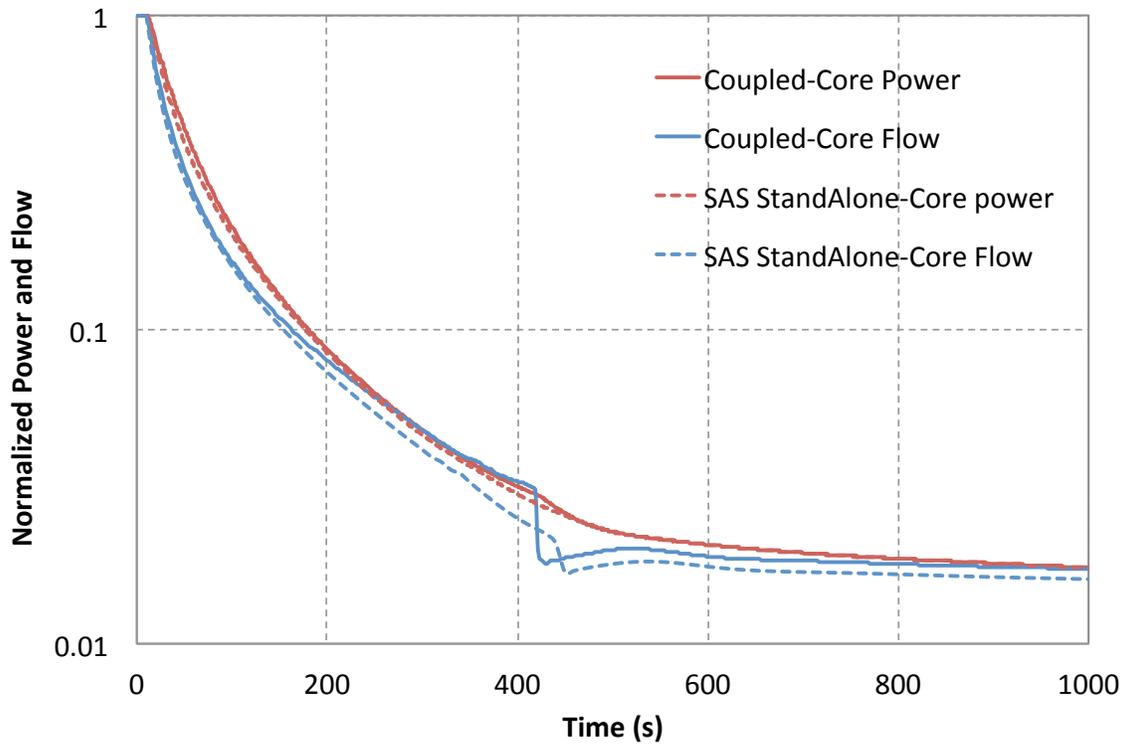


Figure 22: Normalized power and core flow, comparison between stand-alone SAS and coupled SAS/SAM simulation results

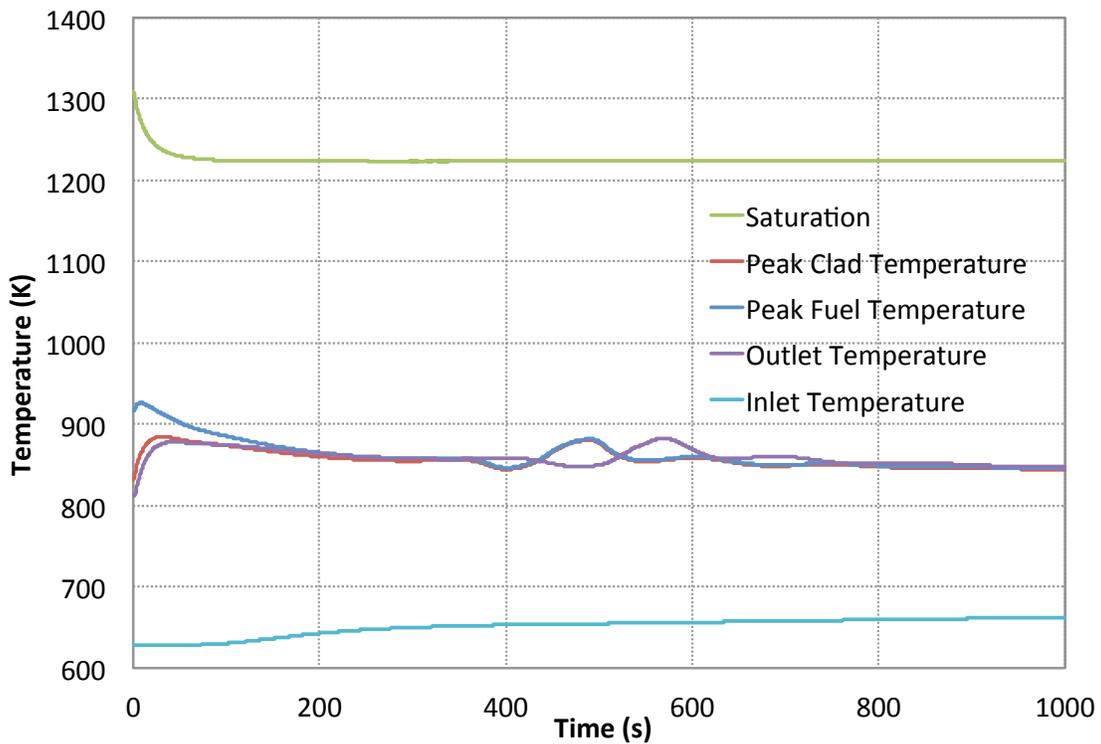


Figure 23: Transient temperatures for Channel 5, stand-alone SAS simulation

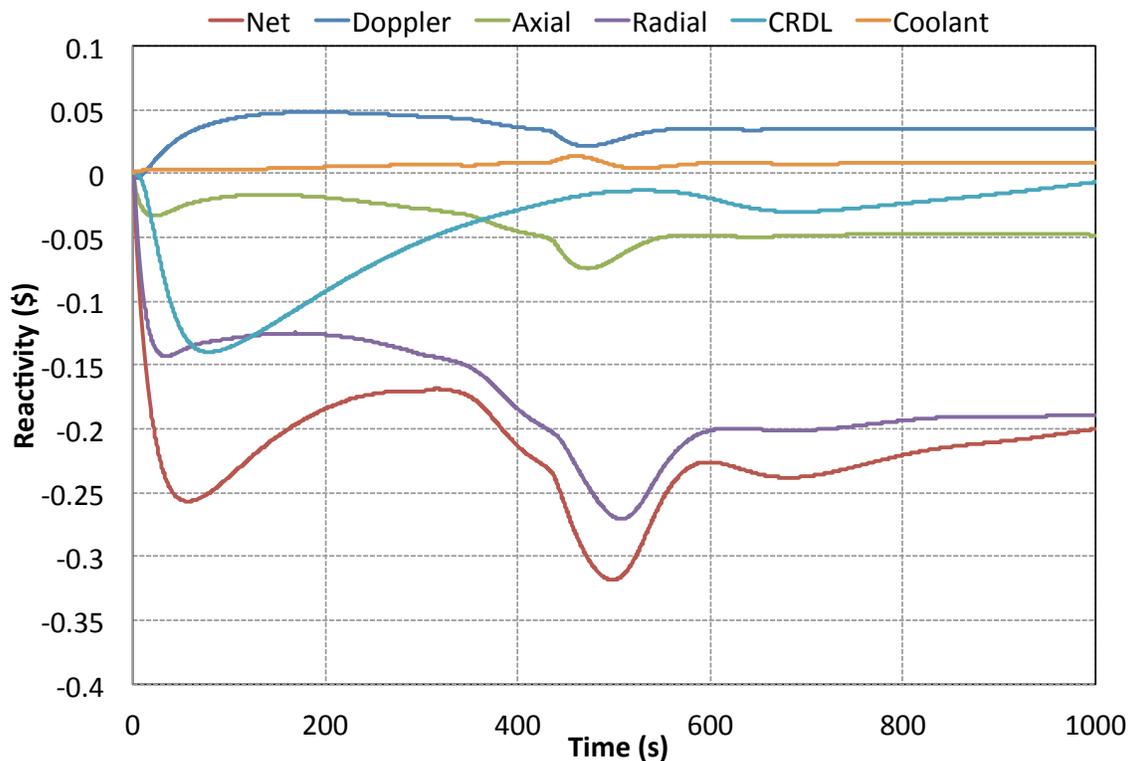


Figure 24: Transient reactivity feedback, stand-alone SAS simulation

## 5 Path Forward

SAS4A/SASSYS-1 with PRIMAR-4 will continue to be the main workhorse for SFR safety analysis in the near term. And the severe accident modeling capabilities in SAS4A/SASSYS-1 (sodium boiling, fuel melting and relocation) will continue to play a vital role for a long time. Therefore, the SAS4A/SASSYS-1 modernization effort should remain a high priority task under the ART program to ensure continued participation in domestic and international SFR safety collaborations and design optimizations. On the other hand, SAM is an advanced system analysis tool, with improved numerical solution schemes, data management, code flexibility, and accuracy. SAM is still in early stages of development and will require continued support from NEAMS to fulfill its potential and to mature into a production tool for advanced reactor safety analysis. The effort to couple SAS4A/SASSYS-1 and SAM is the first step on the integration of these modeling capabilities. Continued development on SAS/SAM coupling will be needed to include the missing reactivity feedbacks (control rod drive line expansion and vessel elongation), the missing component models, and to improve the efficiency of the coupling interface. Over time, the advanced modeling and simulation capabilities provided by NEAMS are expected to play more and more significant roles in advanced reactor safety analyses.

## 6 References

1. T. H. Fanning, ed., *The SAS4A/SASSYS-1 Safety Analysis Code System*, ANL/NE-12/4, Nuclear Engineering Division, Argonne National Laboratory, January 31, 2012.
2. R. Hu, T.H. Fanning, T. Sumner, Y. Yu, "Status Report on NEAMS System Analysis Module Development," ANL/NE-15/41, Argonne National Laboratory, December 2015.
3. Y. Chang, P. Finck, and C. Grandy, "Advanced Burner Test Reactor Preconceptual Design Report," ANL-ABR-1, Argonne National Laboratory, Sept. 5, 2006.



## **Nuclear Engineering Division**

Argonne National Laboratory  
9700 South Cass Avenue, Bldg. 208  
Argonne, IL 60439-4842

[www.anl.gov](http://www.anl.gov)



Argonne National Laboratory is a U.S. Department of Energy  
laboratory managed by UChicago Argonne, LLC