Integrated Simulation Capabilities for Analysis of Experiments in the Versatile Test Reactor

Nuclear Science and 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.

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
Phone: (800) 553-NTIS (6847) or (703) 605-6000
Fax: (703) 605-6900
Email: 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
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: 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.

Integrated Simulation Capabilities for Analysis of Experiments in the Versatile Test Reactor

prepared by

Acacia J. Brunett, Thanh Q. Hua, Guojun Hu, Dan O'Grady, Rui Hu, Thomas H. Fanning, and George Zhang

Nuclear Science and Engineering Division, Argonne National Laboratory

October 31, 2019

ABSTRACT

The DOE-initiated Versatile Test Reactor (VTR) program aims to establish a domestic fast-neutron irradiation testing capability that meets a variety of domestic and international nuclear energy needs. Currently, integrated tools capable of mechanistic modeling of VTR and a test vehicle do not exist. To address this modeling and analysis deficiency, Argonne's SAS4A/SYSSYS-1 safety analysis code has been coupled with SAM (System Analysis Module) to provide a novel modeling capability that supports VTR and other fast test facilities. This report documents the design, implementation, and testing of this integrated capability.

A coupling boundary has been identified at the test vehicle and primary coolant interface, where SAS4A/SASSYS-1 treats primary coolant thermal hydraulics outside the test vehicle, while SAM treats all thermal hydraulic behavior within the test vehicle, including the vehicle walls. Essential to this integrated tool is its newly developed capability to properly model the conjugate heat transfer process which ensures equality of temperatures and heat fluxes at the vehicle wall interface while ensuring energy conservation.

A range of testing has been completed to support demonstration of this interface. The testing scope includes steady-state verification using a series of increasingly complex analytical solutions and transient demonstration for a range of design basis accident scenarios using prototypic VTR and test vehicle (i.e. cartridge loop) configurations. Results of this testing confirm verification of the steady-state solutions and provide reasonable and expected transient behavior.

The coupling interface has been developed to be robust yet flexible. The implementation within SAS4A/SASSYS-1 supports coupling to any external software or module. The use of decomposed domains and the existing in-core thermal-hydraulic calculational framework within SAS4A/SASSYS-1 enable treatment of arbitrary test vehicle geometries with nonuniform meshing between SAS4A/SASSYS-1 and the coupled code. Modeling of multiple test locations is also supported. Furthermore, computational efficiency is enhanced by utilizing named pipes (or FIFOs), an interface for interprocess communication (IPC).

TABLE OF CONTENTS

Abstract	iii
Table of Contents	iv
List of Figures	v
List of Tables.....	vi
Acronyms.....	vii
1 Introduction.....	1
2 Background.....	2
2.1 Versatile Test Reactor Program.....	2
2.2 SAS4A/SASSYS-1	3
2.3 SAM.....	4
3 Features and Capabilities.....	6
4 Coupling Implementation.....	7
4.1 Coupling Interfaces.....	7
4.1.1 SAS4A/SASSYS-1 Interface.....	7
4.1.2 SAM Interface	8
4.2 Iteration and Convergence Schemes.....	8
4.2.1 Iteration and Data Transfer Schemes.....	8
4.2.2 Quasi-Newton Coupling Algorithm.....	9
4.2.3 Numerical Instability Prevention.....	11
5 Steady-State Verification.....	14
6 Demonstration for VTR Test Vehicle	19
6.1 System Code Models.....	19
6.1.1 SAS4A/SASSYS-1 Model (VTR).....	19
6.1.2 SAM Model (Cartridge Loop).....	20
6.2 Steady State Results.....	23
6.3 Transient Results.....	26
6.3.1 Unprotected Loss of Heat Sink.....	26
6.3.2 Unprotected Transient Overpower.....	27
6.3.3 Unprotected Station Blackout.....	29
7 Summary and Path Forward	31
8 Acknowledgements	32
References	33

LIST OF FIGURES

Figure 2.1: Cartridge Loop Conceptual Design [4].....	3
Figure 4.1: Definition of the Coupling Boundary Interface and Boundary Condition Options	8
Figure 4.2: Coupled and Internal Program Flow Diagram	9
Figure 4.3: Communicating Solution Convergence with the (a) Boundary Conditions (left),or (b) Independently (right)	11
Figure 5.1: Comparison of SAS-SAM Coupled Results for Coolant Temperatures with Analytical Solution.....	15
Figure 5.2: Comparison of SAS-SAM Coupled Results for Wall Heat Flux with Analytical Solution.....	16
Figure 5.3: Coolant Heat Transfer Coefficients Calculated in SAS4A/SASSYS-1.....	17
Figure 5.4: Comparison of SAS-SAM Coupled Results for ΔT_w with Analytical Solution	18
Figure 6.1: Schematic of VTR Core (left) and a Test Assembly with a Test Cartridge Loop (right).....	20
Figure 6.2: Representation of the Two Structure Nodes NSI and NSO with an Argon Buffer in the SAS4A/SASSYS-1 Model.....	20
Figure 6.3: Two-dimensional Representation of the SAM Cartridge Model	21
Figure 6.4: Power and Flow Distributions in the SAS4A/SASSYS-1 Channels	24
Figure 6.5: Ratio of Power to Flow in the SAS4A/SASSYS-1 Channels	24
Figure 6.6: Steady State Coolant Temperatures in the Fuel and Test Channels	25
Figure 6.7: Test Vehicle Coolant Velocity (left) and Temperature Distribution (right) ...	26
Figure 6.8: ULOHS Power and Flow (left), and Reactivity Feedbacks (right)	27
Figure 6.9: ULOHS VTR Coolant Temperatures (left) and Test Vehicle Temperatures (right).....	27
Figure 6.10: UTOP Power and Flow (left), and Reactivity Feedbacks (right)	28
Figure 6.11: UTOP VTR Coolant Temperatures (left) and Test Vehicle Temperatures (right).....	29
Figure 6.12: USBO Power and Flow (left), and Reactivity Feedbacks (right)	29
Figure 6.13: USBO VTR Coolant Temperatures (left) and Test Vehicle Temperatures (right).....	30

LIST OF TABLES

Table 6.1 Dimensions of the Cartridge Loop Fuel Assembly.....22

Table 6.2 Dimensions of the Cartridge Loop.....23

ACRONYMS

CRBR	Clinch River Breeder Reactor
CRDL	Control Rod Driveline
FFTF	Fast Flux Test Facility
FHR	Fluoride-cooled High-temperature Reactor
IFR	Integral Fast Reactor
IPC	Interprocess Communication
KAERI	Korean Atomic Energy Research Institute
LDRD	Laboratory Directed Research and Development
LFR	Lead-cooled Fast Reactor
LOF	Loss of Flow
M&S	Modeling and Simulation
MSR	Molten Salt Reactor
NEAC	Nuclear Energy Advisory Committee
PGSFR	Prototype Gen-IV Sodium-cooled Fast Reactor
SAM	System Analysis Module
SFR	Sodium-cooled Fast Reactor
TOP	Transient Overpower
ULOHS	Unprotected Loss of Heat Sink
USBO	Unprotected Station Blackout
UTOP	Unprotected Transient Overpower
VTR	Versatile Test Reactor

1 Introduction

The Versatile Test Reactor (VTR) program, a key DOE initiative, seeks to develop a domestic fast-neutron irradiation and testing capability that meets a variety of advanced nuclear energy needs. As there is currently significant diversity in the advanced reactor R&D technology scope (e.g. liquid-metal, molten-salt, and gas coolants, as well as novel fuel forms), there is a need for the capability to mechanistically analyze the coupled behavior of VTR with a variety of experiments and vehicles which may be utilized in VTR. With the intent of closing this modeling and simulation (M&S) gap, a capabilities development effort has been undertaken to develop a flexible and integrated system simulation capability that is necessary for the mechanistic, coupled M&S of VTR and its test vehicles. This integrated capability enables broad exploration of the potential capabilities of the test reactor by providing VTR designers with the tools necessary to achieve a range of operating conditions and experiment designers with the ability to utilize the entire capability range of the test reactor.

Specifically, this effort focuses on extension of SAS4A/SASSYS-1 [1], the system-level liquid-metal safety analysis software developed and maintained by Argonne, to enable coupling with any external code or model representing a test vehicle. This effort also includes extension of SAM (System Analysis Module) [2], also developed and maintained by Argonne, to enable coupling with other system-level codes at a new interface. Here SAM will be utilized to model VTR test vehicles such as sodium or molten salt test capsules and support demonstration testing of the new SAS4A/SASSYS-1 capability under steady-state and transient conditions. While the primary focus of this effort is to support VTR M&S, the capabilities introduced by this work are not limited to the modeling of test reactors with experimental assemblies. The new coupling interface can support a range of assembly-based M&S needs.

This report discusses the design and implementation of the capability extensions in both SAS4A/SASSYS-1 and SAM, documents verification of the interface, and provides demonstration examples for coupled VTR-cartridge loop behavior for a series of beyond design basis events. This report is structured as follows: Section 2 provides background on VTR and the SAS4A/SASSYS-1 and SAM codes; Section 3 describes the features and capabilities of the coupling interface; Section 4 outlines the coupling interface implementation; details on steady-state verification are provided in Section 5; demonstration of the transient analysis capabilities for the coupling interface is provided in Section 6; and Section 7 provides a summary of the activity and potential path forward.

2 Background

This section provides background on the DOE-initiated program anticipated to utilize this coupled capability, as well as the software targeted for extension. Section 2.1 describes the VTR Program and Sections 2.2 and 2.3 describe the SAS4A/SASSYS-1 and SAM codes, respectively.

2.1 Versatile Test Reactor Program

Fast-spectrum irradiation and testing capabilities are presently limited to a small number of international programs, with no capability being available in the U.S since the 1990s. To support modernization of the existing nuclear energy framework and a means to directly support the Department of Energy's Office of Nuclear Energy (DOE NE) mission to improve the state-of-the-art, competitiveness, and growth of the existing U.S. reactor fleet, the availability of a domestic fast neutron testing capability is a recognized necessity.

The VTR Program was formed to close this gap in domestic fast-spectrum testing capabilities in response to a DOE NE Nuclear Energy Advisory Committee (NEAC) report [3] on this topic. The initial phase of this Program focuses on maturation of the VTR design and associated experiment concepts with the aim of establishing resource and schedule requirements with sufficient detail and confidence to enable Congressional approval to proceed with final design and construction. The VTR program has identified a 300MWth metal-fueled pool type sodium-cooled fast reactor (SFR) as the candidate design. The current core design utilizes the inner enrichment zone, outer enrichment zone, and reflector radial layout typical of SFRs, but maintains sufficient flexibility to enable any assembly position to be utilized for testing. Ten test assembly locations in the fueled region are presently reserved for testing and additional test locations are available in the reflector region to support irradiation at reduced fluxes.

In-core irradiation will utilize a cartridge loop design for the removeable test vehicles. Cartridge loops enable reduction in design, analysis, and construction complexity by housing the majority of experiment-specific components within the cartridge itself. In the candidate design, a counter-current, annular heat exchanger is utilized, where the core mockup, cartridge coolant, annular heat exchanger, and remaining experiment systems are located within the closed cartridge loop. Primary reactor coolant acts as the cartridge heat sink by means of heat transfer through the cartridge loop walls, as shown in Figure 2.1.

Figure 2.1: Cartridge Loop Conceptual Design [4]

2.2 SAS4A/SASSYS-1

Development of the SAS series of codes, which began in the mid-1960s to model the initiating phases of core disruptive accidents in SFRs. The initial iteration, SAS1A, originated as a sodium-boiling model that included single- and two-phase coolant flow dynamics, fuel and cladding thermal expansion and deformation, molten fuel dynamics, and a point kinetics model with reactivity feedback [5]. By 1974, SAS evolved into the SAS2A computer code [6] which included enhanced abilities to model the initiating phases of loss of flow (LOF) and transient overpower (TOP) accidents up to the onset of fuel and cladding motion and cladding failure.

The SAS3A code [7] added mechanistic models of fuel and cladding melting and relocation. This version of the code was used extensively for analysis of accidents in the licensing of the Fast Flux Test Facility (FFTF) and therefore underwent significant verification and validation that aligned with the software qualification practices of that time. In the late 1970s, SAS3A was completely rewritten and released as SAS3D [8] in an effort to address the need for improved code portability, maintainability, data management schemes, and runtimes.

The SAS4A version of the code [9], which included new fuel element deformation, disruption, and material relocation models in anticipation of the LOF and TOP analysis needs for the licensing of the Clinch River Breeder Reactor (CRBR) Plant, underwent extensive validation against TREAT M-Series test data [10]. In the mid-1980s, a variant of SAS4A, named SASSYS-1 [11] with the capability to model ex-reactor coolant systems was developed with the aim of simulating accident sequences involving or initiated by loss of heat removal or other

coolant system events. While SAS4A and SASSYS-1 have historically been released and utilized as separate codes, they have always shared common code architectures, the same data management strategy, and the same core channel representation, and therefore the two code branches were merged into a single code referred to as SAS4A/SASSYS-1 in the late 1980s.

Revisions to SAS4A/SASSYS-1 continued throughout the Integral Fast Reactor (IFR) program between 1984 and 1994 [12] resulting in the completion of SAS4A/SASSYS-1 v 3.0 in 1994 [13]. In this time, the design and analysis emphasis shifted towards metallic fuel and accident prevention by means of inherent safety mechanisms. In terms of SAS4A/SASSYS-1 modeling improvements, this resulted in addition of new models and modification of existing models to treat metallic fuel, its properties, behavior, and accident phenomena, and addition and validation of new capabilities for calculating whole-plant design basis transients, with emphasis on the EBR-II reactor and plant [14]. The whole-plant dynamics capability of SASSYS-1 plays a vital role in predicting passive safety feedback as it enables deterministic identification of meaningful boundary conditions for the core channel models, which are required for reliable prediction of accident progression.

SAS4A/SASSYS-1 v 3.1 had been completed as a significant maintenance update by the mid 1990s, but it was not released until 2012 [15]. In the time since the development of Version 3, a variety of modeling additions and enhancements have been made to meet U.S. DOE programmatic needs. This collection of updates was released in 2012 as SAS4A/SASSYS-1 Version 5.0. The current version of the code, version 5.3, includes the following capabilities:

- Characteristic single-pin channel models for rapid evaluation of transients;
- Multiple channel and subchannel modeling of core thermal-hydraulics;
- Point kinetics and spatial kinetics capabilities including decay heat and reactivity feedback
- models for fuel Doppler; fuel, cladding, and coolant density variations; coolant voiding; core
- radial expansion; control-rod driveline expansion; and primary vessel expansion;
- Detailed mechanistic models for oxide and metal fuel and cladding behavior, including fuel
- melting, in-pin motion, pin-failure, and ex-pin fuel dispersal and freezing;
- Two-phase sodium thermal hydraulics and single-phase thermal hydraulics of NaK, lead and
- LBE, and heavy water;
- Primary and intermediate loop reactor coolant systems models to simulate passive passive heat
- rejection and inherent safety; and
- Detailed plant control systems.

The coupling capability described in this report is expected to be available in official release packages of version 5.4 and later in both SAS4A/SASSYS-1 and Mini SAS. Current details on SAS4A/SASSYS-1 releases can be found at <https://wiki.anl.gov/sas/>.

2.3 SAM

The System Analysis Module (SAM) [2] is a modern system analysis tool being developed at Argonne National Laboratory for advanced non-LWR safety analysis. It aims to provide fast-running, whole-plant transient analysis capabilities with improved-fidelity for advanced

reactors, including SFRs, lead-cooled fast reactors (LFR), and molten salt reactors (MSR), fluoride-cooled high-temperature reactors (FHR), and high-temperature gas-cooled reactors (HTGR). SAM takes advantage of advances in physical modeling, numerical methods, and software engineering to enhance its user experience and usability. It utilizes an object-oriented application framework (MOOSE) [16], and its underlying meshing and finite-element library (libMesh) [17] and linear and non-linear solvers (PETSc) [18], to leverage the modern advanced software environments and numerical methods.

SAM is a system-level modeling and simulation tool with higher fidelity but yet remains computationally efficient. As a new code development, the initial effort has been focused on the modeling and simulation capabilities of the heat transfer and single-phase fluid dynamics responses in reactor systems. Transient simulation capabilities of typical reactor accidents have been demonstrated in the transient simulations of the Advanced Burner Test Reactor and validated against the EBR-II benchmark test results. The key features include:

- Robust and high-order spatial and temporal discretization models of single-phase fluid flow and heat transfer;
- Flexible coupling between fluid and solid components enabling a wide range of engineering applications;
- Enhanced built-in closure models and flexible modeling of fluid properties, friction, and convective heat transfer;
- Built-in 3D flow model for thermal mixing and stratification modeling in large enclosures and distributed resistance modeling of porous medium;
- Point kinetics and reactivity feedback modeling, including reactivity feedbacks due to core radial and axial thermal expansion feedbacks;
- A general mass transport capability based on the passive scalar transport. The code can track any number of species carried by the fluid flow for various applications; and
- Flexible coupling interfaces allowing for convenient integration with other advanced or conventional simulation tools for multi-scale and multi-physics modeling capabilities.

3 Features and Capabilities

The extended modeling capabilities being developed as part of this effort allow users to assess the coupled thermal hydraulic and reactivity behavior of a reactor with an experimental assembly or test vehicle. That is, the coupling interface allows the deterministic analysis of heat transfer between a reactor's primary coolant and the test vehicle as well as the coupled reactivity effects of the core and test articles as they related to point kinetics and feedback mechanisms, all of which are key to assessing reactor and test vehicle safety during normal operation and transient conditions.

Within SAS4A/SASSYS-1, the use of decomposed domains, implementation of an appropriate conjugate heat transfer methodology, and the existing in-core thermal hydraulic calculational framework enable the treatment of arbitrary test vehicle geometries such that explicit vehicle geometry specification is unnecessary in SAS4A/SASSYS-1. This reduces the computational burden within the code and facilitates the efficient implementation of the coupling interface by leveraging the existing code structure. As such, the number of coupled test locations is limited only to the maximum number of channels permitted by the code.

One-to-one mapping of axial nodes at the coupling boundary between SAS4A/SASSYS-1 and SAM is not required. SAS4A/SASSYS-1 provides data at its standard, user-specified nodal locations, assuming that SAM or any coupled code or module will apply the appropriate interpolation scheme to achieve consistent meshing for an inconsistent nodalization. As SAS4A/SASSYS-1 is limited to 24 axial nodes in the fueled region, this allows an external code or module to utilize a higher-fidelity internal calculation scheme, if desired.

Computational efficiency of the coupling interface is increased by utilizing named pipes (or FIFOs), an interface for interprocess communication. This capability is directly supported in version 5.4 of SAS4A/SASSYS-1 on macOS, Linux, and Windows platforms. A file-based data transfer interface is also supported. Beyond the limitation of SAM availability on macOS and Linux architectures, no additional platform dependencies exist for the coupling interfaces in either code.

While this effort explicitly targets extension of SAS4A/SASSYS-1 and SAM, the coupling interfaces in both codes have been developed with sufficient flexibility to support interaction with any code or module that provides the appropriate data structures. To that end, this extended capability is not limited to the treatment of test vehicles within a reactor. The couple interface can be leveraged to deterministically model in-core components not typically treated by SAS4A/SASSYS-1. Similarly, the extended SAM interface can be utilized for a range of coupling applications.

Currently, this extended capability does not support the modeling of test vehicle failure at the boundary, interaction of a failed test vehicle coolant or fuel with the primary VTR coolant, or interaction of failed VTR fuel with the test vehicle. In-vehicle fuel movement is permitted (provided the code/module representing the test vehicle and its articles supports this capability), as SAS4A/SASSYS-1 requires no details regarding in-vehicle geometry. Addition of these capabilities may be provided in a future update to the coupling interface.

4 Coupling Implementation

This section provides a description of coupling interfaces developed as part of this capability extension. The implementations in SAS4A/SASSYS-1 and SAM are described in Sections 4.1.1 and 4.1.2, respectively. Section 4.2.1 describes the iteration and data transfer schemes. Section 4.2.2 provides background on the coupling algorithm utilized for the coupling interface. Lastly, Section 4.2.3 describes issues addressed regarding numerical stability.

4.1 Coupling Interfaces

4.1.1 SAS4A/SASSYS-1 Interface

With respect to the SAS4A/SASSYS-1 model, the interface boundary represents the location where energy deposited in the test vehicle is rejected to the primary coolant. Because convection affects the fields of temperature and heat flux in the wall, the thermal boundary conditions should be properly imposed in order to achieve solution stability and accuracy. In theory, the heat flux and temperature are continuous at the interface. In practice, independent calculations in SAM and SAS4A/SASSYS-1 do not enforce both temperature and heat flux at the boundary simultaneously. Instead, one boundary condition must be enforced for each calculation domain and the two codes are coupled such that the temperature and heat flux are periodically updated. In the iterative process, energy conservation must be enforced so that no energy is lost or artificially produced due to mismatch in heat fluxes in a time integration step.

In an effort to explore iteration scheme stabilization and simultaneously promote flexibility, two options for boundary condition application have been identified, as depicted in Figure 4.1. In option *a*, SAM passes the wall heat flux to SAS4A/SASSYS-1, and in option *b*, SAM passes the wall temperature. In both options SAS4A/SASSYS-1 provides the convective boundary condition for SAM by passing the coolant temperature and heat transfer coefficient. In option *a*, the heat flux equates to the thermal power generated in the SAM structure and rejected to the coolant. This option effectively guarantees that the energy exchanged between the two domains is conserved if the heating profile in the structure is known. In option *b*, energy conservation is achieved through iterations when the heat fluxes calculated independently in both domains are equal. Option *a* is more favorable and leads to faster convergence than option *b*. It is worth noting that another variation of option *a* was explored where SAS4A/SASSYS-1 passes the wall temperature to SAM. This option was found to be unstable under certain conditions and therefore not adopted in the coupling scheme. Details are discussed in Section 4.2.3.

Figure 4.1: Definition of the Coupling Boundary Interface and Boundary Condition Options

4.1.2 SAM Interface

The coupling interface between SAM and SAS4A/SASSYS-1 is achieved through a new *SASInterface* component. This interface accepts the primary coolant temperature and heat transfer coefficient at the fluid-solid interface from SAS4A/SASSYS-1 and returns the wall temperature and wall heat flux to SAS4A/SASSYS-1. Additionally, the interface accepts the total power deposited in the test vehicle. This power can then be distributed to any component within SAM that will accept a heat source. At the beginning of an iteration, the external data is supplied by SAS4A/SASSYS-1 and read into SAM memory. This data is then mapped to the interface boundary mesh within SAM using the built-in MOOSE linear interpolation routine. Upon completion of the heat transfer calculation, SAM calculates the wall temperature and heat flux at the fluid-solid interface boundary on the SAS4A/SASSYS-1 mesh and sends one of the two back to the external source depending on the selected coupling option.

4.2 Iteration and Convergence Schemes

4.2.1 Iteration and Data Transfer Schemes

Because domain decomposition is utilized for this work, the tight coupling scheme depicted in Figure 4.2 has been adopted, where SAS4A/SASSYS-1 effectively drives the main time step. In this coupling scheme, the availability of relevant data from the external module is monitored by SAS4A/SASSYS-1. Once available, SAS4A/SASSYS-1 reads and processes the data and writes the relevant state parameters to the appropriate data transfer mechanism (data structure or file). Once the relevant data calculated by SAS4A/SASSYS-1 is made available, the calculation continues in SAM using the same methodology.

Two methods for data transfer between SAS4A/SASSYS-1 and SAM have been implemented: file-based I/O, and an inter-process communication (IPC) scheme using named pipes. When file-based I/O is utilized, a file-locking scheme is enforced, where each program monitors for the presence of the data file it generated, and the internal calculation can only proceed once the other software deletes the relevant file. When the IPC scheme is utilized, boundary conditions are passed in memory without the system overhead of creating and writing/reading files. Additionally, the need to continuously monitor for new information is not necessary with IPC, as named pipes can be implemented such that they cause blocking. For example, when SAS4A/SASSYS-1 calls for the boundary conditions from SAM, the call hangs until SAM provides the results. The main differences between IPC transfer and file-based transfer is handled at the system level. Therefore, very little programming is needed to support file-based transfer and IPC. However, IPC transfer significantly reduces the run time as the wait calls typically required for file-locking schemes is absent in the IPC scheme.

Figure 4.2: Coupled and Internal Program Flow Diagram

4.2.2 Quasi-Newton Coupling Algorithm

To improve numerical stability and convergence speed, the Quasi-Newton implicit coupling algorithm [19] is adopted by means of an iterative coupling procedure. Within a timestep there

can be multiple coupling iterations where boundary conditions are exchanged multiple times. At the end of an iteration, the boundary condition vector for the SAM domain is updated. The new boundary condition vector is then used in the next iteration, and this process continues until the absolute value of the residual is less than a user-specified convergence criterion. Once convergence is met, the calculations are advanced to the next timestep.

At a given iteration n , vector U_n contains the nodal wall temperatures or heat fluxes calculated in SAS4A/SASSYS-1, and vector Y_n contains the corresponding variables which are derived from the boundary condition vector provided by SAM.

For coupling option a :

$$U_n = T_w^{sas} \quad \text{Eq. 4-1}$$

$$Y_n = \frac{q_w^{sam}}{h} + T_c \quad \text{Eq. 4-2}$$

For coupling option b :

$$U_n = q_w^{sas} \quad \text{Eq. 4-3}$$

$$Y_n = h(T_w^{sam} - T_c) \quad \text{Eq. 4-4}$$

The difference between vectors Y_n and U_n is stored in a residual vector R_n :

$$R_n = Y_n - U_n \quad \text{Eq. 4-5}$$

A correction term related to the residual vector is given by:

$$\Delta U_n = -\frac{R_n}{J_n} \quad \text{Eq. 4-6}$$

where the Jacobian vector can be computed from vectors R and U :

$$J_n = \frac{dR_n}{dU_n} \approx \frac{R_n - R_{n-1}}{U_n - U_{n-1}} \quad \text{Eq. 4-7}$$

and vector U_{n+1} to be used for the next iteration is obtained from:

$$U_{n+1} = U_n + \Delta U_n \quad \text{Eq. 4-8}$$

Convergence is met once:

$$|R_n| < \varepsilon \quad \text{Eq. 4-9}$$

The communication of convergence can be accomplished at two different times during a coupled iteration: while sending boundary conditions, or independently at the end of the iteration. Sending the convergence independently requires additional system overhead, both memory and time, however the alternative prevents the possibility of restarting a calculation.

As shown in Figure 4.3a, when convergence is sent with the boundary conditions (red or green dotted arrows from SAS4A/SASSYS-1 to SAM) the external code never exits the calculation. Instead, at the final time step, SAM waits for a convergence flag from SAS4A/SASSYS-1, which has already exited. In order to support restart capabilities in SAS4A/SASSYS-1, solution convergence and boundary conditions are communicated separately (red or green dashed arrows). This allows SAM to save the solution at the final time step, as shown in Figure 4.3b, which can be used in a restart calculation.

Figure 4.3: Communicating Solution Convergence with the (a) Boundary Conditions (left), or (b) Independently (right)

4.2.3 Numerical Instability Prevention

As mentioned in Section 4.1.1, another variation of option *a* was explored in which SAM passed the wall heat flux to SAS4A/SASSYS-1 and received the wall temperature in return. This method can lead to numerical instability, which is demonstrated by an error analysis of the numerical discretization of the heat transfer equations.

Numerically, the wall heat flux q_w in iteration n is approximately:

$$q_w^n = k \frac{T_2 - T_w}{\Delta r} \quad \text{Eq. 4-10}$$

where T_w is the wall temperature, T_2 is the adjacent point in the heat structure in the SAM domain, Δr is the mesh size, and k is the thermal conductivity. Using this wall heat flux provided by SAM, SAS4A/SASSYS-1 calculates the coolant temperature, T_c , from:

$$\rho C_p \Delta T_c = \frac{P}{A} q_w \Delta t \quad \text{Eq. 4-11}$$

Then the wall temperature in iteration $n+1$ is updated according to:

$$T_w^{n+1} = \frac{q_w^n}{h} + T_c^{n+1} \quad \text{Eq. 4-12}$$

During a transient simulation, the time step size Δt is small, thus the thermal inertial of the structure has an effect such that T_2 will not change as much as the wall temperature. In the limit $\Delta t \rightarrow 0$, suppose there is an error ε^n in T_w . This error will propagate to the wall heat flux by:

$$E_q \propto \frac{k}{\Delta r} \varepsilon^n \quad \text{Eq. 4-13}$$

and the error in the coolant temperature is approximately:

$$E_c \propto \frac{P}{A \rho C_p} E_q \propto \frac{P}{A \rho C_p} \frac{k}{\Delta r} \Delta t \varepsilon^n \quad \text{Eq. 4-14}$$

Thus, the initial error ε^n in T_w is updated in the next iteration as:

$$\varepsilon^{n+1} = \frac{k}{h \Delta r} \varepsilon^n + \frac{P}{A \rho C_p} \frac{k}{\Delta r} \varepsilon^n = \frac{k}{h \Delta r} \left(1 + \frac{P h}{A \rho C_p} \Delta t \right) \varepsilon^n \quad \text{Eq. 4-15}$$

If the ratio $\frac{k}{h \Delta r}$ is not small, this coupling strategy could be unconditionally unstable. In one test case, $\frac{P}{A} = \frac{4}{D_h} = 695.6 \text{ m}^{-1}$, $\rho = 1.134 \times 10^4 \text{ kg/m}^3$, $h = 1.4 \times 10^4 \text{ W/(m}^2\text{K)}$, and $C_p = 140 \text{ J/(kg K)}$. Then, $\frac{P h}{A \rho C_p} \approx 6 \text{ s}^{-1}$. Thus, in the limit of $\Delta t \rightarrow 0$:

$$\frac{\varepsilon^{n+1}}{\varepsilon^n} \approx \frac{k}{h\Delta r} (1 + 6\Delta t) \approx \frac{k}{h\Delta r} \quad \text{Eq. 4-16}$$

In this test problem, $\Delta r = 2.9 \times 10^{-4}$ m and the error ratio between two successive iterations is:

$$\frac{\varepsilon^{n+1}}{\varepsilon^n} \approx 0.246 \times k \quad \text{Eq. 4-17}$$

An error ratio of less than unity is a necessary condition for numerical stability. However, the thermal conductivity, k , suitable for most materials for the wall is in the range that causes the error ratio to exceed 1, resulting in error growth and numerical instability. In the test case, $k = 26.3 \text{ W}/(\text{m} \cdot \text{K})$, and the coupling scheme is indeed unstable. To further illustrate this point, k is reduced to $0.263 \text{ W}/(\text{m} \cdot \text{K})$ and the coupling scheme becomes stable.

5 Steady-State Verification

The new capability in SAS4A/SASSYS-1 that enables coupling with an external code for modeling of one or more test vehicles was verified for steady state conditions. As a first step, results of thermal-hydraulic calculations performed by SAS4A/SASSYS-1 and SAM for basic conjugate heat transfer problems were compared with known analytical solutions. The sample problem considered herein consists of a test channel assembly which is modeled in SAS4A/SASSYS-1, and a heat structure that simulates the thermal hydraulic characteristics of a test vehicle which is modeled in SAM, as previously shown in Figure 4.1. In the SAS4A/SASSYS-1 model, the test channel assembly mimics the layout of a typical fuel assembly, where the fuel and upper/lower reflector regions are replaced by a test vehicle. For this exercise, lead is utilized as the primary reactor coolant. The test cases examine the behavior of the lead coolant that cools the heat structure under steady state conditions.

The heat structure is prescribed with simple heat sources so that analytical solutions can be obtained for verification of the SAS-SAM coupled solutions. Three volumetric heat sources are considered: uniform, linearly varying with distance, and a half-sine function as defined below:

$$Q(z) = \begin{cases} \frac{P}{\pi r^2 L} \\ \frac{2P}{\pi r^2 L^2} z \\ \frac{P}{2r^2 L} \sin\left(\frac{\pi z}{L}\right) \end{cases} \quad \text{Eq. 5-1}$$

where P is the power, r is heat structure radius, and L is its heated length. For a given coolant flow rate, $\dot{m}$, the analytical solutions for the coolant temperature are then given by:

$$\dot{m} \int_{T_i}^T c_p dT = \begin{cases} \frac{P}{L} z \\ \frac{P}{L^2} z^2 \\ \frac{P}{2} \left[1 - \cos\left(\frac{\pi z}{L}\right) \right] \end{cases} \quad \text{Eq. 5-2}$$

In Eq. 5-2, T_i is the coolant inlet temperature and its specific heat varies with temperature according to [1]:

$$c_p(T) = \frac{1.9285 \times 10^8}{(T_{cr} - T)^2} - \frac{412985}{T_{cr} - T} + 499.092 - 0.0120068(T_{cr} - T) + 1.3156 \times 10^{-5}(T_{cr} - T)^2 \quad \text{Eq. 5-3}$$

where T_{cr} is the coolant critical temperature of 5400 K. The analytical solutions for the wall heat flux can be easily obtained from Eq. 5-1 as:

$$q'' = \frac{rQ(z)}{2} \quad \text{Eq. 5-4}$$

Figure 5.1 compares the SAS-SAM results with analytical solutions for the coolant temperatures. The maximum deviations are 0.00002%, 0.015%, and 0.06% for the uniform, linear, and half-sine heat sources, respectively. Figure 5.2 shows that the wall heat fluxes calculated in SAS4A/SASSYS-1 are in very good agreement with the analytical solutions as well.

Figure 5.1: Comparison of SAS-SAM Coupled Results for Coolant Temperatures with Analytical Solution

Figure 5.2: Comparison of SAS-SAM Coupled Results for Wall Heat Flux with Analytical Solution

In SAS4A/SASSYS-1, the coolant heat transfer coefficient, h , is calculated using the form for convective heat transfer for low Prandtl number fluids, such as liquid metal [20]:

$$Nu = \frac{hD}{k} = c_1 Pe^{c_2} + c_3 \quad \text{Eq. 5-5}$$

The user-supplied constants c_1 , c_2 , and c_3 depend on the particular correlation used. The default values for these constants for sodium, lead, and lead-bismuth are built-in and they are derived from published experimental data. For this work, the default values for lead coolant are used.

Figure 5.3 shows the coolant heat transfer coefficient profiles along the heated length. At the outlet, the heat transfer coefficient is ~5.7% higher than that at the inlet. Although h is proportional to coolant temperature, it is fitted as a function of distance in order to obtain analytical solutions for ΔT_w , the temperature drop from the wall to the bulk coolant:

$$\Delta T_w = \frac{q''}{h} \quad \text{Eq. 5-6}$$

Figure 5.3: Coolant Heat Transfer Coefficients Calculated in SAS4A/SASSYS-1

Figure 5.4 compares the SAS-SAM coupled results for ΔT_w with analytical results that are derived from Eq. 5-1, Eq. 5-4, and the fitted expressions for h that are embedded in Figure 5.3. Note the subtle differences between the profiles in Figure 5.2 and Figure 5.4 due to temperature dependence of the coolant heat transfer coefficient. For example, ΔT_w decreases from inlet to outlet even though the wall heat flux is constant and increases slower than linearly in the case of linear wall heat flux.

Figure 5.4: Comparison of SAS-SAM Coupled Results for ΔT_w with Analytical Solution

6 Demonstration for VTR Test Vehicle

This section presents a full demonstration of coupling between SAS4A/SASSYS-1 and SAM for a prototypic test vehicle located in one of several test locations in the VTR core. Three transient events are simulated: unprotected loss of heat sink (ULOHS), unprotected transient overpower (UTOP) and unprotected station blackout (USBO).

6.1 System Code Models

The SAS4A/SASSYS-1 model utilizes the design parameters of the VTR primary system, heat rejection systems, and the core, including a test assembly which houses a test cartridge. The SAM model contains all main components of a prototypic cartridge loop which mimics a test vehicle using sodium coolant.

6.1.1 SAS4A/SASSYS-1 Model (VTR)

The SAS4A/SASSYS-1 model is based on recent VTR design parameters [21]. The 300 MWt reactor features a pool-type configuration. The reactor core consists of 313 hexagonal assemblies, of which 66 are fuel assemblies, 10 are test assemblies, 9 are control/shutdown assemblies, and 228 are reflector/shield assemblies, as depicted in Figure 6.1. The reactor vessel contains the reactor core, reactivity control system, two reactor coolant pumps (RCPs), two intermediate heat exchangers (IHXs), and vessel internals. After being heated in the core, the sodium coolant flows up to the upper plenum and then through the IHXs, where it is cooled, and into the cold pool. The RCPs pump the sodium from the cold pool into the core. Each IHX is connected to its own intermediate heat transport loop that rejects heat to the environment via the sodium-to-air dump heat exchangers. The emergency decay heat removal is provided by the Shutdown Heat Removal System (SHRS) which has three natural circulation NaK-to-air units.

The core is modeled using 19 channels, where one channel represents 10 test assemblies. For this coupling demonstration, a new channel, channel 20, was created to model one test assembly that accommodates a test vehicle. Details of the test vehicle are described in Section 6.1.2. Therefore, the SAS4A/SASSYS-1 model utilized for this demonstration contains 20 channels:

- Channels 1 - 9 are representative of the 66 VTR fuel assemblies,
- Channel 10 is representative of nine empty test vehicle assemblies,
- Channel 11 contains six control assemblies,
- Channel 12 contains three shutdown assemblies,
- Channels 13 - 16 are representative of the 114 VTR reflector assemblies,
- Channels 17 - 19 are representative of the 114 VTR shield assemblies, and
- Channel 20 contains the coupled VTR test vehicle which is the focus of this analysis.

Figure 6.1 shows a schematic of the VTR core and a hexagonal test assembly (channel 20) which occupies one of ten test locations (shown in green). The test vehicle concept adopted for this demonstration is positioned in the central portion of the test assembly. The buffer space between the test vehicle and the assembly duct is filled with argon in order to reduce the influence of the test vehicle on surrounding fuel assemblies. To account for this buffer in the SAS4A/SASSYS-1 input model, the outer node in the structure is modeled with an effective

thermal conductivity that accounts for the thermal resistance through the argon buffer zone, as illustrated in Figure 6.2.

The thermal resistances in series are represented by:

$$\frac{1}{H_{stio}} = \frac{d_{sti}}{2k_{si}} + \frac{1}{h_g} + \frac{d_{sto}}{2k_{so}} = \frac{d_{sti}}{2k_{si}} + \frac{d_{sto}}{2k_{eff}} \quad \text{Eq. 6-1}$$

so that:

$$k_{eff} = \frac{h_g d_{sto}}{2k_{so} + h_g d_{sto}} k_{so} \quad \text{Eq. 6-2}$$

where k_{si} and k_{so} are the thermal conductivities of the inner and outer structure nodes (typically equivalent) and h_g is the heat transfer coefficient of argon at atmospheric pressure. Taking typical value of $h_g = 20 \frac{W}{m^2K}$, then $k_{eff} \approx 0.001k_{so}$.

Figure 6.1: Schematic of VTR Core (left) and a Test Assembly with a Test Cartridge Loop (right)

Figure 6.2: Representation of the Two Structure Nodes NSI and NSO with an Argon Buffer in the SAS4A/SASSYS-1 Model

6.1.2 SAM Model (Cartridge Loop)

A two-dimensional representation of the cartridge loop model is shown in Figure 6.3. The SAM model consists of a mock-up fuel assembly, coolant pump, hot pool, cover gas, downcomer,

and cold pool. The wall between the inner cartridge and outer sodium loop acts as the heat exchanger where coupling is implemented. In order to control the inlet and outlet temperatures of the mock-up fuel assembly, the composition of the heat exchanger wall is axially defined. Moving downward from the hot pool, the heat exchanger wall consists of stainless steel, shown as solid blue. Once the desired inlet and outlet temperatures have been achieved, the heat exchanger wall includes an argon gap, shown in green, insulating the vehicle cartridge from the VTR sodium, shown in orange. In order to reduce the complexity of the SAM model, the insulating portion of the heat exchanger wall is treated as an adiabatic boundary condition. The flow in the cartridge is driven by a pump located at the entrance of the hot pool. An argon gap between the downcomer and the mock-up fuel assembly allows for adiabatic boundary conditions to be applied at the fuel assembly outer boundary and the downcomer inner boundary.

The mock-up fuel assembly is based on the Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR). The PGSFR is a sodium cooled fast reactor designed by the Korean Atomic Energy Research Institute (KAERI) [22]. The fuel is a cylindrical U-10Zr alloy contained within stainless steel cladding. A total of 7 fuel rods are included in the mock-up hexagonal fuel assembly within the test vehicle's inner cartridge. The relevant dimensions of the fuel assembly can be found in Table 6.1. Most dimensions are consistent with the PGSFR design, however a VTR design constraint requires the active fuel length to be reduced from 0.9 m to 0.8 m. The remaining dimensions for the SAM model of the test vehicle can be found in Table 6.2. At this time, only the hot pool and the cold pool account for minor pressure losses within the system. The loss coefficients used at the inlet and outlet of each pool are 1.0 and 0.5, respectively.

Figure 6.3: Two-dimensional Representation of the SAM Cartridge Model

Table 6.1 Dimensions of the Cartridge Loop Fuel Assembly

Fuel Stack	
Inner Diameter [cm]	0
Outer Diameter [cm]	0.554
Length [cm]	80.0
Z offset [cm]	0.0
Material	U-10Zr
Fuel Cladding	
Inner Diameter [cm]	0.64
Outer Diameter [cm]	0.74
Length [cm]	165.485
Z offset [cm]	-3.81
End Plug length [cm]	3.81
Wire Diameter [cm]	0.095
Material	FC92 Steel
Mock-up Fuel Assembly	
Inner Flat to Flat [cm]	2.4
Outer Flat to Flat [cm]	2.8
Length [cm]	194.16
Z offset [cm]	-11.161
Number of Pins	7
Coolant	Sodium
Length of Bottom Plate [cm]	7.351
Flow Area of Bottom Plate [m ²]	2.813E-4
Dh of Bottom Plate [cm]	[0.51]
Structural Material	SS-316H

Table 6.2 Dimensions of the Cartridge Loop

Cartridge Downcomer	
Inner Diameter [cm]	2.93
Outer Diameter [cm]	4.0
Length [cm]	194.16
Z offset [cm]	-11.161
Material	SS-316H
Hot Pool	
Inner Diameter [cm]	0.0
Outer Diameter [cm]	8.89
Length [cm]	32.896
Z offset [cm]	207.8523
Cover Gas Height [cm]	15.24
Cold Pool	
Inner Diameter [cm]	0.0
Outer Diameter [cm]	4
Length [cm]	0.635
Z offset [cm]	-14.336
Pump Intake	
Inner Diameter [cm]	0.0
Outer Diameter [cm]	2.53
Length [cm]	4.25
Z offset [cm]	186.8090
Pump Outlet	
Inner Diameter [cm]	0.0
Outer Diameter [cm]	7.5
Length [cm]	4.25
Z offset [cm]	191.0598

6.2 Steady State Results

All transient simulations in SAS4A/SASSYS-1 are preceded by a steady state calculation. Figure 6.4 shows the power and flow per subassembly for the 20 core channels. The power delivered to a test assembly is about 95 kW. In channel 20, the total power is ~114.4 kW due to additional gamma heating in the cartridge loop. The sodium flow rates in the subassemblies are also shown in Figure 6.4. For channel 20, a flow rate of 0.6 kg/s is prescribed. Figure 6.5 shows the power to flow ratio per channel throughout the VTR core. It is desirable to maintain fairly uniform power/flow ratio to avoid large fluctuation in coolant outlet temperature across the assemblies. The coupled SAS4A/SASSYS-1 results for coolant temperature in channel 20,

shown in Figure 6.6, indicate that the coupled channel is behaving as expected. The monotonic increase in the coolant temperature along the coupled interface is expected for a counter-current heat exchanger. The total temperature rise across the channel is consistent with the amount of heat being rejected from the cartridge loop.

Figure 6.4: Power and Flow Distributions in the SAS4A/SASSYS-1 Channels

Figure 6.5: Ratio of Power to Flow in the SAS4A/SASSYS-1 Channels

Figure 6.6: Steady State Coolant Temperatures in the Fuel and Test Channels

The SAM results, Figure 6.7, highlight the iterative process that is required for designing the test vehicle. The target inlet and outlet temperature of the PGSFR fuel assemblies are 390 and 545 °C, respectively. The current configuration obtains an inlet and outlet temperature of 438 and 572 °C, respectively. Due to the coupled nature of the vehicle flow rate, the heat exchanger length, and the channel flow rate, an iterative process will need to be implemented in order to obtain the proper temperatures across the mock-up fuel assembly.

Figure 6.7: Test Vehicle Coolant Velocity (left) and Temperature Distribution (right)

6.3 Transient Results

In the transient simulations, each event is preceded by a zero transient, or a transient simulation where no operating conditions are changed. The ULOHS, and UTOP null transients are 500 seconds, while the USBO null transient is 100 seconds. The ULOHS and UTOP cases were able to capture the behavior of the test vehicle and the VTR using a timestep of 1 s. However, at 1 s timesteps, the transition from forced circulation to natural circulation following the cartridge loop pump trip in a USBO introduced numerical instability within the SAM model. Such instability was eliminated using finer time steps of 0.1 seconds.

6.3.1 Unprotected Loss of Heat Sink

At the start of the transient, the intermediate pumps in the VTR model are tripped, leading to a loss of heat sink. The reactor protection system is assumed to fail, so that the power excursion was entirely controlled by reactivity feedback. The Shutdown Heat Removal System (SHRS) remains functioning, allowing for some heat rejection to occur. The transient was simulated for approximately 5400 s (1.5 hr). The normalized core power, flow rate, and reactivity feedback are shown in Figure 6.8. The decrease in reactor power is largely due the negative reactivity inserted by the radial core expansion. The positive reactivity introduced by the control rod driveline (CRDL) results from a decrease in the VTR outlet temperature, which causes the control rods to contract and move further out of the core.

Figure 6.8: ULOHS Power and Flow (left), and Reactivity Feedbacks (right)

The temperature of the VTR channels as well as the test vehicle is shown in Figure 6.9. The VTR inlet and outlet temperature both begin to increase at the onset of the transient. The increase in outlet temperature (hot pool) is due to the loss of heat sink, while mixing of coolant between hot and cold pools raises the inlet temperature which then causes the grid plate and the core to expand and introduces negative reactivity. Shortly thereafter, the VTR outlet temperature reaches a maximum and begins to decrease as a result of the decrease in reactor power. As the sodium continues to circulate between the hot and cold pools, the inlet and outlet temperatures approach equilibrium. The vehicle temperature follows a similar trend, however the maximum fuel temperature and outlet coolant temperature decreases rapidly, as the vehicle operates at a lower power level than the fuel channel and the cartridge pump is still operating. One hour after the transient was initiated the inlet and outlet temperatures of both the VTR channels and the test vehicle have approached equilibrium when heat removed by the Shutdown Heat Removal System is equal to the decay heat in the core.

Figure 6.9: ULOHS VTR Coolant Temperatures (left) and Test Vehicle Temperatures (right)

6.3.2 Unprotected Transient Overpower

In the unprotected transient overpower simulation a positive reactivity insertion of 0.5 cents/second over 200 s [23] is initiated after the transient simulation time reaches 500 seconds. At the end of the ramp, the external reactivity is held constant at 1 dollar. Similar to the ULOHS scenario, the reactor protection system fails, leaving the reactor at full power. However, in this

transient the intermediate pumps remain functioning, allowing for the nominal heat rejection to occur. The transient was simulated for approximately 7200 s (2 hr). The normalized core power, flow rate, and reactivity feedback are shown in Figure 6.10. The decrease in reactor power is due to the negative reactivity inserted by the radial core expansion and the expansion of the CRDL. The negative reactivity feedback is able to offset the positive reactivity insertion after 1000 s, which then stabilizes the VTR at the elevated power and temperature.

Figure 6.10: UTOP Power and Flow (left), and Reactivity Feedbacks (right)

The temperature of the VTR channels, as well as the test vehicle, are shown in Figure 6.11. The increase in inlet temperature causes the grid plate to expand which introduces negative reactivity via radial core expansion. Likewise, the increase in outlet temperature causes the net response of the CRDL to expand into the core, which also introduces negative reactivity. Both inlet and outlet temperatures approach new equilibrium after approximately 3600 s. The vehicle temperature follows a similar trend.

It is important to note the relationship between the inlet temperature of the mock-up fuel assembly, the outlet temperature of the assembly, and the inlet temperature of the coupled channel. Initially the inlet temperature of the mock-up fuel assembly follows the behavior of the outlet temperature. However, as the outlet temperature begins to decrease, with the reduction in power, the inlet temperature of the mock-up fuel assembly is influenced by the increase in the channel inlet temperature and continues to rise. This trend is also observed in the outlet temperature of the coupled channel, highlighting the importance of investigating the test vehicle using the coupled interface.

Figure 6.11: UTOP VTR Coolant Temperatures (left) and Test Vehicle Temperatures (right)

6.3.3 Unprotected Station Blackout

In the unprotected station blackout simulation, the VTR primary pump, VTR intermediate loop pump, and the test vehicle internal pump trip at $t=100$ seconds due to a complete loss of power. Similar to the ULOHS and UTOP scenarios, the reactor protection system fails, leaving the reactor unscrammed. It is assumed that the coast down period of the test vehicle pump is 3 s. The transient was simulated for approximately 3600 s. The normalized core power, flow rate, and reactivity feedback are shown in Figure 6.12. The driver behind the decrease in reactor power is the negative reactivity inserted by the radial core expansion and the net expansion of the CRDL, as shown in Figure 6.12. The large negative reactivity feedback causes the reactor power to decrease rapidly.

Figure 6.12: USBO Power and Flow (left), and Reactivity Feedbacks (right)

The temperature of the VTR channels as well as the test vehicle are shown in Figure 6.13. It can be observed that the VTR fuel channel (CH 1) outlet temperature increases rapidly at the start of the transient because of the loss of both heat sink and the ability to mix with colder sodium in the cold pool. The increase in outlet temperature in the test channel (CH 20) is gradual. Once the core power decreases, so does the outlet temperature. Note that the inlet temperature continues to increase slowly, where this is due to natural circulation between the hot and cold pools. The test vehicle follows a similar trend, however the temperature peaking at the start of the transient is not as significant in the test vehicle. The maximum temperature

experienced in the test vehicle is a function of the pump coast down period. The selected pump coast period of three seconds prevents the boiling of sodium in the test vehicle. This value was selected due to the fact that SAM currently does not have sodium boiling models.

Figure 6.13: USB0 VTR Coolant Temperatures (left) and Test Vehicle Temperatures (right)

7 Summary and Path Forward

In order to support VTR program design and analysis needs, a novel M&S capability that enables integrated analyses of test vehicles or non-standard in-core components within VTR has been developed. Specifically, this work focused on extension of the SAS4A/SASSYS-1 and SAM codes to model VTR and its test vehicles, where SAS4A/SASSYS-1 treats primary coolant thermal hydraulics of an assembly, while SAM treats thermal hydraulic behavior within the test vehicle, including the vehicle walls.

By utilizing a coupling interface boundary at the test vehicle wall, the existing SAS4A/SASSYS-1 infrastructure can be leveraged to pursue decomposed domain analysis methodology that enables analysis of arbitrary geometries and allows rapid implementation of this capability. Additionally, domain decomposition combined with an efficient implementation of conjugate heat transfer schemes allows for adoption of a tight coupling strategy. The flexibility of the new capability is extended by providing users with the option for boundary condition specification.

Verification work which examines SAS-SAM coupled simulations shows excellent agreement with known analytical solutions, indicating appropriate implementation of the coupling interfaces. Additionally, to support development of a robust yet efficient coupling interface, numerical stability of the coupling interface has been enforced. Transient demonstration simulations show successful implementation of the coupling interface in SAS4A/SASSYS-1 and demonstrate the importance of an integrated assessment of VTR and its test vehicles.

This capability is considered to be comprehensive in its treatment of phenomena anticipated to occur in the design basis space. Follow-on activities to this work potentially include implementation of a sensitivity analysis (SA) and uncertainty quantification (UQ) framework that treats characteristics in SAS4A/SASSYS-1 and the coupled code. This SA/UQ framework would enable efficient, mechanized assessment of the integral behavior of VTR and a test vehicle. Additional capabilities which may be considered for future development would also include the incorporation of direct interaction of primary reactor coolant with test vehicle coolant/materials.

8 Acknowledgements

This work was supported by Laboratory Directed Research and Development (LDRD) funding from Argonne National Laboratory, provided by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-06CH11357.

References

- [1] T. H. Fanning, A. J. Brunett, and T. Sumner, eds., *The SAS4A/SASSYS-1 Safety Analysis Code System: User's Guide*, Argonne National Laboratory, ANL/NE-16/19, 2017.
- [2] R. Hu, L. Zou, and G. Hu, *SAM User's Guide*, Argonne National Laboratory, ANL/NSE-19/18, 2019.
- [3] U.S. DOE-NE Nuclear Energy Advisory Committee, *Assessment of Missions and Requirements for a New U.S. Test Reactor*, 2017.
- [4] M. T. Farmer, C. Grandy, S. G. Wiedmeyer, et al., *Unpublished information*, Argonne National Laboratory, 2018.
- [5] J. C. Carter et al., *SAS1A, A Computer Code for the Analysis of Fast-Reactor Power and Flow Transients*, Argonne National Laboratory, ANL-7607, 1970.
- [6] F. E. Dunn et al., *The SAS2A LMFBR Accident-Analysis Computer Code*, Argonne National Laboratory, ANL-8138, 1974.
- [7] M. G. Stevenson et al., "Current Status and Experimental Basis of the SAS LMFBR Accident Analysis Code System," in *Proceedings of the Fast Reactor Safety Meeting*, Beverly Hills, CA, 1974, pp. 1303-1321.
- [8] F. E. Dunn, "Code Portability and Data Management Considerations in the SAS3D LMFBR Accident-Analysis Code," presented at the National Computer Conference, Chicago, IL, 1981.
- [9] G. Birgersson et al., *The SAS4A LMFBR Accident Analysis Code System*, Argonne National Laboratory, ANL/RAS-83-38, Rev. 2, Vol. 1 and 2, 1988.
- [10] A. M. Tentner and Kalimullah, *SAS4A Analysis of the M7 Metal Fuel Treat Experiment*, Argonne National Laboratory, ANL-IFR-186, 1993.
- [11] F. E. Dunn et al., *The SASSYS-1 LMFBR Systems Analysis Code*, Argonne National Laboratory, ANL/RAS-84-14, Rev. 1, 1987.
- [12] C. E. Till, "Fast Reactor Directions: The LMR Integral Fast Reactor Program at Argonne," in *Proceedings of the International Fast Reactor Safety Meeting*, Snowbird, UT, 1990.
- [13] Argonne National Laboratory, *The SAS4A/SASSYS-1 LMR Analysis Code System, Vol. 1-5*, ANL-FRA-1996-3, 1996.
- [14] J. Sackett et al., "EBR-II Test Programs," in *Proceedings of the International Fast Reactor Safety Meeting*, Snowbird, UT, 1990.
- [15] T. H. Fanning, ed., *The SAS4A/SASSYS-1 Safety Analysis Code System: User's Guide*, Argonne National Laboratory, ANL/NE-12/4, 2012.
- [16] D. Gaston, et al., "MOOSE: A Parallel Computational Framework for Coupled Systems of Nonlinear Equations," *Nuclear Engineering and Design*, vol. 239, pp. 1768-1778, 2009.
- [17] B. S. Kirk, et al., "libMesh: a C++ Library for Parallel Adaptive Mesh Refinement/Coarsening Simulations," *Engineering with Computers*, vol. 22.3-4, pp. 237-254, 2006.
- [18] S. Balay, et al., *PETSc Users Manual: Rev. 3.10*, Argonne National Laboratory, ANL-95/11 Rev. 3.10, 2018.
- [19] A. Toti, J. Vierendeels, and F. Belloni, "Improved Numerical Algorithm and Experimental Validation of a System Thermal-Hydraulic/CFD Coupling Method for

- Multi-scale Transient Simulations of Pool Type Reactors," *Annals of Nuclear Energy*, vol. 103, pp. 36-48, 2017.
- [20] S. Kutateladze, V. Borishanskii, and I. Novikov, "Heat Transfer in Liquid Metals," *Journal of Nuclear Energy II*, vol. 9, pp. 214-229, 1959.
- [21] "Personal communication between D. O'Grady and T. Sumner," ed, 2019.
- [22] J. Yoo, J. Chang, J. Lim, *et al.*, "Overall System Description and Safety Characteristics of Prototype Gen IV Sodium Cooled Fast Reactor in Korea," *Nuclear Engineering and Technology*, vol. 48, pp. 1059-1070, 2016.
- [23] T. Sumner, F. Heidet, T. H. Fanning, *et al.*, *Unpublished information*, Argonne National Laboratory, 2018.

Nuclear Science and Engineering Division
Argonne National Laboratory
9700 South Cass Ave, Bldg 208
Argonne, IL 60439-4842

www.anl.gov

U.S. DEPARTMENT OF
ENERGY

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