

RECENT DEVELOPMENTS FOR THE SAS4A/SASSYS-1 SAFETY ANALYSIS CODE

T. H. Fanning, J. W. Thomas, T. Sumner, and A. Brunett

Nuclear Engineering Division
Argonne National Laboratory
9700 S Cass Ave
Argonne, IL 60439-4842
fanning@anl.gov

ABSTRACT

SAS4A/SASSYS-1 is a software simulation tool used to perform deterministic analysis of transients in sodium-cooled reactors. This paper summarizes recent developments to extend the capabilities of SAS4A/SASSYS-1 and to modernize internal data management. The motivation for performing these updates stems from the growing importance of SAS4A/SASSYS-1 to a number of U.S. Department of Energy programs as well as domestic and international collaborations.

New modeling capabilities include a detailed sub-channel model for intra-assembly flow and temperature simulations; visualization capabilities for sub-channel results; an extended decay heat model to support advanced, actinide-bearing fuels; treatment of axial expansion feedback from assembly structures; support for spatial kinetics with new models for dynamic control-rod motion; support for user-defined and heavy liquid-metal coolants; a coupling capability to use external computational fluid dynamics solvers to resolve flow distribution and thermal stratification effects in large volumes; and a capability to couple with external power conversion system models.

KEYWORDS

safety analysis, sodium-cooled fast reactor

1. INTRODUCTION

SAS4A/SASSYS-1 is a software simulation tool used to perform deterministic analysis of anticipated events as well as design basis and beyond design basis accidents for sodium cooled fast reactors.[1] With its origin as SAS1A in the late 1960s, the SAS series of codes has been under continuous development for over forty-five years. The most significant development period was in the 1970s and 1980s to support the Fast Flux Test Facility and the Clinch River Breeder Reactor program. Considerable development continued into the 1990s in support of the Advanced Liquid Metal Reactor program, during which the modeling emphasis shifted to inherent safety and metallic fuel performance. In the twenty years since the termination of the ALMR program, modeling developments have continued but at a slower pace.

The reduction in the development effort on SAS4A/SASSYS-1 ironically coincided with rapid growth in the development of modern, object-oriented programming practices that greatly facilitate code development and maintenance. For a time, SAS4A/SASSYS-1 continued in a state that reflected legacy software development practices. Significant improvements have since been made by modernizing the data-management strategies to eliminate those that were developed for resource-limited computing hardware.

Modernization of the SAS4A/SASSYS-1 code system and updates to the code documentation are motivated by the relevance of the simulation capability to a number of U.S. Department of Energy programs as well as domestic and international collaboration.[2,3] In the sections that follow, a brief historical background is offered for context, a summary of recent developments is given, and a description of current developments is provided. The developments described here will be released as Version 5.1 in late 2015.

2. HISTORICAL BACKGROUND

In the late 1960s, the U.S. Atomic Energy Commission gave development of a liquid-metal-cooled fast reactor (LMR) a high priority, and the development of the Fast Flux Test Facility (FFTF) became a cornerstone of that program. To provide adequate support for the FFTF and for the expected LMRs to follow, a major base technology program was established which provided a continuous stream of experimental information and design correlations. This experimental data would either confirm design choices or prove the need for design modifications. At the time, the “tremendous amount of data and experience pertaining to thermal design” of LMRs was expected to provide the technical foundation for the future commercial development of LMRs.[4]

Along with the generation of experimental data came the development of safety analysis methods that used that data in correlations for mechanistic, probabilistic, or phenomenological models. These models were developed for a variety of needs ranging from individual components, such as heat exchangers, pumps, or containment barriers, to whole core or even whole-plant dynamics. A major portion of the overall effort since that time has been allocated to safety considerations, and the SAS4A/SASSYS-1 safety analysis code is the result of that dedication.

Development of the SAS series of codes[5–8] began in the mid 1960s. SAS was originally developed to model the transient behavior of several representative coolant channels to evaluate the initiating phase of hypothetical core disruptive accidents. SAS1A originated from a sodium-boiling model and 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 to the SAS2A computer code[6] which included a detailed multiple slug and bubble coolant boiling model which greatly enhanced the ability to simulate the initiating phases of loss-of-flow (LOF) and transient overpower (TOP) accidents up to the point of cladding failure and fuel and cladding melting.

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 FFTF. In anticipation of LOF and TOP analysis requirements for licensing of the Clinch River Breeder Reactor Plant (CRBRP), new fuel element deformation, disruption, and material relocation models were written for the SAS4A version of the code,[8] which saw extensive validation against TREAT M-Series test data. In addition, a variant of SAS4A, named SASSYS-1, was developed with the capability to model ex-reactor coolant systems to permit the analysis of accident sequences involving or initiated by loss of heat removal or other coolant system events. This allows the simulation of whole-plant dynamics feedback for both shutdown and off-normal conditions, which have been validated against EBR-II Shutdown Heat Removal Test (SHRT) data and data from the FFTF LOF tests.

Although SAS4A and SASSYS-1 were portrayed as two computer codes, they had always shared common code architectures, the same data management strategy, and the same core channel representation. Subsequently, the two code branches were merged into a single code referred to as SAS4A/SASSYS-1. At this point, a more modern version notation was also adopted. Version 2.1 of the SAS4A/SASSYS-1 code was distributed in the late 1980s and served as the starting point for international oxide fuel model developments.

Beyond the release of Version 2.1, revisions to SAS4A/SASSYS-1 continued throughout the Integral Fast Reactor (IFR) program between 1984 and 1994,[9] culminating with the completion of Version 3.0 in 1994.[10]. During this time, the modeling emphasis shifted towards metallic fuel and accident prevention by means of inherent and passive safety mechanisms. This resulted in 1) the addition of new models and modification of existing models to treat metallic fuel, its properties, behavior, and accident phenomena, and 2) addition and validation of new capabilities for calculating whole-plant design basis transients, with emphasis on the EBR-II reactor and plant.[11,12] The whole-plant dynamics capability of the SASSYS component plays a vital role in predicting passive safety feedback. Without it, meaningful boundary conditions for the core channel models are not available, and accident progression is not reliably predicted.

By the mid 1990s, SAS4A/SASSYS-1 Version 3.1 had been completed as a significant maintenance update, but it was not released until 2012.[1]

3. RECENT DEVELOPMENTS

In the time since the development of Version 3.1, several modeling additions and enhancements have been made to meet U.S. Department of Energy programmatic needs. Significant among these are the following:

- Detailed sub-channel models to resolve intra-assembly temperature and flow distributions
- 3D visualization capabilities for sub-channel results
- Extended decay-heat models to support long-term transients and complex, actinide-bearing fuels
- Support for coupling with external CFD simulations to resolve flow distribution and thermal stratification effects
- Treatment of axial expansion feedback from assembly structural components
- Support for spatial kinetics (requires DIF3D-K)
- Extension of the control-system model to include sinusoidal functions that can be used to represent seismic oscillation effects
- Addition of heavy liquid-metal coolants (lead and lead-bismuth eutectic)
- Support for user-defined coolant properties
- Detailed steam-generator model updates
- Modernization of data management practices
- Expansion of verification testing

Because the sub-channel modeling and CFD coupling capabilities have been covered extensively in previous publications (see References 13–16 and 17–19, respectively) they are not repeated here. Some of the other modeling capabilities described above are summarized in the following subsections.

3.1 Extended Decay Heat Modeling

A more detailed decay heat model has been developed that allows greater flexibility than the previous model and can more accurately represent decay heat during long-term transients. The key features of the new model include extending the number of exponential terms that can be used to represent decay heat from six to twenty-four, the inclusion of built-in decay heat parameters from the American Nuclear Society/American National Standards Institute (ANS/ANSI) standard for decay heat power in light water reactors (LWRs) [20], the ability to mix multiple user-supplied and/or built-in decay heat curves within a single region, and the inclusion of a pre-defined non-decay-heat region.

For cases involving reactor operation at constant power followed by a sudden shutdown, using the tabular data in the ANS standard is fairly straightforward. On the other hand, for analyzing transients in which rapid shutdown does not occur but in which the reactor power is calculated as a function of time in response to inherent feedback mechanisms, the methods prescribed cannot be used directly, since the fission power as a function of time is not known beforehand.

3.1.1 Transient Decay Heat Calculations

At the beginning of a transient calculation, the initial decay heat power and fission power are known as a result of the steady-state initialization (see below). From that point on, fission power is determined based on the point (or spatial) kinetics equations. Given the normalized fission power, the normalized decay power can be solved. To facilitate notation, a term for *decay heat precursors* (i.e. energy) is introduced, where the decay power $P_d(t)$ is defined in terms of decay-heat precursors, $H_n(t)$, by $P_d(t) = \sum \lambda_n H_n(t)$. The sum over n includes all precursors for all fissionable isotopes, with appropriate weighting. At transient time step k , the time varies from t_k to $t_k + \tau$:

$$H_n(t_k + \tau) = H_n(t_k)e^{-\lambda_n\tau} + \beta_n e^{-\lambda_n\tau} \int_0^\tau P_f(t_k + t)e^{\lambda_n t} dt$$

where β_n is a decay heat precursor yield with decay constant λ_n . SAS4A/SASSYS-1 uses a kinetics solver based on the Kaganove method [21] that is second-order accurate in time. The fission amplitude is represented by the polynomial, $P_f(t_k + t) = P_0 + P_1 t + P_2 t^2$. At the end of time step k , then, the decay heat precursors are

$$H_n(t_{k+1}) = H_n(t_k)e^{-\lambda_n\tau} + \frac{\beta_n}{\lambda_n} \left[P_0 I_0(\tau) + \frac{P_1 I_1(\tau)}{\lambda_n} + \frac{P_2 I_2(\tau)}{\lambda_n^2} \right]$$

where the $I_i(\tau)$ represent recursive solutions for the integral terms:

$$\begin{aligned} I_0(\tau) &= 1 - e^{-\lambda_n\tau} \\ I_1(\tau) &= \lambda_n\tau - I_0(\tau) \\ I_2(\tau) &= \lambda_n^2\tau^2 - 2I_1(\tau) \end{aligned}$$

3.1.2 Steady-State Initialization

Prior to transient initiation, steady-state fission and decay power need to be determined. This is typically accomplished by defining a number of constant *total power* intervals with power P_t^k . Assuming no initial decay heat is present (i.e. fresh fuel with no fission products) the initial fission power will be equal to the initial total power. However, as decay heat builds, fission power will decrease to maintain constant power. The governing equation for a single decay heat precursor during constant power interval k is

$$H_n(t_k + \tau) = H_n(t_k)e^{-\lambda_n\tau} + \beta_n e^{-\lambda_n\tau} \int_0^\tau \left[P_t^k - \sum_{n'} \lambda_{n'} H_{n'}(t_k + t) \right] e^{\lambda_n t} dt$$

This equation represents a large set of coupled equations, especially when multiple fissionable isotopes contribute to a single decay heat region in the core. To partially decouple the equations, two assumptions are made. First, the fraction of fission power contributed by each fissionable isotope is assumed to be fixed during each constant-power interval. Second, the fission power is assumed to be a constant such that the total power at the *end* of the constant-power interval matches the value supplied by the user. The first assumption only applies to decay heat regions that use more than one decay heat curve and may not be

valid where there is significant depletion or breeding of fissionable isotopes during the course of steady-state initialization.

The second assumption was chosen for a number of reasons. First, by matching power at the end of the initiating power interval, it maintains continuity between the steady-state initialization and the transient calculation. Second, it can be shown to introduce at most only a few hundredths of a percent error in most cases, and up to a few tenths of a percent error in very unusual situations. Third, it correctly predicts the two bounding cases of fresh fuel (no decay heat) and infinitely long, steady-state equilibrium. With these assumptions, it can be shown that the fission power that satisfies the above equation is

$$P_f^k = \frac{P_t^k - \sum \lambda_n H_n(t_k) e^{-\lambda_n \tau}}{1 + \sum \beta_n (1 - e^{-\lambda_n \tau})}$$

and the fission power at the end of steady state becomes the initial power for the transient calculation.

3.2 Axial Expansion of Associated Structure

Reactivity feedback modeling in SAS4A/SASSYS-1 accounts for numerous phenomena, including fuel, cladding, and coolant density changes; fuel Doppler effects; fuel and clad melting and relocation; sodium boiling; radial expansion; control-rod driveline expansion; and reactor vessel expansion. Depending on the reactor design and the nature of the transient, any one of these may contribute significant reactivity to the evolution of the simulation.

The representation of channels in SAS4A/SASSYS-1 includes components for fuel, clad, coolant, and “associated structure” (see Figure 1). The associated structure is a simplified model that is often used to represent the thermal effects of the assembly duct wall, wire wrap, or interstitial (inter-assembly) sodium. Although these components also contribute to reactivity feedback, their contributions were typically lumped into an existing model, such as the coolant or cladding reactivity feedback models. This results in an implicit assumption that the temperature change for these components is similar to the temperature change of the coolant or cladding.

For most designs and transients, this assumption is acceptable. However, designs were encountered in which the structure composition was different from the clad or where the interstitial volume fraction was atypical. In these cases, questions arose about the validity of the assumption.

An additional reactivity feedback model has been incorporated into SAS4A/SASSYS-1 to account for the axial thermal expansion of the associated structure. This model allows users to treat the reactivity feedback due to cladding and structural temperature changes separately. Additionally, the structure reactivity worth can be adjusted to account for interstitial coolant in an analogous fashion to lumping interstitial and subassembly coolants. This method improves the accuracy of modeling the reactivity effect associated with temperature changes in the interstitial coolant without requiring the complexity of developing an explicit model.

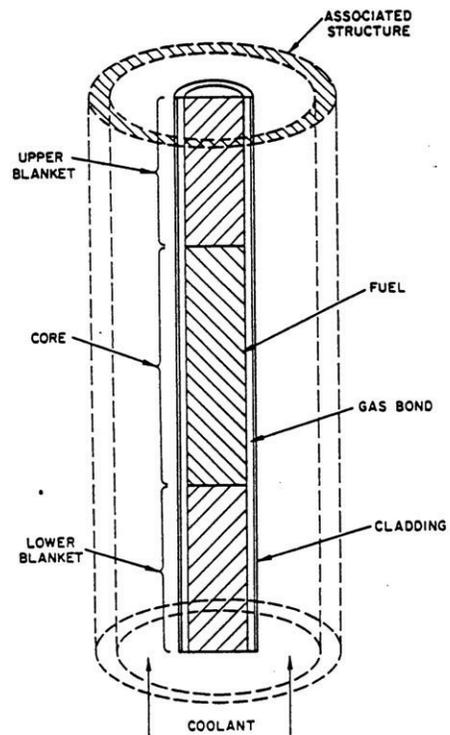


Figure 1: SAS4A/SASSYS-1 Channel

Subsequent testing of the new model showed that the explicit treatment did not offer any significant accuracy advantages compared the previous practice of adjusting existing models. Nevertheless, the new model simplifies the process of specifying input for the reactivity feedback models.

3.3 Alternative Liquid Metal Coolants

SAS4A/SASSYS-1 continues to focus primarily on transient analyses for sodium-cooled reactors. In the evolution from SAS3D to SAS4A, sodium properties were updated based on extensive material property studies conducted during the 1980s and early 1990s.[22] Sodium-potassium eutectic properties were added to support passive safety decay heat removal loops, and heavy water properties were added to support production reactor studies. During the 1990s, lead and lead-bismuth eutectic properties were added to support studies of accelerator-driven systems, and user-defined correlation coefficients are supported to provide even more flexibility.

Of course lead and LBE properties are also useful for evaluating lead-cooled fast reactor concepts. SAS4A/SASSYS-1 has recently been used to study natural circulation and passive safety transient behavior in the ELECTRA concept.[23]

Despite the support for alternative coolants, two-phase coolant dynamics and severe accident phenomena are only supported for sodium. Significant research would be required to understand fuel and cladding relocation dynamics in the presence of other fluids.

3.4 Improved Data Management

Most of SAS4A/SASSYS-1 originated on computing architectures with extremely limited memory capacities compared to current hardware. Code development practices revolved around minimizing memory usage. A fundamental strategy was to overlay, or reuse, the same memory locations for multiple different models. Data that was not needed for an immediate calculation was cached to some larger capacity storage, such as disk or tape. When part of a calculation was completed, its results would be cached, and other data would be loaded into memory to continue the next phase of the calculation.

Even though it came with serious drawbacks, this data management strategy was essential for small memory machines. With the availability of larger memory machines, memory replaced disk for cache storage, but the memory overlay model still persisted. Consumer computing hardware today has three orders of magnitude more memory than in the 1990s, so now the drawbacks impose limitations on code development and performance with no return benefit. These limitations include

- **Maintainability:** Code improvements that change the length or interpretation of the shared memory location can have unintended, far-reaching consequences.
- **Scale:** The current data management strategy is limited to 32-bit addressing, which imposes a practical upper limit of around 10,000 channels. This means full-core sub-channel analysis is not yet possible.
- **Speed:** Even though data transfer in memory is much faster than data transfer to disk, it is still much slower than direct access.
- **Parallelism:** Because channels are generally independent, they could be solved in parallel. The current channel model depends on shared memory locations, so simultaneous use is not possible, and multi-threaded parallelism is not practical.

To remove these limitations, a number of significant changes have been implemented in the data management strategy in SAS4A/SASSYS-1. Updates that improve code maintainability are being prioritized ahead of scale, speed, and parallelism. To this end, updates have focused on developing object-

oriented data modules that encapsulate many of the abstract data overlays described above into concrete user-defined data types with well-defined structures. New or existing features of SAS4A/SASSYS-1 that use the new data modules can alter them without concern for disrupting other features of the code because each data module is independent of the others.

A hybrid data management approach was devised to significantly reduce the extent of code changes that were needed to use the new modules. Each of the new modules maintains its own, semi-private shared memory to accommodate portions of the existing code that expect to access data via shared memory. The hybrid data management approach greatly accelerated deployment of the new data modules. But it doesn't completely eliminate the overhead of shared memory data transfers since each module implements a private copy. Nevertheless, the approach allows future updates to be added at an incremental pace without disrupting the entire code.

3.5 Code Verification

An extensive set of test cases has been created to perform verification of SAS4A/SASSYS-1 as the code continues to evolve. The cases defined in the test suite cover a wide range of basic code capabilities. Analytical solutions were developed for many of the cases; for the more complex cases, simple numerical models were used to provide reference solutions. Comparisons between SAS4A/SASSYS-1 predictions and the reference solutions show negligible errors as determined by the discretization used in the code. Significant discrepancies between SAS4A/SASSYS-1 and the reference solutions would indicate a deficiency in the code that needs to be addressed.

The test cases were designed to build upon each other. Incremental changes allow each test to focus on one particular area of the code. By creating test cases with small changes, issues within the code can be identified more efficiently if one test fails but others do not. For the base test case, a simple single pin was defined with a flat axial power profile and constant material properties. The reference solution provides the axial and radial temperature distributions in the fuel, cladding, and coolant as well as the axial coolant pressure distribution.

Additional test cases were created to test temperature-dependent fuel, cladding, and coolant material properties, the point kinetics, decay heat, and reactivity feedback models, and many aspects of the thermal hydraulics calculations for the PRIMAR-4 heat removal systems module. For almost all cases, the difference between the SAS4A/SASSYS-1 and reference solutions was negligible. An issue with the acceleration pressure drop for pipes was identified and has already been corrected. The test suite will continue to expand to improve code coverage.

4. CURRENT DEVELOPMENTS

4.1 Spatial Kinetics and Control-Rod Motion

Application of spatial kinetics to SFR transient analysis has not received significant attention because typical fast reactor core designs are very tightly coupled.[24,25] Separating the spatial power distribution from the time-varying amplitude allows the use of computationally efficient point kinetics. Therefore, it is not surprising that the coupling between SAS4A/SASSYS-1 and the spatial kinetics code DIF3D-K was originally performed to support the analysis of *water*-cooled reactors. In particular, an internal version of SAS4A/SASSYS-1 (called "SAS-HWR") was developed to support the analysis of a proposed heavy-water production reactor.[26] Later, a second internal version of SAS4A/SASSYS-1 (called "SAS-RBMK") was developed to analyze the Chernobyl accident.[27] These internal versions were validated in the OECD Main Steam Line Break benchmark exercise.[28]

The coupling interface from these internal versions has been ported back to the main SAS4A/SASSYS-1 code to provide a spatial kinetics capability for SFR analyses. This capability may be important for novel designs such as long-lived, high burnup cores like TWR[29] or axial heterogeneous cores like ASTRID[30]. Furthermore, spatial kinetics capabilities allow for the evaluation of transients driven by asymmetric control-rod motion. It is this latter use that is the subject of this section.

Often in SAS4A/SASSYS-1 transient analysis, core channels are defined to represent core assemblies that are significant in a thermal-hydraulic sense. This usually includes core and blanket assemblies, but may also include reflector and shield assemblies. Non-fueled assemblies, particularly control assemblies, often are not modeled explicitly. Although not significant in a thermal-hydraulic sense, these assemblies are essential in a neutronic calculation. To accommodate this, the DIF3D-K coupling interface (DCI) includes models for *external* channels that are not part of the SAS4A/SASSYS-1 model, but whose compositions can be manipulated during the transient to affect the spatial kinetics solution and transient power distribution.

In the DCI, external channels have been modified to support two composition layers. The “rods-out,” or normal, composition is the same as in the original DCI. For control rod positions, this composition might include coolant and structure consistent with an empty position. The “rods-in” composition is new and might include coolant, structure, and absorber compositions consistent with an inserted control rod. The rods-in composition is movable as a function of time and replaces a portion of the rods-out composition depending on position.

The axial position of the lower tip of the rods-in composition can be specified in a number of different ways. If the control rod motion is known *a priori*, the simplest approach is to provide a user-defined function that returns the axial position as a function of time. This capability can be used to define a prescribed rod withdrawal. And since multiple control rods may be defined, complex, asymmetric control rod motions can be represented.

Another way to define rod tip positions is through the control system module of SAS4A/SASSYS-1. This module can be used to define arbitrary logic that is dependent on transient plant data. For example, channel inlet and outlet temperatures or primary coolant system temperatures, flows, or pressures can be used to trigger control rod motion or stuck rod scenarios.

4.2 Coupling with External Power Conversion Simulations

In prior work[31], SAS4A/SASSYS-1 was “coupled” to a super-critical CO₂ power conversion system (PCS) code through code restarts at every time step. While useful in assessing the feedback effects between the reactor and this specific process plant, the inefficient means of code linking is not suitable as a general interface between SAS4A/SASSYS-1 and a PCS code. The ability to interface with any PCS code has been implemented directly in SAS4A/SASSYS-1, significantly improving performance. Incorporation of this interface enables the system code to be extremely flexible in that the effects of any advanced power conversion cycle on a primary system can now be analyzed.

A new component, ExtHX (External Heat EXchanger), was created within the primary coolant system module, PRIMAR-4. The ExtHX module communicates with a PCS code through input/output files, although other data transfer mechanisms could be used. At a high level, the ExtHX module operates on the following cycle:

- Sodium side inlet temperature and mass flow rate for each coupled flow element are determined by SAS4A/SASSYS-1 and passed to the PCS code, along with timing synchronization information.

- The power conversion simulation advances a single time step with these boundary conditions. The PCS is responsible for determining temperature distributions, sodium-side outlet temperatures, and effective gravity head, and returning these to SAS4A/SASSYS-1.
- The PRIMAR-4 component of SAS4A/SASSYS-1 completes the TH calculation for the sodium side loop.

Implementation of this module is shown below for two test cases of the AFR-100, an advanced small modular reactor design.[32] In these cases, the reactor is not paired with any specific PCS, so it should be emphasized that this is solely a functionality demonstration, and not an analysis of the AFR-100 design or the performance of a PCS. In both demonstration cases, the reactor is operating at full power at the beginning of the transient.

In Case 1, discrete changes in the heat removal capacity of the PCS are implemented over several hours to emulate intentional programmatic changes in the PCS. It is assumed that the PCS trips at 100 seconds and heat removal is reduced by 50%. The system remains at 50% for one hour and then an additional 50% of capacity is lost for 30 minutes. Heat rejection is restored to 50% capacity for 30 minutes, then to 75% capacity for one hour. At 10800 seconds into the PCS transient, capacity of the PCS is restored to 100%. The effects of these load demand changes on the interface element inlet and outlet temperatures and core outlet temperature are shown in Figure 2.

In Case 2, a cosine wave is imposed on the PCS heat rejection capacity to emulate dynamic loading on the primary system. In this case, the normalized heat rejection is assumed to cycle between 100% and 50% over a period of one hour. The effect of continuous changes in PCS capacity on the inlet and outlet temperatures of the PCS interface element and the propagation to the primary system is shown in Figure 3.

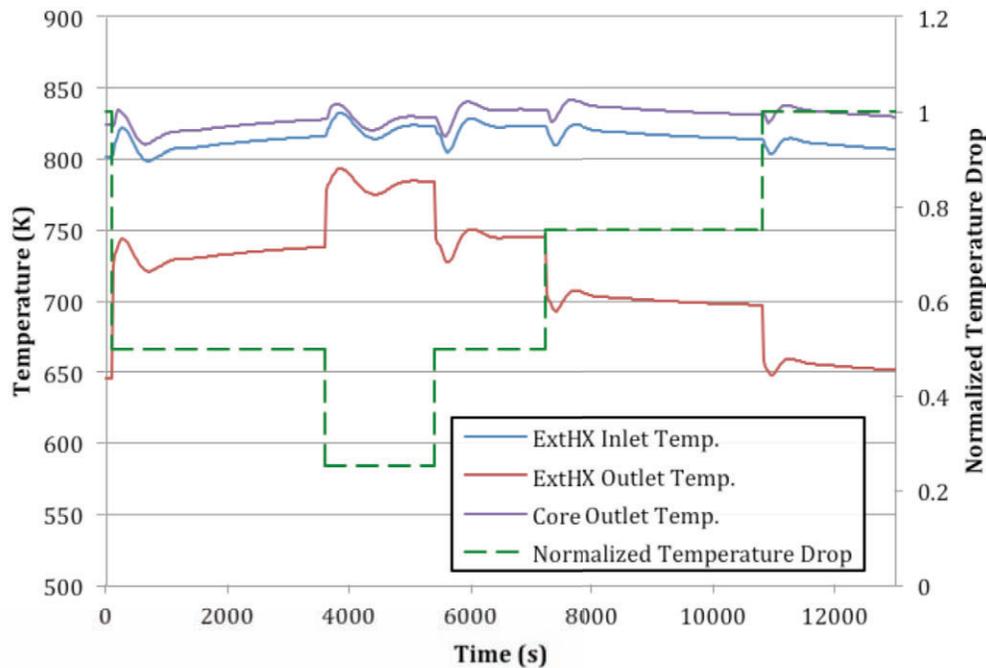


Figure 2: Inlet/outlet temperatures of PCS interface point and core outlet temperature for discrete changes in PCS capacity (Case 1).

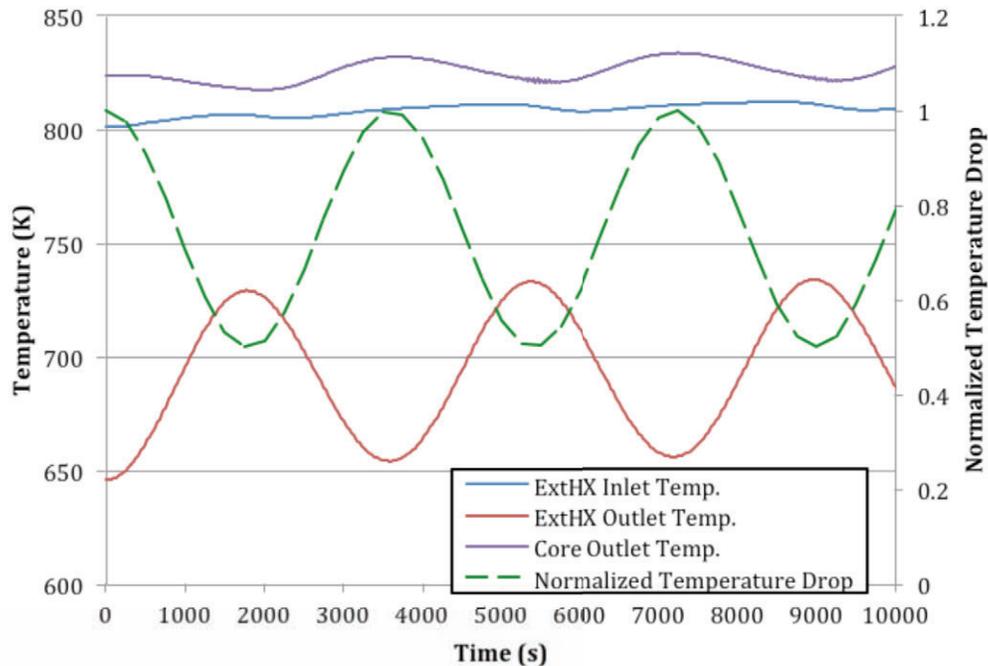


Figure 3: Inlet/outlet temperatures of PCS interface point and core outlet temperature for cosine imposition on PCS capacity (Case 2).

5. SUMMARY

Much of the development history of SAS4A/SASSYS-1 was uniquely focused on severe accident conditions in support of a single program. Current developments, however, are driven by a broader spectrum of modeling needs to support inherent safety and design optimizations. Code development and modernization are being continued to minimize gaps in the simulation capabilities for sodium fast reactor accident analysis and reactor safety. Some of the more recent developments include extended decay heat modeling, structure axial expansion, spatial kinetics with control-rod motion, and coupling with external power conversion systems.

These developments help ensure that the SAS4A/SASSYS-1 safety analysis code system continues meet the objectives of U.S. Department of Energy programs and domestic and international collaborations.

6. ACKNOWLEDGMENTS

This work was performed by Argonne National Laboratory and was supported by the U.S. Department of Energy, Office of Nuclear Energy, under contract DE-AC02-06CH11357.

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