Benchmark Modeling and Simulation of the FFTF LOFWOS Test #13 Using SAM

Nuclear Science and Engineering Division

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ABSTRACT

The Fast Flux Test Facility (FFTF) was a 400 MW thermal powered, oxide-fueled, liquid sodium cooled test reactor, built to assist development and testing of advanced fuels and materials for fast breeder reactors. In July 1986, a series of unprotected Loss of Flow Without Scram (LOFWOS) transients were performed in FFTF as part of the Passive Safety Testing (PST) program. The LOFWOS Test #13, which was initiated at 50% power and 100% flow with the pump pony motors left off, has been chosen as a benchmark case by IAEA to support collaborative efforts within international partnerships on the validation of simulation tools and models in the area of sodium fast reactor passive safety in an IAEA Coordinated Research Project (CRP), launched in October 2018.

The System Analysis Module (SAM) is an advanced and modern system analysis tool under development at Argonne National Laboratory for advanced non-LWR safety analysis. It utilizes the object-oriented application framework MOOSE to leverage the modern software environment and advanced numerical methods. The capabilities of SAM are being extended to enable the transient modeling, analysis, and design of various advanced nuclear reactor systems.

To participate the IAEA CRP and enhance the SAM validation base for advanced reactor transient safety analysis, benchmark simulations of the FFTF LOFWOS Test #13 are performed using the SAM code. In this first phase of the validation effort, the thermal-hydraulic behavior of the reactor system is the focus and the reactor kinetics is not considered in the SAM FFTF model. Instead, the results of Argonne's neutronics calculations are directly used, including the power shape of the active core region and the power history during the transient. The simulation results of FFTF at steady state agreed well with the measured data from the test. During the transient, reasonably good agreement were also obtained. Future work to improve the model will focus on introducing the reactivity predictions into the model, as well as better understanding or resolving the current discrepancies with the measured data.

TABLE OF CONTENTS

ABSTRACT.....	i
TABLE OF CONTENTS.....	ii
TABLE OF FIGURES	iii
TABLE OF TABLES	v
ACRONYMS	vi
1. Introduction.....	1
2. FFTF LOFWOS #13 Test	2
3. SAM Model of FFTF	5
3.1 Reactor Vessel Model	5
3.2 Pump model	10
3.3 Heat exchanger model	12
3.4 Primary system loop	12
3.5 Secondary system loop	13
3.6 Numerical setup	14
4. LOFWOS Test #13 Simulation Results.....	15
4.1 Results for steady state initialization	15
4.2 Results for transient analysis	17
5. Summary and Conclusions	30
ACKNOWLEDGMENTS	31
REFERENCES	31
Appendix A. Implementation of fuel thermo-physical properties in SAM FFTF model	32

TABLE OF FIGURES

Figure 2.1 Overview of FFTF Coolant system	2
Figure 2.2 Normalized total reactor power for FFTF LOFWOS #13	3
Figure 3.1. Schematics of the FFTF model.....	5
Figure 3.2 FFTF core layout and assembly flow zones	6
Figure 3.3 FFTF core model scheme	8
Figure 3.4 SAM model zones and regions for driver fuel assembly	10
Figure 3.5 Iterative process to determine primary pump head	11
Figure 4.1 Peak fuel temperature of different core channels prior to transient	16
Figure 4.2 Axial temperature distributions of PIOTA Row 2 at different radial locations	17
Figure 4.3 Axial temperature distributions of PIOTA Row 6 at different radial locations	17
Figure 4.4 Primary pump discharge pressure	18
Figure 4.5 Mass flow rate of one primary loop	19
Figure 4.6 Secondary loop cold leg temperature	19
Figure 4.7 Secondary loop hot leg temperature	20
Figure 4.8 Primary loop cold leg temperature	21
Figure 4.9 Primary loop hot leg temperature	21
Figure 4.10 Reactor vessel inlet and outlet temperatures	22
Figure 4.11 Inlet and outlet temperatures of the IHX primary side.....	23
Figure 4.12 Inlet and outlet temperatures of the IHX secondary side	23
Figure 4.13 Outlet temperature of PIOTA, Row 2, assembly-to-assembly heat transfer considered with actual contacting area.....	24
Figure 4.14 Outlet temperature of PIOTA, Row 6, assembly-to-assembly heat transfer considered considered with actual contacting area.....	25
Figure 4.15 Outlet temperature of PIOTA, Row 2, no assembly-to-assembly heat transfer	26
Figure 4.16 Outlet temperature of PIOTA, Row 6, no assembly-to-assembly heat transfer	26
Figure 4.17 Outlet temperature of PIOTA, Row 2, assembly-to-assembly heat transfer with 50% effective contact area	27
Figure 4.18 Outlet temperature of PIOTA, Row 6, assembly-to-assembly heat transfer considered considered with 50% effective contacting area	27
Figure 4.19 Peak coolant temperature of non-fuel assemblies	28
Figure 4.20 Peak coolant temperature of fuel assemblies.....	28
Figure 4.21 Peak cladding temperature of fuel assemblies.....	29

Figure 4.22 Peak fuel temperature of fuel assemblies	29
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TABLE OF TABLES

Table 2.1 Initial conditions of FFTF LOFWOS Test #13	2
Table 3.1. Initial core flow distribution	7
Table 3.2 FFTF core model parameters	8
Table 3.3 Primary pump parameters	11
Table 3.4 Primary loop piping segments	12
Table 3.5 Heat sources and sinks of primary loop at nominal full power conditions.....	13
Table 3.6 Secondary loop piping segments	14
Table 3.7 Heat sources and sinks of secondary loop at nominal full power conditions	14
Table 4.1 Core channel flow distributions	15

ACRONYMS

FFTF	Fast Flux Test Facility
GEM	Gas Expansion Module
ICSA	In Core Shim Assembly
IHX	Intermediate Heat Exchanger
LOFWOS	Loss of Flow Without Scram
MOTA	Materials Open Test Assembly
PIOTA	Proximity Instrumented Open Test Assembly
PST	Passive Safety Testing
QoI	Quantity of Interest
RTD	Resistance Temperature Detectors
SAM	System Analysis Module
SFR	Sodium Fast Reactor

1. Introduction

The Fast Flux Test Facility (FFTF) was a 400 MW thermal powered, oxide-fueled, liquid sodium cooled fast reactor. It was built to assist the development and testing of the advanced fuels and materials for fast breeder reactors. In July 1986, a series of unprotected transients were performed in FFTF as part of the Passive Safety Testing (PST) program. Among these transients were 13 unprotected Loss of Flow Without Scram (LOFWOS) tests. The goals of this program included confirming the safety margins of FFTF as a liquid metal reactor, providing data for computer code validation, and demonstrating the inherent and passive safety benefits of its specific design features.

The LOFWOS Test #13, which was initiated at 50% power and 100% flow with the pump pony motors left off, is chosen as a benchmark case to support collaborative efforts within international partnerships on the validation of simulation tools and models in the area of sodium fast reactor passive safety. The detailed specification of the FFTF LOFWOS Test #13 has been completed by Argonne in FY17 and served as the basis for a new Coordinated Research Project with the IAEA [1], which was launched in October 2018.

As part of the assessment efforts for the System Analysis Module (SAM) [2,3], benchmark simulation of FFTF LOFWOS Test #13 was performed to participate the IAEA CRP. SAM is an advanced and modern system analysis tool being developed at Argonne National Laboratory for advanced non-LWR safety analysis. SAM code development has attracted a wide range of interests from the advanced non-LWR community, and recently, U.S. Nuclear Regulatory Commission (U.S. NRC) also stated its intent to use SAM as the system and core thermal-hydraulics analysis code for design basis events of advanced non-LWRs.

The SAM FFTF model was developed solely based on the technical specifications of FFTF and the LOFWS Test #13 provided in the benchmark specification. In this first phase of the modeling effort, the thermal-hydraulic behavior of the reactor system is the focus and the reactor kinetics is not considered in the SAM model. Instead, the results of Argonne's neutronics calculations are directly used for the power shape of the active core region and the power history during the transient.

The following of the report is organized in the following manner. Section 2 of this report provides a brief overview and specifications of FFTF and the LOFWOS Test #13. Section 3 describes the modeling details of the SAM FFTF model. Section 4 presents the simulation results and discussions for the LOFWOS #13 Test. Section 5 summarizes the work performed so far and the planed future work.

2. FFTF LOFWOS #13 Test

FFTF was a 400 MW-thermal loop type SFR. Heat was removed from reactor core by liquid sodium circulating under low pressure. Sodium exited the reactor vessel and flew into one of three primary sodium loops. The heat was then transmitted to the secondary sodium loop through three Intermediate Heat Exchangers (IHX), with one in each primary loop. FFTF did not generate electricity, instead rejecting all heat to the environment via twelve air Dump Heat Exchangers (DHX), with four in each secondary loop. An overview of the FFTF coolant system is depicted in Figure 2.1 [1].

Figure 2.1 Overview of FFTF Coolant system [1]

The benchmark focused on the LOFWOS #13 Test, which was initiated at 50% power and 100% flow. The three primary sodium pumps were simultaneously tripped, and natural circulation was established in the primary loop. The secondary loop sodium pumps remained operational throughout the test.

Table 2.1 defines the initial conditions for the transient.

Table 2.1 Initial conditions of FFTF LOFWOS Test #13

Parameter	Initial value
Reactor power	199.2 MW
Primary loop mass flow rate, all loops	2202.2 kg/s
Secondary loop mass flow rate, all loops	2202.2 kg/s
Primary loop cold leg temperature	590.4 K

The transient was initiated when the primary pumps were tripped from full-flow, the core power then decreased from 50% power level to decay heat level due to the negative reactivity feedback from Gas Expansion Modules (GEMs). The total reactor power was measured directly during the experiment, the normalized power as a function of time are depicted in Figure 2.2.

Figure 2.2 Normalized total reactor power for FFTF LOFWOS #13

In the benchmark specification, the following three boundary conditions during the whole transient are provided:

- Primary pump speeds,
- Secondary loop mass flow rates, and
- DHX sodium outlet temperatures.

The following Quantities of Interest (QoIs) were measured during the LOFWOS Test #13:

- Row 2 PIOTA outlet temperature and mass flow rate,
- Row 6 PIOTA outlet temperature and mass flow rate,
- Primary sodium mass flow rate,
- Primary hot leg and cold leg temperatures,
- Secondary hot leg and cold leg temperatures, and
- Fission power.

All the QoIs are calculated, compared against measurements, and presented in this report except for the fission power, which is considered as a known input in the current SAM FFTF model.

As requested by the IAEA CPR, the following QoIs that were not measured during the transients are also calculated and presented in the report for the purpose of code-to-code comparisons,:

- Peak fuel temperature, fuel assemblies,
- Peak cladding temperature, fuel assemblies,
- Peak coolant temperature, fuel assemblies,
- Peak coolant temperature, non-fuel assemblies,
- IHX primary and secondary inlet and outlet temperatures,
- Average fuel temperature at steady state (prior to transient),
- Average reactor vessel inlet and outlet temperatures, and
- Primary pump discharge pressure.

Additionally, the steady state (prior to transient) axial temperature distributions in the Row 2 and Row 6 fast response PIOTA assemblies at the following radial locations are calculated and presented in the report, including:

- Coolant,
- Cladding inner surface,
- Cladding outer surface,
- Fuel surface, and
- Fuel centerline.

3. SAM Model of FFTF

A SAM model was developed for the FFTF LOFWOS #13 Test, using a two-step approach. Firstly, a FFTF model was developed for the initial steady state simulation. The parameters of the model were fine tuned to match the initial conditions of the LOFWOS Test #13. Then, the tuned parameters were frozen, and the boundary conditions for the transient were provided for the scenario simulation. For the whole model, convection is assumed to be the dominant heat transfer mechanism so that the axial liquid sodium heat conduction is neglected in this SAM FFTF model.

The present FFTF model is composed of a reactor vessel model, a detailed primary system loop model based on the layout from the benchmark specification, and a simplified secondary system loop model, as depicted in Figure 3.1. The primary and secondary loops are connected through a detailed IHX model. For the present model, the three primary and three secondary loops are represented by one average primary loop and one average secondary loop. The details of the model are described in this Section.

Figure 3.1. Schematics of the FFTF model

3.1 Reactor Vessel Model

The FFTF reactor vessel was cylindrical with a torispherical head at the bottom. The cold sodium was discharged from the three primary loop inlet pipes flowed into an inlet plenum at the bottom of the reactor vessel. Sodium was then drawn up into the core support structure and distributed to the core assemblies and radial shields, as well as leakage and bypass flow paths that provided sodium flow to the in-vessel storage region, the gap between the reactor vessel and vessel thermal liner, and the gaps between subassemblies. Discharged sodium from these flow paths mixed in a common outlet plenum before exiting the reactor vessel through one of three primary loop outlet pipes.

In this sense, in the FFTF SAM model, the reactor vessel consists of four parts: the inlet plenum at the bottom which is connected to the inlet of primary loop, the outlet plenum at the top which is connected to the outlet of the primary loop, a central plenum which represents the volume of the in-vessel storage region, and most importantly, a core model which consists of multiple core channels.

The FFTF core layout during the LOFWOS #13 Test is depicted in Figure 3.2. The core flow distribution was determined for sixteen assembly flow zones based on hydraulic testing for each type of assembly, as can also be seen in Figure 3.2. Table 3.1 presents the initial flow rates for each of the sixteen assembly flow zones. Each assembly within a flow zone is assumed to have the same initial flow rate.

Noted that in the FFTF core, there were a few special assemblies, including the Materials Open Test Assembly (MOTA), In Core Shim Assembly (ICSA), Fracture Mechanics Assembly (FMA), and Proximity Instrumented Open Test Assembly (PIOTA). The MOTA, ICSA, and FMA had very low power levels and small mass flow rate, thus from the thermal-hydraulic point of view, does not need special attention. The two PIOTAs, on the other hand, were fuel assemblies that associated with the most important FFTF measurements, i.e. the assembly outlet temperature. In the core model, the two PIOTAs are modeled as separate core channels so that the simulation results can be validated against the measurements from LOFWOS Test #13.

Figure 3.2 FFTF core layout and assembly flow zones

Table 3.1. Initial core flow distribution

Flow zone	Description	Number of assemblies	Total flow (kg/s)
1	3.2 drivers	22	558.60
2	3.1 drivers, row 5	12	289.72
3	3.1 drivers, row 6	22	458.08
4	4.1 and 4.2 drivers, rows 2-5	12	304.66
5	4.1 drivers, row 6	5	99.84
6	3.2 drivers with PIOTA, rows 2,4	4	99.26
7	3.1 drivers with PIOTA, row 6	3	61.50
8	MOTA	1	1.79
9	ICSA	1	2.04
10	Control and safety rods	9	40.91
11	FMA	1	0.65
12	Type 1, row 7 reflector	11	19.65
13	Type 2, row 7 reflector	15	13.36
14	Row 8a reflector	24	17.46
15	Row 8b reflector	18	9.525
16	Row 9 reflector	30	11.38

In the current FFTF core model, the MOTA and ICSA are combined with the control rods and are modeled as a single core channel, while FMA are combined with all the reflector assemblies and are modeled as a single core channel. The two PIOTAs are modeled separately. The bypass flow between assemblies are neglected. The leakage flow that did not flow through the reactor core are considered and modeled as a flow path that directly connected to the central volume. The heat transfer among core channels are considered through conjugate heat transfer. The shield structure surrounding reflector is modeled as a solid structure. The core model is illustrated in Figure 3.3, the modeling parameters are summarized in Table 3.2.

Figure 3.3 FFTF core model scheme

Table 3.2 FFTF core model parameters

Zone	Corresponding flow zones	Number of assemblies	Total flow (kg/s)	Total power (MW)
1	1	22	558.60	61.53
2	2	12	289.72	29.47
3	3	22	458.08	42.41
4	4	12	304.66	31.76
5	5	5	99.84	9.22
6	6 without PIOTA on row 2	3	74.45	8.67
7	7 without PIOTA on row 6	2	41.00	4.24
8	8, 9, 10	11	44.74	1.14
9	11 - 16	99	72.03	8.19
10	PIOTA row 2	1	24.82	3.45
11	PIOTA row 6	1	20.50	2.13
Leakage flow	N/A	N/A	213.81	0

In the current SAM model, each core channel is modeled with the representative fuel assembly. The number of assemblies is considered so that the active area of the core channel would be consistent with the actual situation. The model decomposes each core channel into five components, as illustrated in Figure 3.4. The inlet nozzle and orifice region and the outlet handling socket region are modeled as pipes (the *PBPipe* component in SAM). The wire-wrapped bundle region is modeled as three components, i.e. reflector region, active core region, and gas plenum region. Each region is a *PBCoreChannel* component in SAM that are discretized into 17 nodes in the axial direction. At each axial location, the fuel (or reflector/gas plenum) and cladding are discretized radially such that temperatures are calculated across the radial nodes through one-dimensional radial heat conduction. A simplified gap model is included in the active core region [4].

In reality, the core flow distribution of FFTF was determined for sixteen assembly flow zones based on hydraulic testing for each type of assembly. A significant portion of the pressure drop occurred at the orifice/shield block of the assembly, through tuning the orifice, desired flow rate can be achieved for the specific assembly. In current SAM model, a large form loss coefficient is introduced for in the inlet pipe of each core channel. The determination of the form loss coefficients is based on the calculated assembly pressure drop provided in the FFTF specification. Through a few tuning iterations, the flow rate of each core channel is consistent with the initial conditions of the LOFWOS Test #13.

Heat transfer between neighboring assemblies would affect the coolant temperatures of individual fuel assemblies, especially those in contact with cooler non-fueled assemblies. To capture this effect, the channel-to-channel heat transfer is considered in the model. Multiple wall structures are defined in the FFTF model, each of the wall structure is connected to the two neighboring core channels. Coupled boundary conditions are assigned to the wall structure so that the heat conduction within the wall is coupled with the convective heat transfer of the two neighboring core channels. The thickness of the wall structure is set to be slightly thicker than twice the thickness of the duct, as the actual distance between neighboring assemblies was not provided in the benchmark specification.

The fuel assembly of FFTF contained a bundle of 217 fuel pins, which were composed of mixed oxide ($\text{PuO}_2\text{-UO}_2$) pellets. The details of the fuel pellets were provided in the benchmark specification. Based on that, the thermal properties of the fuel pellets can be obtained through empirical correlations and interpolation between tables[5,6]. The gap conductance is considered in current model based on the burnup level of the fuel. The gap conductance is estimated and assumed to be a constant in the SAM model. The detailed implementation is summarized in Appendix A.

Figure 3.4 SAM model zones and regions for driver fuel assembly

3.2 Pump model

Each of the primary and secondary loops contained a vertical, free surface centrifugal pump. The primary loop pumps were located in the hot leg and the secondary loop pumps were located in the cold leg between the DHX and IHX. In the current model, the secondary pump was not modeled as the DHX outlet temperature and mass flow rate are provided as boundary conditions in the benchmark specification.

At the beginning of the LOFWOS Test #13, three primary pumps tripped simultaneously, the pump model should provide correct pump head for the primary pump during the transient.

In the benchmark specification, the rated pump parameters were provided but data for pump performance curves were not provided. Instead, a correlation to estimate the dimensionless (i.e. divided by its rated value) pump head was provided in the benchmark specification that based on the homologous pump theory. Based on the homologous correlation, the pump head can be calculated given the pump speed and pump volumetric flow rate are provided. For the initial conditions, the pump head can be calculated directly based on the homologous correlation, as summarized in Table 3.3.

Table 3.3 Primary pump parameters

	Rated value	Initial value
Speed, N	1110 rpm	950 rpm
Volumetric flow rate, Q	0.9148 m ³ /s	0.8555 m ³ /s
Head, P	152.4 m Na (566 °C)	101.2 m Na (566 °C)

For the transients, however, only the pump speed was provided in the benchmark specification while both the pump head and volumetric flow rate are unknown functions of time. In this sense, neither the pump head nor the volumetric flow rate can be directly derived from the homologous correlation. On the other hand, it is noted that the pump head and the volumetric flow rate are actually determined by two factors: one is the pump performance curve, in this case the homologous correlation. The other is the pressure drop of the primary loop. In this sense, the volumetric flow rate and the pump head can be implicitly determined through an iterative process. The iterative process is depicted in Figure 3.5.

Figure 3.5 Iterative process to determine primary pump head

To take the liquid volume of the sodium pump into account, a VolumeBranch component was implemented into the FFTF model, which was directly connected to pump component. The

liquid volume would introduce thermal inertia during the transient which is consistent with the actual situation.

3.3 Heat exchanger model

In the current SAM FFTF model, only the intermediate heat exchanger in the primary loop is considered, the dump heat exchanger in the secondary loop was not modeled. FFTF had one IHX in each of its three heat transport circuits. The IHX was vertically mounted counterflow shell and tube designs. Primary sodium flowed down through the shell side, while the secondary sodium flowing up through the IHX tubes.

In the current SAM model, the IHX model consists of a *PBHeatExchanger* component and a *HeatStructure* component, the *HeatStructure* component represents the stainless steel shell of the IHX and is connected to the primary side of the IHX. In this way, the conjugate heat transfer can be calculated to take into account the thermal inertia introduced by the heat structure. The flow inside the IHX had a complex flow pattern, but in current model, the standard countercurrent heat exchanger model is used. Such a model only considers the active heat transfer region of the IHX, the heat transfer coefficient is tuned through sensitivity coefficients to match the IHX performance at the initial conditions. Additional form loss coefficient is assigned to the model to match the IHX pressure drop provided in the benchmark specification.

3.4 Primary system loop

Although there were minor differences between each of the three FFTF primary loops, their geometries were very similar. In the current FFTF SAM model, only one primary loop is modeled which represents the average behavior of the three loops. Correspondingly, the three secondary loops are also modeled with one average loop.

The primary loop has three major segments with different tube sizes, as shown in Table 3.4. The primary loop had a large number of bends and elevation changes that could have significant influence on the pressure drop of the loop. In this sense, the FFTF SAM model further breaks the primary loop into multiple segments. The elevation of each segment is preserved and form loss coefficient is assigned at the connection of the segments. In this way, the pressure drop of the primary loop can be accurately represented in the model, combining the homologous curve, the pump head and mass flow rate can be correctly evaluated.

Table 3.4 Primary loop piping segments

Start	Finish	Material	Inner diameter	Outer diameter
Reactor vessel	Primary pump	SS-316H	69.22 cm	71.12 cm
Primary pump	IHX	SS-316H	38.74 cm	40.64 cm
IHX	Reactor vessel	SS-304H	38.74 cm	40.64 cm

It should also be noted that the reactor core was not the only source of heat in FFTF. For example, the pumps generated some heat as the pump head was dissipated overcoming flow resistances. Additionally, the dump heat exchangers were not the only heat sink. Small

amounts of heat were lost through the reactor vessel, reactor head, and loop piping. In this sense, the whole piping system is a heat sink while the pump is a heat source. Such heat sinks/sources are negligible under steady state conditions, but cannot be ignored under the LOFWOS scenario as the mass flow rate driven by natural circulation could be very low. The heat sources and sinks at nominal full power conditions are provided in the benchmark specification, the primary loop part is provided in

Table 3.5. In the current SAM FFTF model, the heat source from primary pump is not considered as the pump already tripped at the beginning of the transient. The heat sinks of the loop are modeled under the assumption that the convective heat transfer exist between the pipes and the outside environment, a constant heat transfer coefficient is assigned to the whole loop. The value of the heat transfer coefficient is determined based on

Table 3.5. In the current model, the heat loss from reactor vessel and reactor head are added to the inlet and outlet pipe segments respectively, thus they are also included in Table 3.5.

Table 3.5 Heat sources and sinks of primary loop at nominal full power conditions

	Parameter	Value
Heat sources	Primary pumps (three)	3.430 MW
	Primary loops piping (three)	0.412 MW
Heat losses	Reactor vessel	0.174 MW
	Reactor head	0.064 MW

3.5 Secondary system loop

As mentioned in Section 3.4, only one secondary loop is modeled in the current SAM FFTF model. The segments of the secondary loop piping are summarized in Table 3.6.

The boundary conditions for the secondary loop as provided in the benchmark specification included the secondary loop mass flow rate and the DHX outlet temperature, so there is no need to model the detailed pressure drop of the secondary loop. In current SAM FFTF model, two *PBPipe* components are used to represent the whole secondary loop. One starts from the DHX outlet (set as inlet for the secondary loop) and ends at the IHX secondary side inlet. The other starts from the IHX secondary side outlet and ends at the DHX inlet (set as the pressure outlet for the secondary loop). The length of the two pipes are consistent with the benchmark specification so that the heat loss of the whole secondary loop can be accurately evaluated.

Table 3.6 Secondary loop piping segments

Start	Finish	Material	Inner diameter	Outer diameter
IHX	DHX inlet	SS-316H	38.74 cm	40.64 cm
DHX inlet	DHX outlet	SS-304H	18.69 cm	20.32 cm
DHX outlet	IHX	SS-304H	38.74 cm	40.64 cm

The heat sources and sinks of the secondary loop are summarized in Table 3.7. Similar to the primary loop, a constant convective heat transfer coefficient is assigned to the pipes of the secondary loop. The secondary pumps were operating under full condition during the whole transient, thus the heat source from secondary pump is considered in the current model through applying a constant wall heat flux in the pipe near the actual pump location.

Table 3.7 Heat sources and sinks of secondary loop at nominal full power conditions

Parameter		Value
Heat sources	Secondary pumps (three)	2.044 MW
Heat losses	Primary loops piping (three)	0.576 MW

3.6 Numerical setup

SAM is a FEM-based code. The “weak forms” of the governing equations are implemented in SAM. It uses the Jacobian-Free Newton Krylov (JFNK) solution method to solve the equation system. In the current SAM FFTF model, the first-order linear elements are used in the finite- element discretization of fluid flow and solid structures. The trapezoidal rule is used for the numerical integration of first-order elements using piece-wise linear Lagrange shape functions.

4. LOFWOS Test #13 Simulation Results

In this Section, the simulation results of the LOFWOS Test #13 using the SAM model are presented and discussed. As mentioned in Section 3, the whole simulation effort has two steps. The first is the simulation of the steady state prior to the transient. In this step, a few parameters were tuned to make the pre-transient simulation results consistent with the benchmark specification, these parameters were then frozen in the following transient simulation.

4.1 Results for steady state initialization

As the first step, the steady state simulation prior to the transient of LOFWOS Test #13 was performed. The initial condition was 50% power and 100% flow. In the steady state simulation, the form loss coefficients for each core channels were tuned so that the mass flow rate of each core channel is consistent with the value provided by the benchmark specification. The tuned form loss coefficients and the corresponding mass flow rate of each core channel is summarized in Table 4.1.

Table 4.1 Core channel flow distributions

Zone No.	SAM predicted value, (kg/s)	Benchmark value, (kg/s)	Relative error, %
1	558.3	558.6	-0.05
2	289.5	289.7	-0.08
3	455.1	458.1	-0.65
4	306.0	304.7	0.44
5	98.4	99.8	-1.44
6	74.4	77.4	-0.06
7	40.5	41.0	-1.22
8	44.7	44.7	-0.09
9	72.3	72.0	0.37
10	24.9	24.8	0.34
11	20.4	20.5	-0.49
Leakage flow	214.5	213.8	0.32
Overall	2199.0	2202.2	-0.15

As can be seen in Table 4.1, after tuning the form loss coefficients of each core channel, the core channel flow distributions agree very well with the values provided in the benchmark specification. The tuned form loss coefficients were then frozen for the following transient simulations.

As requested by the benchmark specification, the following simulation results of fuel temperatures are provided.

Figure 4.1 Peak fuel temperature of different core channels prior to transient

Figure 4.1 illustrates the peak fuel temperature of different core channels prior to the transient. Due to the fluctuations of the boundary conditions, the simulation results demonstrate certain fluctuating behavior, but overall the results can be regarded as the steady state. It can be found that the PIOTA Row 2 has the maximum peak fuel temperature at around 1800 K, while Zone 5 has the minimum peak fuel temperature at around 1000 K.

Furthermore, the steady state axial temperature distributions of PIOTAs, both at row 2 and at row 6, are illustrated in Figure 4.2 and Figure 4.3. It can be observed in both figures that the temperature at the fuel centerline first increase then decrease due to the power shape function specified in the input file of the model. The peak temperatures at the fuel centerline found in Figure 4.2 and Figure 4.3 are consistent with the observation from Figure 4.1. The temperature difference between the fuel centerline and fuel surface is quite large for both assemblies, due to the low heat conductivity of the dioxide fuel. The gap between fuel surface and the cladding inner surface also introduced temperature differences at 100 – 200 K level.

Figure 4.2 Axial temperature distributions of PIOTA Row 2 at different radial locations

Figure 4.3 Axial temperature distributions of PIOTA Row 6 at different radial locations

4.2 Results for transient analysis

LOFWOS Test #13 was performed on July 18, 1986, starting from 50% power and 100% flow. At the beginning of the transient, the three primary sodium pumps were simultaneously tripped, causing flow through the core to decrease and the power-to-flow ratio to increase. Larger temperature changes in the core and a decreased core inlet pressure generated the necessary reactivity feedbacks to significantly reduce the core power level as the system worked to establish natural circulation. As required by the benchmark specification, the simulation is performed for 15 minutes after the official start of the transient.

One minute before the official start of the test, DHX blower speeds were reduced and DHX sodium outlet temperatures began to increase. Such fluctuation at the DHX outlet temperature was reflected at the boundary condition of the secondary loop during the simulation.

Below approximately 100 rpm, the uncertainty of the pump speed measurements was too high to be used reliably for benchmark simulations. For that reason, measured pump speeds are provided for the first 90 seconds of the transient only. In the current SAM FFTF model, it is assumed that the pump was completely stopped at $t = 90$ second, an additional form loss coefficient is assigned to the pump to represent the additional resistance of the locked pump.

The iterative procedure as demonstrated in Figure 3.5 is used to evaluate the pump discharge pressure. The obtained result is illustrated in Figure 4.4. Correspondingly, the mass flow rate of the primary loop is illustrated in Figure 4.5.

Figure 4.4 Primary pump discharge pressure

It can be found in Figure 4.5 that the measured and predicted primary loop mass flow rates agree very well throughout the test. After the pump fully tripped and natural circulated was formed, the measured mass flow rate showed large fluctuation which could be caused by the uncertainty of the measurement for small flow rates. The predicted mass flow rate during the transient showed a stable result at around 16 kg/s, which is close to the averaged measurements.

Figure 4.6 illustrates the cold leg temperature of the secondary loop. The cold leg temperature was measured during the transient using Resistance Thermal Detectors (RTDs). For the secondary cold leg temperature measurements depicted in Figure 4.6, the RTDs were installed after the secondary pump. During the transient, the cold leg temperature is significantly influenced by the outlet temperature of the DHX, which was fluctuating due to the change of DHX blower speed. It can be found that the predicted and measured secondary cold leg temperatures demonstrate similar progressions. However, the predicted temperature shows a fluctuating pattern which occurs approximately 20 seconds before the measured temperature

experience fluctuation. Furthermore, the predicted temperature is slightly higher than the measured value with a few degrees during the transient. Such a discrepancy could be caused by the thermal inertia that exist in the secondary loop but is not taken into account in the model.

Figure 4.5 Mass flow rate of one primary loop

Figure 4.6 Secondary loop cold leg temperature

Figure 4.7 Secondary loop hot leg temperature

Figure 4.7 illustrates the hot leg temperature of the secondary loop. The RTDs for the secondary loop hot leg temperature measurements were installed just before the inlet of the DHX. Because the secondary loop pumps did not trip during the transient while the primary pumps did, heat rejection through the IHXs was significantly reduced. It can be found in Figure 4.7 that comparing to the measured temperature, the simulation results slightly underestimate the temperature at the beginning of the transient then overestimate it when the natural circulation was formed. But such discrepancies are only a few degrees and the simulation results overall can be regarded as in good agreement with the measurements.

Figure 4.8 illustrates the cold leg temperature of the primary loop. The RTDs for the primary loop cold leg temperature measurements were installed between the IHX outlet and the check valve. It is found in Figure 4.8 that the simulation results demonstrate a fluctuating pattern that is quite similar to the pattern of the secondary loop cold leg temperature illustrated in Figure 4.6. In the transient, the secondary loop pump did not trip and the secondary loop maintained 100% flow rate, while the primary mass flow rate decrease significantly under natural circulation after the primary pump fully tripped. It is expected that the IHX outlet temperature on the primary side would follow the inlet temperature on the secondary side (as the countercurrent design of the IHX). Since the cold leg RTDs were install near the IHX outlet, Figure 4.8 demonstrated a similar fluctuating pattern with the secondary loop cold leg in the simulation. However, it is also observed in the same figure that the measurement does not show the fluctuating pattern. Rather, the temperature first increase in the beginning of the transient then keep decreasing. Although the discrepancies between the predictions and the measurements are within a few degrees, such a different fluctuating pattern would need further investigation.

Figure 4.9 illustrates the hot leg temperature of the primary loop. The RTDs for the primary loop hot leg temperature measurements were installed between the hot leg isolation valve and the primary pump inlet. Overall, both the measurements and the predictions change very little

during the whole transient. The simulation results increased a few degrees while the measurements are fairly stable during the transient. Two factors could cause such a minor discrepancy. Firstly, there could be unaccounted thermal inertial in the actual FFTF primary loop that did not take into account in current model. Furthermore, the measurement uncertainty could also be a possible reason. In this work, the effect of measurement uncertainty on the validation is not considered as such information is not provided in the benchmark specification.

Figure 4.8 Primary loop cold leg temperature

Figure 4.9 Primary loop hot leg temperature

For the FFTF heat transport systems, four QoIs were measured, i.e. temperatures of the hot leg and cold leg of the primary/secondary loops. During the LOFWOS Test #13 transients, these results are used to compare with the simulation results. Overall, the simulation results are in good agreement with the measurements, with discrepancies less than 10 degrees. On the other hand, the temperature of the primary loop cold leg showed a fluctuating pattern that differs from the measurement, such a different pattern may need further investigation.

Besides the measured QoIs, a few other QoIs of the heat transport system were required to be reported by the benchmark specification. Figure 4.10 illustrates the inlet and outlet temperatures of the reactor vessel. The reactor vessel outlet temperature is slightly higher than the primary loop hot leg temperature which indicates the heat loss of the piping system has been taken into account in the simulation.

Figure 4.10 Reactor vessel inlet and outlet temperatures

Figure 4.11 and Figure 4.12 illustrate the IHX inlet/outlet temperatures of the primary side and secondary side respectively. The FFTF IHX adopted the countercurrent design, so the primary inlet corresponds to the secondary outlet, while primary outlet corresponds to the secondary inlet. It can be clearly seen that the fluctuation in the secondary inlet is propagated to the primary outlet.

Figure 4.11 Inlet and outlet temperatures of the IHX primary side

Figure 4.12 Inlet and outlet temperatures of the IHX secondary side

One of the challenging problems in this benchmark simulation is to accurately model the detailed flow and temperature of each assembly zones within the reactor core. One issue is the flow distribution during the transient. In this benchmark simulation, form loss coefficients are assigned to the inlet region of each flow assembly zones to make sure the initial flow rate distribution matches the initial conditions of the benchmark case. These form loss coefficients are then fixed as constants during the simulation that could lead to discrepancies with the actual situation as the form loss coefficient should be a function of flow rate. However, figuring out a correct function of the form loss coefficient with flow rate as the variable is impractical due to the complex geometry of the inlet nozzles. Another challenging issue is the

assembly-to-assembly heat transfer during the transient. The assembly-to-assembly heat transfer between fuel assembly and non-fuel assembly is estimated on the 100~300 kW/m² level, which is insignificant under normal operating conditions, but is non-negligible during the transient as the power of the core was significantly reduced. In this report, a preliminary study on the assembly-to-assembly heat transfer is performed which will serve as the basis for a more detailed future investigation.

In FFTF, special fast response thermocouple packages were utilized for a selection of assemblies to record more accurate core outlet temperatures during transient conditions. These assemblies were referred to as Proximity Instrumented Open Test Assemblies (PIOTA). Above each PIOTA, a separate duct assembly with multiple thermocouples was installed. The instrument duct was in direct contact with the assembly duct such that sodium discharged from PIOTA assemblies flowed along thermocouples just above the assembly outlets. The fast response PIOTAs had an expected response time of 3 seconds. Two fast response PIOTAs were installed for the LOFWOS Test #13, one in Row 2, and the other in Row 6.

In the current SAM FFTF model, three different cases are considered to model the assembly-to-assembly heat transfer. In the first case, the assembly-to-assembly heat transfer is modeled through heat conduction between the contacting assembly walls. The actual contacting area is applied, the results are depicted in Figure 4.13 and Figure 4.14

Figure 4.13 Outlet temperature of PIOTA, Row 2, assembly-to-assembly heat transfer considered with actual contacting area

Figure 4.14 Outlet temperature of PIOTA, Row 6, assembly-to-assembly heat transfer considered considered with actual contacting area

Figure 4.13 illustrates the outlet temperature of the PIOTA, Row 2 during the transient. It is found that at the beginning of the transient, the outlet temperature has a sudden increase. This is due to the flow rate decreases faster than the reactor power and caused a jump of the power-to-flow ratio. After reaching the first peak at around $t = 9$ second, the temperature decreased quickly then increase to the second peak at around $t=100$ second. After the second peak, the temperature decreases to the end of the simulation. It is found that the simulation follows the same trend with the measurement and has good agreement with the measured temperature in the natural circulation regime. However, the simulation results underestimate the outlet temperature by over 20 K – 30 K in the first 150 seconds of the transient, both the first and second peak temperature are underestimated. The main reason that caused such a discrepancy could be the inconsistent power-to-flow ratio between the model and the real scenario. As discussed before, the form loss coefficient for each core channel is assumed to be constant during the scenario, while in reality the form loss coefficient would be changed with the flow rate (lower Reynolds number would result in a large form loss coefficient). In this way, flow rate with the core would be redistributed. It is possible that the flow rate obtained in the simulation is larger than the actual flow rate in the scenario. Further investigation would be required to resolve such a discrepancy. Figure 4.14 illustrates the outlet temperature of the PIOTA, Row 6 during the transient. Similar to the PIOTA, Row 2, the outlet temperature at Row 6 also demonstrate two peaks, the temperature then continues decreasing to the end of the transient. The simulation results for PIOTA, Row 6 also follows the same trend of the measurement. However, it also underestimate the two temperature peaks by around 10 K in the first 100 seconds then overestimate the temperature in the natural circulation regime by over 30 K.

In a second case study, a zero contacting area between assemblies is applied which means the assembly-to-assembly heat transfer is not considered. The results are depicted in Figure 4.15 and Figure 4.16. As can be seen in these two figures, without considering the assembly-to-assembly heat transfer, the outlet temperature of PIOTA, Row 2 shows a very good agreement with the experimental measurements. But the outlet temperature of PIOTA, Row 6 exhibit a large overestimation, with the temperature peak 60K higher than the measurement. Considering the fact that PIOTA, Row 2 was in the center of the core that was surrounded by other fuel assemblies with the similar power and flow rate, no assembly-to-assembly heat transfer could be a reasonable assumption. However, the PIOTA, Row 6 had direct contact with non-fuel assemblies, i.e. reflector and GEM, it is reasonable to see a big temperature jump without considering the assembly-to-assembly heat transfer.

Figure 4.15 Outlet temperature of PIOTA, Row 2, no assembly-to-assembly heat transfer

Figure 4.16 Outlet temperature of PIOTA, Row 6, no assembly-to-assembly heat transfer

An additional case study is performed to provide another qualitative evaluation of the effect of assembly-to-assembly heat transfer. This case study considers the assembly-to-assembly heat transfer but with a 50% effective contact area. The results are depicted in Figure 4.17 and Figure 4.18. The results clearly demonstrate the significant influence of the effect of assembly-to-assembly heat transfer on the fuel assembly outlet temperature during the transient.

Figure 4.17 Outlet temperature of PIOTA, Row 2, assembly-to-assembly heat transfer with 50% effective contact area

Figure 4.18 Outlet temperature of PIOTA, Row 6, assembly-to-assembly heat transfer considered considered with 50% effective contacting area

Considering the relatively large discrepancies in the outlet temperature predictions of PIOTA Row 2 and Row 6. Further investigation is required to improve the current SAM FFTF

core model, with a focus on evaluating the core flow distribution, power history, and the assembly to assembly heat transfer. For the IAEA CRP, the results with no assembly-to-assembly heat transfer is adopted for submission.

Besides the two QoIs with measurements available, other QoIs of the reactor core that were not measured during the transient are reported based on the requirement of the benchmark specification. Figure 4.19 and Figure 4.20 depict the peak coolant temperature of core channels which represent the non-fuel assemblies and fuel assemblies during the transient respectively. It can be observed in Figure 4.20 that the peak coolant temperatures of the fuel assemblies all demonstrate the same trend of the outlet temperature of the two PIOTAs. While the peak coolant temperature of the non-fuel assemblies does not have the similar pattern.

Figure 4.19 Peak coolant temperature of non-fuel assemblies

Figure 4.20 Peak coolant temperature of fuel assemblies

Figure 4.21 Peak cladding temperature of fuel assemblies

Figure 4.22 Peak fuel temperature of fuel assemblies

Figure 4.21 and Figure 4.22 illustrate the peak cladding and fuel temperature of different core channels during the transient respectively. It can be found that the fuel peak temperatures of all core channels keep decreasing during the transient. On the other hand, the cladding peak temperatures of these core channels demonstrate two temperature peaks due to the evolution of the power-to-flow ratio as discussed before.

5. Summary and Conclusions

In this work, a SAM model of FFTF is developed for benchmark simulations of the LOFWOS Test #13. The model is developed with the supporting data only from the benchmark specification. In this first phase of the modeling effort, the thermal-hydraulic behavior of the reactor system is the focus and the reactor kinetics is not considered in the SAM model. Instead, the measurements and results of Argonne's neutronics calculations are directly used, including the power shape of the active core region and the power history during the transient.

Based on the requirement of the IAEA CRP, multiple quantities of interest of the transients are presented and discussed in this report. For those QoIs with measurements available, the simulation results are compared with the measurements. It is found that the simulation results of FFTF at steady state agreed well with the measured data of the test. During the transient, reasonably good agreement was also obtained, including the mass flow rate of the primary loop, cold leg and hot leg temperature of primary and secondary loops. The maximum difference of temperature between model prediction and measurements is about 5 K, while the mass flow rate maximum difference is less than 5%.

On the other hand, relative large discrepancies are observed at the outlet temperature at the two fast response PIOTAs. In the case study with no assembly-to-assembly heat transfer considered, over 60K temperature overestimation on the PIOTA Row 6, though the PIOTA Row 2 has pretty good agreement with the measurements. Two factors may result in such discrepancy. One is that even though the overall flow rate during the transient is in good agreement with the measurement, it is still possible that there exists a mismatch in the flow rate distribution among different flow zones within the core. The other factor is the assembly-to-assembly heat transfer is still not well understood or modeled accurately. Further investigation will be conducted on these two issues.

Most simulation results discussed in this report, including those do not have measurements available, have been prepared based on the format required by the IAEA CRP. The results have been officially submitted in January 31st and will be presented and discussed in the next IAEA CRP meeting as a part of the Argonne effort.

Future analysis to improve the model will include the reactivity feedback modeling, therefore, to predict the reactor power in the simulation instead of using the reactor power as an input. Furthermore, investigations will be continued to address the discrepancies between the measurements and current predictions of the outlet temperature at the two fast response PIOTAs.

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Appendix A. Implementation of fuel thermo-physical properties in SAM FFTF model

Four properties are calculated based on empirical correlations:

$O_M = 1.995$; % *O/M ratio*

$\beta = 10$; % *burnup level*

$\text{porosity} = 0.096$;

% *thermal conductivity of fuel*

$k_0 = 1./ (0.06059 + 0.2754*\text{sqrt}(2-O_M) + 2.011e-4.*T) + 4.715e9./T.^2.*\exp(-16361./T)$;

$F1 = (1.09/\beta^{3.265} + 0.0643/\text{sqrt}(\beta)).*\text{sqrt}(T)).*\text{atan}(1./ (1.09/\beta^{3.265} + 0.0643/\text{sqrt}(\beta)).*\text{sqrt}(T)))$;

$F2 = 1 + 0.019*\beta/(3-0.019*\beta)./(1+\exp(-(T-1200)/100))$;

$F3 = 1 - 0.2./(1 + \exp((T-900)/80))$;

$F4 = 1 - 2.5*\text{porosity}$;

$k_{\text{eff}} = k_0.*F1.*F2.*F3.*F4$;

% *density of fuel*

$\text{coeff}_1 = 1.108e4$;

$\text{coeff}_2 = 2.04e-5$;

$\text{coeff}_3 = 8.70e-9$;

$\rho_{\text{fuel}} = \text{coeff}_1./ (1 + (\text{coeff}_2 + \text{coeff}_3*(T - 273.16)).*(T - 273.16))*(1-\text{porosity})$;

% *density of cladding*

$\alpha_c = 1.5e-6$; % *thermal expansion coefficient*

$\rho_{\text{clad}} = 7700*(1.0 - 3.0*\alpha_c*(T - 298.0))$;

% *specific heat of cladding*

$cp_{\text{clad}} = (0.1097 + 3.174e-05*T) * 4.184e+3$;

The specific heat of fuel is interpolated with the function:

% *specific heat of fuel*

$[/cp_{\text{fuel_fn}}]$

$\text{type} = \text{PiecewiseLinear}$

$x = '300.0 \ 600.0 \ 900.0 \ 1200.0 \ 1500.0 \ 1800.0 \ 2000.0 \ 2200.0 \ 2500.0 \ 2800.0 \ 3000.0'$ %
temperature in K

$y = '2.37e2 \ 2.94e2 \ 3.11e2 \ 3.16e2 \ 3.25e2 \ 3.48e2 \ 3.74e2 \ 4.13e2 \ 4.96e2 \ 6.13e2 \ 7.10e2'$ %
specific heat

[../]

% thermal conductivity of cladding

[./k_clad_fn]

type = PiecewiseLinear

*x = '2.73150e2 3.73150e2 4.73150e2 5.73150e2 6.73150e2 7.73150e2 8.73150e2 9.73150e2
1.07315e3 1.17315e3 1.27315e3 1.37315e3 1.47315e3 1.57315e3 1.67315e3 1.77315e3
1.87315e3 1.97315e3 ' % temperature in K*

*y = '1.39500e1 1.51130e1 1.62760e1 1.74390e1 1.86020e1 1.97650e1 2.09280e1 2.20910e1
2.32540e1 2.44170e1 2.55800e1 2.67430e1 2.79060e1 2.90690e1 3.02320e1 3.13950e1
3.25580e1 3.37210e1' % thermal conductivity*

[../]

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