Benchmark Specifications and Data Requirements for Initial Modeling of the China Experimental Fast Reactor

Nuclear Engineering Division

About Argonne National Laboratory

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne, see <http://www.anl.gov>.

Availability of This Report

This report is available, at no cost, at <http://www.osti.gov/bridge>. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.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.

Benchmark Specifications and Data Requirements for Initial Modeling of the China Experimental Fast Reactor

T. H. Fanning

Nuclear Engineering Division
Argonne National Laboratory

June 4, 2010

SUMMARY

A specification is proposed for an initial transient benchmark analysis of the China Experimental Fast Reactor design based on the analysis capabilities of the SAS4A/SASSYS-1 code. For the initial benchmark, a single-channel protected transient overpower accident is defined. Reactivity feedback coefficients will not be required and simplified material properties are recommended. This report also describes the data required for developing the modeling input. This data includes assembly geometry, reactor power distributions, kinetics and decay heat data, and material properties. Comparisons of benchmark results will take place at a future SAS4A/SASSYS-1 training meeting planned to occur at Argonne National Laboratory. Future benchmark specifications will be planned to expand upon this initial model to include more complex reactivity feedback models, material properties, additional assembly geometry, and primary and intermediate coolant systems.

TABLE OF CONTENTS

Summary	i
Table of Contents	iii
List of Tables	v
1 Introduction	1
2 Benchmark Specifications	1
3 Data Requirements	2
3.1 Steady-State Conditions	3
3.2 Transient Conditions	3
3.3 Assembly Geometry	3
3.4 Power Distribution and Decay Heat	5
3.1 Point Kinetics	7
3.2 Material Properties	7
3.2.1 Fuel, Cladding, and Structures	7
3.2.2 Coolant	8
3.3 Heat Transfer	8
3.4 Pressure Drop	9
4 Calculated Data	10
5 Future Activities	10

LIST OF TABLES

Table I: Data Required for Defining Steady-State Conditions	3
Table II: Data Required for Defining Transient Conditions	3
Table III: Data Required for Defining Assembly Geometry in the Fuel Zone	4
Table IV: Data Examples for Upper and Lower Reflector/Shield Regions.....	5
Table V: Data Required for Core Power Distributions.....	6
Table VI: Data Required for Decay Heat Modeling.....	6
Table VII: Data Required for Point Kinetics Modeling.....	7
Table VIII: Thermophysical Properties Required for Fuel, Cladding, Reflector, and Structure Materials.....	8
Table IX: Data Required for Heat Transfer Correlations.....	9
Table X: Data Required for Pressure Drop Correlations.....	9

1 Introduction

As part of a joint collaboration between the U.S. Department of Energy (DOE) and the China Institute of Atomic Energy (CIAE), staff from Argonne National Laboratory are providing training to staff from CIAE in the use of the U.S. safety analysis code SAS4A/SASSYS-1. During the first training session, held 10–14 May 2010, participants recognized the importance of completing a series of benchmark problems based on the China Experimental Fast Reactor (CEFR) design. Joint participation in the benchmark activities achieves two goals. First, it provides confirmation that the use and modeling capabilities of SAS4A/SASSYS-1 have been thoroughly and accurately described by Argonne staff and understood by CIAE staff. Second, it provides a foundation for the development of more complex models of CEFR with broader applications for safety analysis.

This report defines the first in a series of benchmark problems designed for comparative analysis of the coupled thermal, hydraulic, and neutronic performance of CEFR during transients. Comparisons will be made between independent models developed by CIAE and Argonne staff. As the first in a series of benchmark problems progressing from simple to complex, this benchmark is designed to have the minimum phenomenological and computational complexity needed for consistency with prototypic system performance.

The transient is an assumed protected transient overpower (TOP) accident, which is terminated with a reactor scram. Computational results that will be compared consist of computed temperatures in the fuel, coolant, and structure as well as reactor power and flow as a function of time during the transient. Analytical methods used to evaluate safety performance are incorporated in the SAS4A/SASSYS-1 computer code. In the following sections, the benchmark specifications are defined and the data required to construct the model input are described. Based on the required data, CIAE and Argonne staff will construct independent models and evaluate the safety performance of CEFR based on the assumed transient conditions.

2 Benchmark Specifications

The initial benchmark problem is the simulation of a protected (with scram) transient overpower (TOP) accident. Prior to the initiation of the TOP, normal steady-state operating conditions at full power and flow are assumed. Insertion of positive reactivity initiates the transient. When the reactor reaches a predetermined overpower condition, the reactor control system inserts a large, negative scram reactivity. At the initiation of the scram, the positive reactivity insertion is assumed to cease. Therefore, the external reactivity applied to the reactor as a function of time is

$$\rho(t) = \begin{cases} \dot{\rho}_+ t & t \leq t_s \\ \dot{\rho}_+ t_s + \rho_s (t - t_s) / \Delta t_s & t_s < t \leq t_s + \Delta t_s \\ \dot{\rho}_+ t_s + \rho_s & t_s + \Delta t_s < t \end{cases} \quad (1)$$

where $\dot{\rho}_+$ is the positive reactivity insertion rate that causes the TOP, t_s is the time at which the scram initiates due to overpower conditions, ρ_s is the scram reactivity (negative), and Δt_s is the time it takes for the scram to complete.

During the transient, the coolant inlet temperature is assumed to remain constant at its initial steady-state value. Two cases for the coolant flow rate following the scram will be considered. In the first case, it is assumed that the primary coolant pumps remain operational, and the coolant flow rate remains constant at its initial steady-state value. That is,

$$F(t) = F(0).$$

In the second case, it is assumed that the primary coolant pumps trip at the same time as the initiation of the scram. Coolant flow in the primary system is assumed to decline according to a flow halving time, such that

$$F(t) = \frac{F(0)}{1 + (t - t_s)/t_{1/2}}, \quad t \geq t_s \quad (2)$$

where $t_{1/2}$ is the initial flow halving time, in seconds.

To simplify the model development and evaluation of this initial transient, a number of assumptions are specified. As future benchmark specifications are defined, many of these assumptions will be eliminated to increase the complexity of the modeling so that additional transient conditions can be evaluated. The following assumptions are specified:

1. A single, average fuel assembly will represent the thermal-hydraulic behavior of the entire core. A single, average fuel pin will represent all the fuel pins in the average assembly.
2. Primary loop, intermediate loop, and balance-of-plant components and performance characteristics are neglected. Steady-state boundary conditions for the core are defined by inlet temperature, inlet flow rate, and outlet pressure. Transient conditions for the initial benchmark are as described above.
3. All reactivity feedbacks will be ignored, so that only the insertion and scram reactivities are applied for determining the reactor fission power. Reactor decay heat is calculated based on the initial power level and the fission power history during the transient.
4. Temperature-independent thermophysical properties for fuel, cladding, and structure are used. Burnup-independent properties are used for fuel. Bond gap conductance is specified as a constant.
5. Temperature-dependent thermophysical properties for sodium coolant are those defined in the SAS4A/SASSYS-1 code.

These assumptions are not meant to be exclusive and other assumptions may be required. Either CIAE staff or Argonne staff may propose additional assumptions, and upon agreement the assumptions become part of this benchmark specification.

3 Data Requirements

In addition to the assumptions described above, certain data on the CEFR design and performance characteristics will be required so that CIAE and Argonne staff can create independent models. Some of the required data may be obtained from literature, in which case citations are required. When possible, however, data and correlations should reflect known

performance of CEFR. In particular, assembly geometry, power distributions, flow characteristics, and material properties shall be specific to CEFR.

3.1 Steady-State Conditions

Basic steady-state conditions include total reactor power and flow, as well as assembly inlet temperature and outlet pressure. Other conditions, such as outlet temperature and pressure drop, are calculated based on power distributions, assembly geometry, and other data. Required data for initializing steady-state conditions is shown in Table I. Additional details on power distributions and decay heat parameters will be described in the following sections.

Table I: Data Required for Defining Steady-State Conditions

Parameter	Symbol	Units
Total Reactor Power	POWTOT	W
Total Primary Flow	n/a	kg/s
Inlet Temperature	NTOTAB	K
Coolant Exit Pressure	PX	Pa

3.2 Transient Conditions

The initial transient to be evaluated is a protected transient overpower accident, as described in Section 2. Data required for this transient include the positive reactivity insertion rate, overpower condition to initiate a scram, and the negative scram reactivity. A summary of required data for the transient is shown in Table II. Note that the overpower condition is used in determining the value of t_s in Equations (1) and (2).

Table II: Data Required for Defining Transient Conditions

Parameter	Symbol	Units
Reactivity Insertion Rate	$\dot{\rho}_+$	\$/s
Scram Reactivity	ρ_s	\$
Scram Duration	Δt_s	s
Overpower Condition	n/a	%
Pump Halving Time	$t_{1/2}$	s

3.3 Assembly Geometry

A traditional sodium-cooled, fast reactor design is assumed for the core and assembly components of CEFR. Liquid metal coolant flows upward through the reactor core that consists of a uniform lattice of hexagonal, ducted assemblies. Each fuel assembly consists of a number of fuel pins within the duct, with additional regions, or zones, above and below the

fuel. Fuel pins are composed of cylindrical fuel material clad with stainless steel. The fuel pin may also contain upper and lower fertile blanket regions. A fission gas plenum may exist within the cladding either above or below the fuel.

In SAS4A/SASSYS-1, the thermal-hydraulic performance of the reactor core is analyzed with a computational model that represents the core as a number of single-pin channels. Each single-pin channel describes the response of a single fuel pin and its associated coolant and structure. In a multiple-channel, whole-core model, each single-pin channel characterizes the average pin in a fuel assembly, and assemblies with similar reactor physics and thermal-hydraulics characteristics are grouped together. For the initial benchmark, a single channel is used to represent all assemblies in the core. Future benchmark specifications will expand upon this model and use multiple channels to represent different regions within the core.

Based on the above description, a number of parameters are required for representing the fuel pin geometry. These include fuel diameter, core height, cladding thickness, pin pitch, duct wall diameter, and many other parameters. The required geometric data for modeling the fuel zone is summarized in Table III.

Table III: Data Required for Defining Assembly Geometry in the Fuel Zone

Parameter	Units
<i>General Assembly Parameters</i>	
Assembly Lattice Pitch	cm
Outer Flat-to-Flat Diameter	cm
Duct Wall Thickness	cm
Overall Assembly Length	cm
<i>Fuel Zone Parameters</i>	
Number of Pins per Assembly	#
Fuel Central Void Diameter	mm
Fuel Outer Diameter	mm
Cladding Outer Diameter	mm
Cladding Thickness	mm
Pin Pitch	mm
Wire-Wrap Diameter	mm
Wire-Wrap Axial Pitch	mm
Fission Gas Plenum Height	cm
Upper Axial Blanket Height	cm
Active Core Height	cm
Lower Axial Blanket Height	cm

Table IV: Data Examples for Upper and Lower Reflector/Shield Regions.

Parameter	Units
<i>Pin Bundle Geometry Parameters</i>	
Number of Pins	#
Pin Outer Diameter	mm
Pin Pitch	mm
Wire-Wrap Diameter	mm
Wire-Wrap Axial Pitch	mm
Shield Height	cm
<i>Central Hole Geometry Parameters</i>	
Number of Holes	#
Hole Diameter	mm
Hole Pitch	mm
Shield Height	cm

Above and below the fuel zone, one or more axial reflector or shield zones will be present. In these zones there may be a variety of complex geometric configurations. Two common configurations that might be encountered include solid pin bundle shielding, similar to the core zone, or one or more central flow holes surrounded by shield material. Basic geometric parameters for these alternatives are presented in Table IV. The general assembly parameters shown in Table III are assumed to extend through the upper and lower reflector/shield zones. For this benchmark, as much information as possible should be provided about these zones to ensure that thermal-hydraulic conditions can be accurately represented in the individual models created by CIAE and Argonne.

3.4 Power Distribution and Decay Heat

Power distributions within a core are dependent upon assembly position and fuel enrichment, axial position, and intra-fuel radial position. Because this initial benchmark represents the CEFR core with a single channel, the dependence on assembly position is neglected, and a single average assembly represents the entire core. The normalized axial power distribution within the assembly is required, and up to 24 segments may be defined. The normalized intra-fuel radial power distribution is also required, but may be specified as flat. Power distribution data requirements are shown in Table V. Intra-fuel radial power distributions may be specified on an equal radius or equal volume basis.

The power distributions defined by Table V apply for the duration of the transient and apply to both fission and decay power. Decay heat production is tracked by decay heat “precursors” that build up due to fission and decay to produce heat:

$$\frac{dh_n}{dt} = \beta_{h,n} \phi(t) - \lambda_{h,n} h_n,$$

where $\beta_{h,n}$ is the decay heat power fraction, and $\lambda_{h,n}$ is the corresponding decay constant for group n . Up to six decay heat groups may be defined. Decay heat data requirements are shown in Table VI. For the initial benchmark, it is assumed that decay heat is initialized based on an infinite steady-state irradiation time.

SAS4A/SASSYS-1 also supports allocating a fraction of the total power to direct heating of structure, cladding, and coolant. For the initial benchmark, direct heating of non-fueled regions will be neglected.

Table V: Data Required for Core Power Distributions.

Parameter	Normalized Power	Dimension
<i>Axial Power Distribution</i>		
Segment 1	PSHAPE(1)	AXHI(1)
Segment 2	PSHAPE(2)	AXHI(2)
...	...	...
Segment MZ (≤ 24)	PSHAPE(MZ)	AXHI(MZ)
<i>Radial Power Distribution</i>		
Radial Node 1	PSHAPR(1)	IEQMAS*
Radial Node 2	PSHAPR(2)	
...	...	
Radial Node NT (≤ 11)	PSHAPR(NT)	

*IEQMAS determines whether radial fuel nodes are evaluated on an equal radius or equal volume basis.

Table VI: Data Required for Decay Heat Modeling.

Group	Power Fraction	Decay Constant (s^{-1})
1	$\beta_{h,1}$	$\lambda_{h,1}$
2	$\beta_{h,2}$	$\lambda_{h,2}$
3	$\beta_{h,3}$	$\lambda_{h,3}$
4	$\beta_{h,4}$	$\lambda_{h,4}$
5	$\beta_{h,5}$	$\lambda_{h,5}$
6	$\beta_{h,6}$	$\lambda_{h,6}$

3.1 Point Kinetics

During the transient, fission power amplitude will be determined by the conventional point kinetics equations:

$$\begin{aligned}\frac{d\phi(t)}{dt} &= \frac{\phi(t)[\delta k(t) - \beta]}{\Lambda} + \sum_i \lambda_i C_i(t) \\ \frac{dC_i(t)}{dt} &= \frac{\beta_i \phi(t)}{\Lambda} - \lambda_i C_i(t) \\ \beta &= \sum_i \beta_i\end{aligned}$$

where ϕ is the normalized fission power amplitude, Λ is the average prompt neutron lifetime, δk is the reactivity, and β_i and λ_i are the delayed neutron fraction and decay constant for delayed neutron group i , respectively.

Table VII: Data Required for Point Kinetics Modeling.

Group	Delayed Neutron Fraction	Decay Constant (s ⁻¹)
1	β_1	λ_1
2	β_2	λ_2
3	β_3	λ_3
4	β_4	λ_4
5	β_5	λ_5
6	β_6	λ_6

3.2 Material Properties

3.2.1 Fuel, Cladding, and Structures

For the initial benchmark, the thermophysical properties of fuel, cladding, assembly duct wall, and other structures are assumed to be independent of temperature. In the core zone, fuel, cladding, and duct wall properties are required. For purposes of modeling, wire-wrap properties are assumed to be the same as the duct wall. A summary of the required data for all materials is presented in Table VIII.

Above and below the fuel zone, thermophysical properties for reflector/shield compositions and surrounding structures are required. SAS4A/SASSYS-1 resolves the features in these zones using a simplified two-node slab treatment. In this case, reflector/shield properties represent materials within the flow area, and structure properties represent materials that surround the flow area (such as the duct wall).

It is worth noting that material properties in the zones below the core have no significance in this first benchmark specification. This is because the core inlet temperature is held constant during the transient, so no temperature changes will be predicted in the lower zones.

Nevertheless, these properties will be required for future benchmarks and are included in the requirements here.

Table VIII: Thermophysical Properties Required for Fuel, Cladding, Reflector, and Structure Materials.

Property	Units
Density	kg/m ³
Heat Capacity	J/kg-K
Thermal Conductivity	W/m-K

3.2.2 Coolant

Correlations for the temperature-dependent thermophysical properties of liquid sodium are included in the SAS4A/SASSYS-1 code. As with the fuel and structural materials listed above, these properties include density, heat capacity, and thermal conductivity. The correlations used are the following:

Coolant Density (kg/m³):

$$\rho(T) = 1004.23 - 0.21390T - 1.1046 \times 10^{-5} T^2 \quad (3)$$

Coolant Heat Capacity (J/kg-K):

$$c_p(T) = \frac{738980}{(T_c - T)^2} + \frac{3.154 \times 10^5}{(T_c - T)} + 1134.0 - 0.22153(T_c - T) + 1.1156 \times 10^{-4}(T_c - T)^2 \quad (4)$$

$$T_c = 2503.3\text{K}$$

Coolant Thermal Conductivity (W/m-K):

$$k(T) = 110.45 - 6.5112 \times 10^{-2} T + 1.5430 \times 10^{-5} T^2 - 2.4617 \times 10^{-9} T^3 \quad (5)$$

3.3 Heat Transfer

For heat transfer between the coolant and the surfaces of the fuel element, the reflectors, and the structure, the Lyon-Martinelli heat transfer correlation is used:

$$\text{Nu} = C_1 \text{Pe}^{C_2} + C_3 \quad (6)$$

where Nu is the Nusselt number and Pe is the Peclet number. The correlation coefficients C_1 , C_2 , and C_3 are required. The coolant heat transfer coefficient, h_c , can then be solved using the relationship $\text{Nu} = h_c D_e / k$, where D_e is the effective hydraulic diameter.

Heat transfer across the gap between the outer fuel surface and the inner cladding surface is a complex function of fuel and cladding conditions and the extent of fission gas release. For this benchmark, a constant gap heat transfer coefficient, h_g , will be required. To achieve the effect of a constant gap heat transfer coefficient, the input values HBMIN and HBMAX must

be set equal to the required value. Heat transfer data requirements are summarized in Table IX.

Table IX: Data Required for Heat Transfer Correlations.

Parameter	Symbol	Units
Coolant Heat Transfer	C_1	—
Coolant Heat Transfer	C_2	—
Coolant Heat Transfer	C_3	—
Gap Conductance	h_g	W/m ² -K

3.4 Pressure Drop

Pressure drop through core assemblies is a combination of both friction and form pressure losses. Turbulent friction pressure losses are represented as

$$f_t = A_{fr} \text{Re}^{B_{fr}}, \quad (7)$$

while laminar friction pressure losses are represented as

$$f_l = \frac{A_{flam}}{\text{Re}}. \quad (8)$$

SAS4A/SASSYS-1 supports two options for transitioning between laminar and turbulent friction factors. The first is to specify the Reynolds number for the transition between laminar and turbulent flow regimes, while the second is to add both components together for all Reynolds numbers. For this initial benchmark, the second option will be used.

Form pressure loss coefficients can be used between zones in a channel to represent losses due to complex geometry that is not explicitly represented. For the initial benchmark, inlet and outlet loss coefficients are required for the single channel, but loss coefficients between zones will be neglected. Table X summarizes the data required for pressure loss calculations.

Table X: Data Required for Pressure Drop Correlations.

Parameter	Symbol	Units
Turbulent Friction	A_{fr}	—
Turbulent Friction	B_{fr}	—
Laminar Friction	A_{flam}	—
Inlet Loss Coefficient	K_{in}	—
Outlet Loss Coefficient	K_{out}	—

4 Calculated Data

Once the required data described in Section 3 are provided by CIAE, both CIAE and Argonne participants will create models of CEFR using the SAS4A/SASSYS-1 safety analysis code. Simulations of the protected TOP will be carried out, and selected computed results from steady-state and transient conditions will be compared for two transients. As stated earlier, the two transients differ in that one assumes the primary pumps continue to operate at nominal flow during the transient, while the second assumes the primary pumps trip at the same time as the scram.

For both cases, the single channel flow rate and pressure drop will be recorded. In addition, the following steady-state axial temperature distributions will be tabulated for comparison:

1. Fuel centerline temperature.
2. Fuel surface temperature.
3. Coolant temperature in the fueled region.
4. Structure temperature (inner node) in the fueled region.

During each of the two transients, the following time-dependent data will be recorded for comparison:

1. Scram time.
2. Total power.
3. Decay power.
4. Reactivity.
5. Coolant flow.
6. Fuel centerline temperature at the core midplane.
7. Fuel centerline temperature at the top of the core.
8. Peak fuel centerline temperature and its axial location.
9. Coolant temperature at the top of the core.
10. Coolant temperature at the top of the fission gas plenum.
11. Coolant temperature at the assembly outlet.
12. Structure temperature (inner node) at the top of the core.
13. Structure temperature (inner node) at the top of the fission gas plenum.

Specific locations for core mid-plane, top of core, top of fission gas plenum, and assembly outlet can only be defined once the data from Section 3 is available.

Results will report time in seconds (s), reactivity in dollars (\$), temperature in Kelvin (K), and elevation in meters (m) relative to the bottom of the core. Power and flow will be reported in dimensionless units normalized to initial steady-state values. Time-dependent data shall be recorded every 0.1 seconds following the initiation of the transient. A minimum of 600 seconds of transient data will be plotted.

5 Future Activities

This document defines an initial benchmark specification and data requirements for comparative analysis of the coupled thermal, hydraulic, and neutronic performance of CEFR during transients based on simulations performed by the SAS4A/SASSYS-1 code. In order to complete the benchmark analysis, modeling data specific to the CEFR design is required.

These data requirements are defined in Section 3. Benchmark participants from CIAE will provide the necessary data. Benchmark participants from Argonne National Laboratory will update this document with the provided data and issue a revision of this document.

Once the benchmark specifications are completed and a revision to this document is issued, participants from CIAE and Argonne will develop independent models of the CEFR based on these specifications using the capabilities of the SAS4A/SASSYS-1 code. Comparisons of the simulation results will take place at a future training meeting to be held at Argonne National Laboratory. These comparisons will provide an opportunity to identify discrepancies in the models and to correct sources of error. In this way, these benchmark models will provide a foundation for the development of more complex models of CEFR with broader applications for safety analysis.

Nuclear Engineering Division

Argonne National Laboratory

9700 South Case Avenue

Argonne, IL 60439

www.anl.gov

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