SSC-K 전산코드 사용자 지침서 (Rev.0)

SSC-K Code User's Manual (Rev.0)

2000. 7

한국 원자력 연구소
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제출 문

한국원자력연구소장 귀하

본 보고서를 2000 년도 "액체금속로 안전해석 기술개발" 과제의 기술보고서로 제출 합니다.

제목: SSC-K 전산코드 사용자 지침서 (Rev.0)
SSC-K Code User's Manual (Rev.0)

2000. 7

과제명 : 액체금속로 안전해석 기술개발
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요 약 문

한국원자력연구소 (KAERI)는 Pool 형 액체금속로인 KALIMER의 다양한 비정상 조건 및 사고를 분석하기 위하여 최적열수력 전산코드인 SSC-K (Supper System Code of KAERI)를 개발하고 있다. SSC-K는 미국 BNL에서 투프형 액체금속로의 안전해석을 위해 개발된 SSC-L을 기반으로 하여 KALIMER와 같은 투프 원자로에 적응할 수 있도록 개발되었다. 현재 SSC-K 코드는 투프형과 총형의 액체금속로를 모두 모의할 수 있다. SSC-K는 과도상태의 열수역, 핵 및 기계적 모델을 포함하고 있으므로 사고시 노심과 냉각계, 핵연료의 거동 및 구조물의 은도변화를 모의할 수 있다.

본 보고서는 SSC-K를 위하여 새로이 개발된 여러 현상학적 모델들을 기술하고 있으며 부록에는 코드입력에 대한 설명을 포함하고 있다. 투프형 원자로 열수력 계산을 위해 개발된 정상상태 및 과도상태의 모델을 2장과 3장에 상세히 설명하였다. 4장에는 기존 SSC-L 코드의 IHX 모델을 투프형 원자료 구성에 적합하도록 변경한 중간열전달교환기 (IHX) 모델에 대해서 기술하였다. 5장에는 전자펌프 모델을 설명하였으며, SSC-K는 기존의 원심펌프와의 KALIMER 설계에 도입된 전자펌프 모델을 선택적으로 사용 가능하다. 6장에는 노심에서 발생되는 릴리얼 원자로 벽면과 압력용기 벽면을 통하여 주변의 공기로 제거하는 PSDRS 모델을 기술하였다. 7장에는 포플러와 소듐일도 변화에 의한 반응도 모델 및 노심의 기하학적 변형에 의한 여러 반응도 계획 모델에 대하여 설명하였다. 마지막으로 8장에는 SSC-K 에 사용되는 상 편식 및 물성치에 대하여 기술하였다. 참고로 부록 A 와 B에는 코드 입력에 대한 설명 및 SSC-K 에 사용된 Subroutines을 포함시켰다.

시험계산을 통하여 개발된 SSC-K 코드의 예측능력에 대한 타당성을 경정적으로 확인하였다. 전형적인 액체금속로 사고들에 대하여 SSC-K를 사용한 안전해석 결과는 별도의 보고서로 발간될 예정이다. 시험해석 결과에 의하면 개발된 SSC-K 코드는 향후 KALIMER 예비 안전해석에 사용할 수 있을 것으로 판단된다. SSC-K 코드는 계속 개발 중에 있으므로 사용자 지침서 역시 앞으로 개정될 예정이다.
SUMMARY

The Supper System Code of KAERI (SSC-K) is a best-estimate system code for analyzing a variety of off-normal or accidents in the heat transport system of a pool type LMR design. It is being developed at Korea Atomic Energy Research Institution (KAERI) on the basis of SSC-L, originally developed at BNL to analyze loop-type LMR transients. SSC-K can handle both designs of loop and pool type LMRs. SSC-K contains detailed mechanistic models of transient thermal, hydraulic, neutronic, and mechanical phenomena to describe the response of the reactor core, coolant, fuel elements, and structures to accident conditions.

This report provides an overview of recent model developments of the SSC-K computer code, focusing on phenomenological model descriptions for new thermal, hydraulic, neutronic, and mechanical modules. A comprehensive description of the models for pool-type reactor is given in Chapters 2 and 3; the steady-state plant characterization, prior to the initiation of transient is described in Chapter 2 and their transient counterparts are discussed in Chapter 3. In Chapter 4, a discussion on the intermediate heat exchanger (IHX) is presented. The IHX model of SSC-K is similar to that used in the SSC-L, except for some changes required for the pool-type configuration of reactor vessel. In Chapter 5, an electromagnetic (EM) pump is modeled as a component. There are two pump choices available in SSC-K; a centrifugal pump which was originally imbedded into the SSC-L, and an EM pump which was introduced for the KALIMER design. In Chapter 6, a model of passive safety decay heat removal system (PSDRS) is discussed, which removes decay heat through the reactor and containment vessel walls to the ambient air heat sink. In Chapter 7, models for various reactivity feedback effects are discussed. Reactivity effects of importance in fast reactor include the Doppler effect, effects of sodium density changes, effects of dimensional changes in core geometry. Finally in Chapter 8, constitutive laws and correlations required to execute the SSC-K are described.

Test runs for typical LMFBR accident analyses have been performed for the qualitative verification of the developed SSC-K modules. The analysis results will be issued as a separate report. It was found that the present version of SSC-K would be used for the preliminary safety analysis of KALIMER. However, the further validation of SSC-K is required for real applications. It is noted that the user's manual of SSC-K will be revised later with the further development of SSC-K code.
Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>제목문</td>
<td>i</td>
</tr>
<tr>
<td>요약문</td>
<td>ii</td>
</tr>
<tr>
<td>Summary</td>
<td>iii</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>iv</td>
</tr>
<tr>
<td>List of Figures</td>
<td>viii</td>
</tr>
<tr>
<td>List of Tables</td>
<td>x</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1-1</td>
</tr>
<tr>
<td>2. STEADY-STATE MODELS</td>
<td>2-1</td>
</tr>
<tr>
<td>2.1 Global Heat Balance</td>
<td>2-1</td>
</tr>
<tr>
<td>2.1.1 Steady State Calculation in IHX</td>
<td>2-2</td>
</tr>
<tr>
<td>2.2 Hot Pool Pressure Distribution</td>
<td>2-7</td>
</tr>
<tr>
<td>2.3 Thermal-Hydraulics for Fuel Assembly Region</td>
<td>2-8</td>
</tr>
<tr>
<td>2.3.1 Core Thermal-Hydraulics</td>
<td>2-8</td>
</tr>
<tr>
<td>2.3.2 Core Pressure Distribution</td>
<td>2-9</td>
</tr>
<tr>
<td>2.3.3 Upper Plenum Thermal-Hydraulics</td>
<td>2-14</td>
</tr>
<tr>
<td>2.3.4 Core Outlet Module Hydraulics</td>
<td>2-16</td>
</tr>
<tr>
<td>2.4 Loop Hydraulics</td>
<td>2-17</td>
</tr>
<tr>
<td>2.4.1 Hydraulics for IHX</td>
<td>2-17</td>
</tr>
<tr>
<td>2.4.2 Hydraulics for Pipes</td>
<td>2-18</td>
</tr>
<tr>
<td>2.4.3 Pump</td>
<td>2-19</td>
</tr>
<tr>
<td>2.4.4 Pressure Distribution of Pipes</td>
<td>2-20</td>
</tr>
<tr>
<td>2.4.5 Cold Pool Hydraulics</td>
<td>2-21</td>
</tr>
<tr>
<td>3. TRANSIENT MODELS</td>
<td>3-1</td>
</tr>
<tr>
<td>3.1 Flow Equations</td>
<td>3-1</td>
</tr>
<tr>
<td>3.1.1 Intact System</td>
<td>3-1</td>
</tr>
<tr>
<td>3.1.2 Damaged System</td>
<td>3-2</td>
</tr>
<tr>
<td>3.2 Pump Suction Pressure</td>
<td>3-3</td>
</tr>
<tr>
<td>3.3 Liquid Levels in Pools</td>
<td>3-4</td>
</tr>
<tr>
<td>3.4 Reactor Internal Pressure</td>
<td>3-6</td>
</tr>
<tr>
<td>3.4.1 Intact System</td>
<td>3-6</td>
</tr>
<tr>
<td>3.4.2 Damaged System</td>
<td>3-8</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>7.3.3.1 Free Fuel Expansion Model</td>
<td>7-18</td>
</tr>
<tr>
<td>7.3.3.2 Force Balance Controlled Expansion Model</td>
<td>7-20</td>
</tr>
<tr>
<td>7.3.3.3 Other Models</td>
<td>7-22</td>
</tr>
<tr>
<td>7.3.4 Radial Expansion Effect</td>
<td>7-23</td>
</tr>
<tr>
<td>7.3.4.1 SSC-K Model</td>
<td>7-23</td>
</tr>
<tr>
<td>7.3.4.2 Other Models</td>
<td>7-25</td>
</tr>
<tr>
<td>7.3.5 Control Rod Driveline Expansion Effect</td>
<td>7-27</td>
</tr>
<tr>
<td>7.4 Input Requirements for Reactivity Feedback Models</td>
<td>7-30</td>
</tr>
<tr>
<td>7.4.1 Doppler Effect</td>
<td>7-30</td>
</tr>
<tr>
<td>7.4.2 Sodium Density Effect</td>
<td>7-32</td>
</tr>
<tr>
<td>7.4.3 Axial Expansion Effect</td>
<td>7-33</td>
</tr>
<tr>
<td>7.4.4 Radial Expansion Effect</td>
<td>7-34</td>
</tr>
<tr>
<td>7.4.5 Control Rod Driveline Expansion Effect</td>
<td>7-35</td>
</tr>
<tr>
<td>7.5 Flowcharts</td>
<td>7-36</td>
</tr>
<tr>
<td>7.6 GEM Model</td>
<td>7-36</td>
</tr>
<tr>
<td>7.6.1 Current GEM Model</td>
<td>7-36</td>
</tr>
<tr>
<td>7.6.2 GEM Model Improvement</td>
<td>7-38</td>
</tr>
<tr>
<td>8. CONSTITUTIVE LAWS AND CORRELATIONS</td>
<td>8-1</td>
</tr>
<tr>
<td>8.1 Constitutive Laws</td>
<td>8-1</td>
</tr>
<tr>
<td>8.1.1 SSC-L Properties</td>
<td>8-1</td>
</tr>
<tr>
<td>8.1.1.1 Core and Blanket Fuel</td>
<td>8-1</td>
</tr>
<tr>
<td>8.1.1.2 Cladding and Structural Materials</td>
<td>8-5</td>
</tr>
<tr>
<td>8.1.2 Constitutive Laws for SSC-K</td>
<td>8-6</td>
</tr>
<tr>
<td>8.1.2.1 Metal Fuel Properties</td>
<td>8-6</td>
</tr>
<tr>
<td>8.1.2.2 Limitations and Future Work</td>
<td>8-12</td>
</tr>
<tr>
<td>8.1.3 Control Rod Material</td>
<td>8-12</td>
</tr>
<tr>
<td>8.1.4 Sodium</td>
<td>8-13</td>
</tr>
<tr>
<td>8.1.5 Water and Steam</td>
<td>8-19</td>
</tr>
<tr>
<td>8.2 Correlations</td>
<td>8-28</td>
</tr>
<tr>
<td>8.2.1 Friction Factor Correlations</td>
<td>8-28</td>
</tr>
<tr>
<td>8.2.1.1 Pressure Drop in Pipe</td>
<td>8-28</td>
</tr>
<tr>
<td>8.2.1.2 Pressure Drop in Wire-Wrapped Rod Bundles</td>
<td>8-33</td>
</tr>
<tr>
<td>8.2.2 Heat Transfer Correlations</td>
<td>8-37</td>
</tr>
<tr>
<td>9. TWO-DIMENSIONAL HOT POOL MODEL</td>
<td>9-1</td>
</tr>
<tr>
<td>9.1 Introduction</td>
<td>9-1</td>
</tr>
</tbody>
</table>
List of Figures

Fig. 1.1 KALIMER Primary System ................................................. 1-3
Fig. 1.2 Primary System Schematics ............................................. 1-4
Fig. 1.3 Schematic Diagram of KALIMER System ............................ 1-5
Fig. 2.1 Flowchart for Steady-State Calculation ............................... 2-22
Fig. 2.2 Steady-State Conditions for an IHX Nodal Section ............... 2-23
Fig. 3.1 Flowchart for Transient Calculation ................................. 3-22
Fig. 3.2 Schematic of SSC-K Modeling for KALIMER ....................... 3-23
Fig. 3.3 Two Mixing Zone Model for Hot Pool ............................... 3-24
Fig. 4.1 Flow Paths of KALIMER IHX ........................................ 4-10
Fig. 4.2 Nodal Diagram for Thermal Balance .................................. 4-11
Fig. 6.1 PSDRS Model .............................................................. 6-10
Fig. 6.2 Flowchart of PSDRS Program ......................................... 6-11
Fig. 6.3 Top View of KALIMER PSDRS ....................................... 6-12
Fig. 7.1 Overall Scheme for Calculating Total Reactor Core Power .... 7-40
Fig. 7.2 Components of Reactivity Feedback Effect ...................... 7-41
Fig. 7.3 Schematic of Core Layout for Reactivity Model Development .... 7-42
Fig. 7.4 SSC-K Representation of Core Subassemblies ..................... 7-43
Fig. 7.5 SSC-K Representation of Fuel Rod ................................... 7-44
Fig. 7.6 Typical Core Restarint System ....................................... 7-45
Fig. 7.7 GEM Operation Scheme ................................................. 7-46
Fig. 7.8 Schematic for GEM Model Development ............................. 7-47
Fig. 7.9 Flow Diagram of Reactivity Feedback Calculation for SSC-K .... 7-48
Fig. 9.1 Flowchart of One-dimensional Hot Pool Model ................... 9-12
Fig. 9.2 Flowchart of Two-dimensional Hot Pool Model ................. 9-13
Fig. 9.3 Flowchart of HP2D, Steady-State .................................. 9-14
Fig. 9.4 Flowchart of HP2D, Transient ..................................... 9-15
Fig. 9.5 Two-Dimensional Hot Pool Model .................................. 9-16
Fig. 9.6 Sodium Velocity Distribution in HOT Pool during Normal Operation 9-17
Fig. 9.7 Hot Pool Sodium Outlet Temperatures ............................... 9-18
Fig. 9.8 Power and Flow during 10 Cent UTOP ............................ 9-18
Fig. 9.9 Hot Pool Temp. during 10 Cent UTOP .............................. 9-19
Fig. 9.10 Hot Pool Temperature Distribution during 10 Cent UTOP ...... 9-20
Fig. B.1 Subroutines for Input Processing ................................. B-2
Fig. B.2 Subroutines for Steady-State Calculation ....................... B-4
Fig. B.3 Subroutines for Transient Calculation ........................................... B-8
Fig. B.4 Subroutines for Steam Generator (MINET Portion) .......................... B-17
Fig. B.5 All Subroutines Employed into SSC-K ........................................... B-21
List of Tables

Table 3-1  Code Modification List .................................................. 3-19
Table 5-1  Correlation Coefficients for Use with the LMR Pumps .................. 5-4
Table 8-1  Parameters on Fuel Thermal Conductivity and Specific Heat Correlations ...... 8-2
Table 8-2  Parameters in Fuel Coefficient of Thermal Expansion, Density and Emissivity Correlations .................................................. 8-4
Table 8-3  Parameters for Cladding and Structural Material Properties .................. 8-6
Table 8-4  Parameters for Control Rod Material Properties ................................. 8-14
Table 8-5  Values of Coefficients for Temperature of Compressed Liquid Water ........ 8-22
Table 8-6  Values of Coefficients for Temperature of Compressed Water Vapor ........ 8-22
Table 8-7  Values of Coefficients for Density of Compressed Liquid Water ............. 8-22
Table 8-8  Values of Coefficients for Viscosity of Compressed Liquid Water ........... 8-25
Table 8-9  Values of Coefficients for Viscosity of Superheated Water Vapor ............. 8-26
Table 8-10 Roughness of various piping materials ........................................ 8-29
Table 8-11 FormLoss Coefficient for Various Flow Restrictions .......................... 8-32
Table 8-12 Values of Constants in Equation $\text{8-92}$ .................................... 8-34
Table 8-13 Important Parameters of CRBR Hexagonal Assemblies ......................... 8-35
Table 8-14 Comparison of correlations used for SSC-L and SSC-K ....................... 8-40
Table 9-1  Initial and Key Operating Parameters ........................................ 9-11
1. INTRODUCTION

The Supper System Code of KAERI (SSC-K) is a best-estimate system code for analyzing a variety of off-normal or accidents in KALIMER [1-1] which is a pool type design. It is developed at Korea Atomic Energy Research Initititution (KAERI) on the basis of SSC-L [1-2] developed at BNL to analyze loop-type LMR transients. Because of inherent difference between the pool and loop design, the major modifications of SSC-L has been made for the safety analysis of KALIMER.

The major difference between KALIMER and general loop type LMRs exists in the primary heat transport system as shown in Fig. 1.2. In KALIMER, all of the essential components consisted of the primary heat transport system are located within the reactor vessel. This includes reactor, four EM pumps, primary side of four intermediate heat exchangers, sodium pools, cover gas blanket, and associated pipings. This is contrast to the loop type LMRs, in which all the primary components are connected via piping to form loops attached externally to the reactor vessel. KALIMER has only one cover gas space. This eliminates the need for separate cover gas systems over liquid level in pump tanks and upper plenum. The IHX outlet is directly connected to cold pool instead of the piping into pump suction which is a typical configuration in loop type LMRs. Since the sodium in hot pool is separated from cold pool by insulated barrier in KALIMER, the liquid level in hot pool is different from that in the cold pool mainly due to hydraulic losses and pump suction heads occuring during flow through the circulation pathes. In some accident conditions the liquid in the hot pool is flooded into cold pool and it forms the natural circulation flow path. During the loss of heat sink transients, this will provided as a major heat rejection mechanism with the passive decay heat removal system. Since the pipes in the primary system exist only between pump discharge and core inlet plenum and are submerged in cold pool, a pipe rupture accident becomes less severe due to a constant back pressure exerted against the coolant flow from break. The intermediate and steam generator systems of both designs are generally identical (Fig. 1.3).

The SSC-K is designed to predict plant response under various off-normal and accident conditions until sodium boiling occurs. This code can also perform the steady-state initialization.
This feature is provided so that user can easily obtain the various preaccident initial conditions based on user-specified design parameters and minimum operating values.

This report provides an overview of recent model developments in the SSC-K compute code, focusing on phenomenological model descriptions for new thermal, hydraulic, neutronic, and mechanical modules. Since SSC-K is developed on the basis of SSC-L, many portions of SSC-K utilized the same methods and models as its parent code SSC-L. Therefore, the primary emphasis in the development and its description in the report has been focused on the differences between the two codes.

A comprehensive description of the models for pool-type reactor is given in Chapters 2 and 3; the steady-state plant characterization, prior to the initiation of transient is described in Chapter 2 and their transient counterparts are discussed in Chapter 3. In Chapter 4, a discussion on the intermediate heat exchanger (IHX) is presented. The IHX model of SSC-K is similar to that used in the SSC-L, except some changes required for the pool-type configuration of reactor vessel. In Chapter 5, an electromagnetic (EM) pump is modeled as a component. There are two pump choices available in SSC-K; a centrifugal pump which was originally imbedded into the SSC-L, and an EM pump which was introduced for the KALIMER design. In Chapter 6, a model of passive safety decay heat removal system (PSDRS) is discussed, which removes decay heat through the reactor and containment vessel walls to the ambient air heat sink. In Chapter 7, models for various reactivity feedback effects are discussed. Reactivity effects of importance in fast reactor include the Doppler effect, effects of sodium density changes, effects of dimensional changes in core geometry. Finally in Chapter 8, constitutive laws and correlations required to execute the SSC-K are described.
Fig. 1.1 KALIMER Primary System
Fig. 1.2 Primary System Schematics

(a) Loop-type LMR

(b) Pool-type LMR
Fig. 13: Schematic Diagram of KALIMER System

STEAM GENERATOR

EMP
2. STEADY-STATE MODELS

In the initial part of the transient calculation, a stable and unique steady state or pre-transient solution for entire plant must be obtained. As a result, the continuity, energy, and momentum conservation equations in time-independent form are reduced to a set of nonlinear algebraic equations. These equations are solved in two steps. First, the global parameters are obtained. More detailed characterization is achieved by using the global conditions obtained in the first step, as boundary conditions. Since the SSC-K is developed based on SSC-L, the most of the steady-state routine in SSC-L is used with minimum changes. Some modifications are required due to including the cold pool model into SSC-K. The flow chart for steady-state solution routine is in Fig. 2.1.

2.1 Global Heat Balance

At steady state, the fluid and metal in the core inlet plenum are assumed to be thermal equilibrium. The temperatures are then equal to the user specified fluid temperature at the inlet nozzle, i.e.,

\[ T_{\text{plenum}} = T_{\text{metal}} = T_{\text{inlt}} \]  \hspace{1cm} (2-1)

The core inlet temperature is specified as input. The hot pool sodium enthalpy and temperature can be obtained using known values of core power and mass flow rate:

\[ h_{\text{outl}} = h_{\text{inlt}}(T_{\text{inlt}}) + P_{\text{core}} / W_{\text{tot}} \]  \hspace{1cm} (2-2)

\[ T_{\text{outl}} = f(h_{\text{outl}}) \]  \hspace{1cm} (2-3)

The IHX inlet and outlet temperatures are determined according to the location of pump in
order to account the temperature rise due to pump heat generation.

\[
\begin{align*}
T_{\text{INHX}} & = T_{\text{out}} + AT_{\text{pump}} & \text{if pump is between hot pool and IHX} \\
T_{\text{INHX}} & = T_{\text{out}} & \text{if pump is located after IHX} \\
T_{\text{OUTX}} & = T_{\text{in}} - AT_{\text{pump}} & \text{if pump is between IHX and core inlet plenum} \\
T_{\text{OUTX}} & = T_{\text{in}} & \text{if pump is located before IHX}
\end{align*}
\]

(2-4)

(2-5)

The total heat removal rate by IHX can be calculated as following:

\[
Q_{\text{TOTAL}} = W_{\text{loop}} \left[ h(T_{\text{INHX}}) - h(T_{\text{OUTX}}) \right]
\]

(2-6)

2.1.1 Steady State Calculation in IHX

To start the steady state calculations for IHX, the boundary temperatures at one end of IHX, in this case \( T_{\text{INHX}} \), \( T_{\text{OUTX}} \) and \( W_{\text{loop}} \), must been known. \( T_{\text{INHX}} \) is known from global thermal balance calculations. The IHX outlet temperature and flow rate for intermediate side are guessed for first pass:

\[
\begin{align*}
W_{\text{loop}} & = W_{\text{loop}} + 1.0 \\
T_{\text{OUTX}} & = T_{\text{INHX}} - 20 & \text{where } T_{\text{OUTX}} = \text{known}
\end{align*}
\]

(2-7)

The iteration procedure for the temperature distribution of IHX is as following:

Step 1. Find out the node length and heat transfer areas for tube and shell sides:

\( \Delta x \) : length of IHX node
\( A_2 \): primary side (shell side) heat transfer area for each IHX node
\[ = \pi \cdot (\text{IHX tube outer diameter}) \cdot \Delta x \cdot (\# \text{ tubes}) \]

\( A_i \): intermediate side (tube side) heat transfer area for each IHX node

Step 2. Compute the constants for computation of Peclet numbers:

\[
A_{p\text{ep}} = (\text{diameter})(\text{velocity})(\text{density}) = P_e \cdot k / c_p = \frac{W_{\text{loop}} \cdot d_i}{A_{\text{IHX}}} \tag{2-8}
\]

\[
A_{p\text{es}} = (\text{diameter})(\text{velocity})(\text{density}) = P_e \cdot k / c_p = \frac{W_{\text{loop}} \cdot d_i}{A_{2\text{IHX}}} \tag{2-9}
\]

Step 3. Guess the tube structure temperature (Fig. 2.2):

\[
TT = \frac{T_{i,p} + T_{i,s}}{2} \tag{2-10}
\]

\( T_{po} = T_{pi} \), \( T_{to} = T_{si} \)

Step 4: Calculate the node average sodium temperatures:

\[
\bar{T}_p = \frac{T_{po} + T_{pi}}{2}, \quad \bar{T}_s = \frac{T_{to} + T_{si}}{2} \tag{2-11}
\]

Step 5: Find out the non-dimensional numbers for heat transfer coefficients:

Peclet numbers for primary and intermediate sides

\[
P_{ep} = A_{p\text{ep}} \cdot c_p / k_p, \quad P_{es} = A_{p\text{es}} \cdot c_p / k_s \tag{2-12}
\]

Nusselt number

\[
Nu_p = a + b \cdot P_e^c \quad \text{Shell side (primary)} \tag{2-13}
\]
Aoki's correlation for tube side (intermediate)

\[ Nu_s = 6.0 + 0.025 \cdot (\overline{\varphi} P_{\text{es}})^{0.8} \]  \hspace{1cm} (2-14)

where

\[ \overline{\varphi} = \frac{0.014(1 - e^{-71.8x})}{x} \]  \hspace{1cm} (2-15)

\[ x = \frac{1}{Re_s^{0.45} \cdot Pr_s^{0.2}} \]  \hspace{1cm} (2-16)

\[ Re_s = \frac{\rho u d}{\mu} = \frac{A_{\text{PES}}}{\mu} \]  \hspace{1cm} (2-17)

\[ Pr_s = \frac{v}{\alpha} = \frac{c_p \cdot \mu_s}{k_s} \]  \hspace{1cm} (2-18)

Step 6: Calculate the overall heat transfer coefficients:

\[ U_{pl} = \frac{1}{\frac{D_{b,p}}{Nu_s \cdot k_p} + r_{\text{wall},p} + r_{\text{fou},p}} \]  \hspace{1cm} (2-19)

\[ U_{sl} = \frac{1}{\frac{D_{b,s}}{Nu_s \cdot k_s} + r_{\text{wall},s} + r_{\text{fou},s}} \]  \hspace{1cm} (2-20)

Step 7: Calculate the node outlet temperatures for primary and intermediate sides:

\[ e_{p,o,l} = e_{p,l} + \frac{A_p \cdot U_{pl} (T_T - T_p)}{W_{\text{loop}}} \]  \hspace{1cm} (2-21)

\[ e_{s,o,l} = e_{s,l} + \frac{A_s \cdot U_{sl} (T_T - T_s)}{W_{2\text{loop}}} \]  \hspace{1cm} (2-22)
Step 8: Calculate the node average sodium temperatures and tube temperature based on the calculated node exit temperatures:

\[ T_{pol} = T(e_{pol}) \]  \hfill (2-23)

\[ T_{sol} = T(e_{sol}) \]  \hfill (2-24)

\[
\bar{T}_p = \frac{T_{pol} + T_{pl}}{2}
\]  \hfill (2-25)

\[
\bar{T}_s = \frac{T_{sol} + T_{sl}}{2}
\]  \hfill (2-26)

\[
TT_i = \frac{A_1U_{st}\bar{T}_s + A_2U_{st}T_{pl}}{A_1U_{st} + A_2U_{st}}
\]  \hfill (2-27)

Step 9: Perform the convergence test for the node:

\[
\text{if } |T_{po} - T_{pol}| > \varepsilon \text{ and } |T_{so} - T_{sol}| > \varepsilon \text{ and } |TT - TT_i| > \varepsilon \text{ then}
\]  \hfill (2-28)

\[ T_{pol} \rightarrow T_{po}, \ T_{sol} \rightarrow T_{so}, \ TT_i \rightarrow TT \]  \hfill (2-29)

go to Step 4 and iterate again.

Step 10: Reset the node exit temperatures into the inlet temperatures for next node until \( i = nihxl \):

\[ T_{pol} \rightarrow T_{pl}, \ T_{sol} \rightarrow T_{sl}, \ TT_i \rightarrow TT \text{ and go to Step 4 and continue for next node.} \]
Step 11. Perform the error checking if the energy gain is equal to energy loss:

\[ T_{1OUX} = T(e_{po}) \]

\[ T_{2INHX} = T(e_{po}) \]

\[ Q_{loss} = W_{loop}(e_{pIn} - e_{po}) \]

\[ Q_{gain} = W_{loop}(e_{z end} - e_{z In}) \]

\[ \text{if} \left| \frac{1 - Q_{gain}}{Q_{loss}} \right| > \varepsilon \quad \text{error} \]

Step 12. Check for convergence based on total energy balance:

The heat rejection from IHX should equal to the reactor heat plus heat addition at the pump within specified limits:

\[ \text{if} \left| \frac{Q_{TOTAL} - Q_{gain}}{Q_{TOTAL}} \right| < \varepsilon \quad \text{quit iteration} \]

Step 13. If not, the secondary outlet temperature and flow rate have to be reselected and the computation repeated until convergence is obtained:

Log-mean temperature difference

\[ \Delta \bar{T} = \frac{(T_{1OUX} - T_{2INHX}) - (T_{1INHX} - T_{2OUX})}{\ln[(T_{1OUX} - T_{2INHX})/(T_{1INHX} - T_{2OUX})]} \]

\[ UA = Q_{gain} / \Delta \bar{T} \]
Assuming UA constant, determine new \( Imtd \) guess

\[
\Delta T_{\text{new}} = \frac{Q_{\text{TONT}}}{UA} \quad (2-38)
\]

\[
\Delta T_A = T_{1\text{OUHX}} - T_{2\text{INHX}} \quad (2-39)
\]

\[
\Delta T_{\text{new}} = \Delta T_A - \Delta T_B \quad \text{\( \Rightarrow \) Find } \Delta T_B \text{ using root finding scheme.} \quad (2-40)
\]

\[
T_{2\text{OUHX}} = T_{1\text{INHX}} - \Delta T_B \quad (2-41)
\]

\[
W_{2\text{loop}} = \frac{Q_{\text{TONT}}}{[\mu(T_{2\text{OUHX}}) - \mu(T_{2\text{INHX}})]} \quad \text{Return to Step 1} \quad (2-42)
\]

After calculating the temperature distribution of IHX, the similar process is performed for the energy balance for steam generator.

### 2.2 Hot Pool Pressure Distribution

Subroutine PINT1S calculates the interface pressure between the hot pool and IHX.

\[
P_{1\text{INLT}} = P_{6\text{CGAS}} + \rho(T_{6\text{OUTL}}) \cdot g(Z_{6\text{UPPLN}} - Z_{6\text{ONOZ}}) \quad (2-43)
\]

where

- \(Z_{6\text{UPPLN}}\): relative height of sodium in vessel upper plenum to \(Z_{6\text{REF}}\)
- \(Z_{6\text{ONOZ}}\): elevation of vessel outlet nozzle above \(Z_{6\text{REF}}\)

\[
T_{1\text{INLT}} = T_{6\text{OUTL}} \quad (2-44)
\]

\[
P_{6\text{OUTL}} = P_{1\text{INLT}} \quad (2-45)
\]

\[
P_{6\text{INLT}} = P_{6\text{OUTL}} + P_{1\text{PDRT}} \quad (2-46)
\]

where

- \(P_{1\text{PDRT}}\): pressure drop between core inlet and IHX inlet
2.3 Thermal-Hydraulics for Fuel Assembly Region

2.3.1 Core Thermal-Hydraulics

The core region is divided into $N_{6\text{CHAN}}$ parallel channels. These channels represent either fuel, blanket, or control rods. The flow rate for each channel is obtained by user specified flow fraction of the total flow through these channels.

\[ W_{6\text{CHAN},i} = W_{6\text{STOT}} \cdot F_{6\text{FLOW},i} \]  \hspace{1cm} (2-47)

\[ G_{6i,j} = \frac{W_{6\text{CHAN},j}}{N_{6\text{RODS},j} \cdot A_{6\text{ROD},j}} \]  \hspace{1cm} (2-48)

where

- $G_{6i,j}$: mass flux of channel $j$
- $N_{6\text{RODS},j}$: number of rods in channel $j$
- $A_{6\text{ROD},j}$: sodium flow area per rod in channel $j$

Each of the flow channels is divided into a user-controlled number of axial slices. The axial distributions of coolant enthalpy and pressure in all channels are determined in this subroutine.

\[ F_{\text{CONS}1} = \frac{P_{6\text{TPOW},j} \cdot F_{6\text{TPOW},j}}{Z_{6\text{CHAN},j} \cdot W_{6\text{CHAN},j}} \]  \hspace{1cm} (2-49)

where

- $F_{6\text{TPOW},j}$: Total normalized power fraction in channel $j$ from fission and decay heating

\[ Q_{\text{FACT},i,j} = \frac{dh}{dz} \Delta z = \frac{1}{W_{6\text{CHAN},j}} \cdot \frac{P_{6\text{TPOW},j} \cdot F_{6\text{TPOW},j} \cdot F_{6\text{NPWA},j} \cdot Z_{6\text{DELT},i,j}}{Z_{6\text{CHAN},j}} \]  \hspace{1cm} (2-50)

\[ = F_{\text{CONS}1} \cdot F_{6\text{NPWA},j} \cdot Z_{6\text{DELT},i,j} \]
where $Q_{FACT,i,j}$: enthalpy change in axial slice $i$ of channel $j$  
$F_{SNPW,i,j}$: normalized axial power in axial slice $i$ of channel $j$  
$L_{DELT,i,j}$: length of axial slice $i$ in channel $j$

$$T_{AVG} = \frac{T_{in} + T_{OLD}}{2}$$  \hspace{1cm} (2-51)$$

$$T_{OUT} = T_{in} + \frac{Q_{FACT,i,j}}{C_p(T_{AVG})}$$  \hspace{1cm} (2-52)$$

where $T_{in}$: inlet temperature of axial slice $i$ in channel $j$ (known)  
$T_{OLD}$: outlet temperature of axial slice $i$ in channel $j$ (unknown)  
$T_{OUT}$: calculated outlet temperature of axial slice $i$ in channel $j$

if the temperature difference between initial guessing value and calculated value, $|T_{OUT} - T_{OLD}|$, is greater than user specified limit, $T_{OLD}$ is reset to $T_{OUT}$ and $T_{OUT}$ is calculated again until $|T_{OUT} - T_{OLD}|$ is less than the limit. Then, the friction and heat transfer coefficients are calculated based upon the new outlet temperature of the axial slice.

$$f_{FRIC,i,j} = f\left[D_h, G_{6i}, \mu(T_{OUT}), (P/D)_{rod}, (P/D)_{wire\ wrap}, L_{ATYP}\right]$$  \hspace{1cm} (2-53)$$

$$h_{NODE,i,j} = \frac{Nu[D_h, G_{6i}, T_{AVG}, (P/D)_{rod}] \cdot K(T_{AVG})}{D_h}$$  \hspace{1cm} (2-54)$$

After completing the calculations for the current axial slice, the same calculations perform for the next axial slice.

### 2.3.2 Core Pressure Distribution

Because the current version of SSC-K simulates single phase flow, the flow is assumed to be incompressible. The axial distributions of coolant pressure in all channels are determined by momentum equations.
The pressure of the core bottom is obtained from the pressure of core inlet plenum by substracting the pressure drop due to form loss and gravitational loss:

\[ G_{LPLN} = \frac{W_{TOT}}{A_{LPLN}} \]  \hspace{1cm} (2-55)

\[ \Delta P_{LP}^{grav} = \rho g \cdot (Z_{BCOR} - Z_{BNOZ}) \]  \hspace{1cm} (2-56)

\[ \Delta P_{LP}^{loss} = -F_{PKLP} \]  \hspace{1cm} (2-57)

where
- \( G_{LPLN} \): mass flux of lower plenum
- \( \Delta P_{LP}^{grav} \): gravitation pressure drop from inlet nozzle to bottom of core
- \( \Delta P_{LP}^{loss} \): pressure drop due to form loss from inlet nozzle to bottom of core
- \( F_{PKLP} \): user specified pressure drop due to form loss from inlet nozzle to bottom of core

\[ P_{BCOR} = P_{INLT} - \Delta P_{LP}^{loss} - \Delta P_{LP}^{grav} \]  \hspace{1cm} (2-58)

\[ K_{LP} = 2 \rho \cdot \frac{\Delta P_{LP}^{loss}}{(G_{LPLN})} \]  \hspace{1cm} (2-59)

where
- \( P_{BCOR} \): Pressure of the core bottom
- \( K_{LP} \): Equivalent form loss coef. from inlet nozzle to bottom of core

The pressure of the core top is obtained from the cover gas pressure by adding the pressure drop due to form loss and gravitational loss:

\[ G_{UPLN} = \frac{W_{TOT}}{A_{UPLF}} \]  \hspace{1cm} (2-60)

\[ \Delta P_{UPLF}^{grav} = \rho g \cdot (Z_{UPLN} - Z_{TCOR}) \]  \hspace{1cm} (2-61)
\[ \Delta P_{\text{loss}}^{\text{UP}} = -F_{6} \cdot \Delta P_{\text{PKUP}} \]  

(2-62)

where  
- \( G_{\text{UPLN}} \): mass flux of upper plenum  
- \( \Delta P_{\text{grav}}^{\text{UP}} \): gravitation pressure drop from top of core to top of hot pool  
- \( \Delta P_{\text{loss}}^{\text{UP}} \): pressure drop due to form loss from top of core to top of hot pool  
- \( F_{6} \cdot \Delta P_{\text{PKUP}} \): user specified pressure drop due to form loss from top of core to top of hot pool

\[ P_{6 \text{TCOR}} = P_{6 \text{CGAS}} + \Delta P_{\text{grav}}^{\text{UP}} + \Delta P_{\text{loss}}^{\text{UP}} \]  

(2-63)

\[ K_{6 \text{UP}} = 2 \rho \cdot \Delta P_{\text{loss}}^{\text{UP}} / (G_{\text{UPLN}} |G_{\text{UPLN}}|) \]  

(2-64)

where  
- \( P_{6 \text{TCOR}} \): Pressure of the core bottom  
- \( K_{6 \text{UP}} \): equivalent form loss coef. from inlet nozzle to bottom of core

Before calculating the pressure distribution for the active core region, the pressure drop in inlet orifice zone has to be estimated:

\[ \Delta P_{\text{grav}}^{\text{INOZ}} = \rho g \Delta Z_{6 \text{INOZ}} \]  

(2-65)

\[ W_{\text{INOZ}} = \frac{W_{6 \text{TOT}} \cdot F_{6 \text{FLOW}}}{N_{5 \text{ASS} j}} \]

where  
- \( \Delta P_{\text{grav}}^{\text{INOZ}} \): Pressure drop for inlet orifice zone  
- \( W_{\text{INOZ}} \): flow rate per subassembly for channel \( j \)  
- \( F_{6 \text{FLOW}} \): flow fraction for channel \( j \)

Because the pressure drop due to friction in inlet orifice zone is given by user, the hydraulic diameter for orifice zone can be found by Bisection or Newton’s method (YHYD6S).
1. Guess the initial value for \( D_h^* \)

2. Calculate the pressure drop due to friction

\[
\Delta P_{\text{fric}} = f(D_h, G, \mu) \frac{\Delta Z_{\text{bend}} G |G|}{D_h 2 \rho}
\]  
(2-66)

3. Find the difference between user specified pressure drop and calculated pressure drop

\[
\Delta P^{*+1} = \Delta P^{*+1}_{\text{fric}} - \Delta P^{\text{calc}}_{\text{fric}}
\]  
(2-67)

4. Reset the upper and lower limits for Bisection method.

\[
\begin{cases}
\Delta P^{UP} = \Delta P^{*+1} \\
\Delta P^{LOW} = \Delta P^{*+1}
\end{cases}
\]  
if \( \Delta P^{*+1} > 0.0 \) \( \Delta P^{*+1} < 0.0 \)  
(2-68)

5. Convergence test

\[
\text{if} \quad \Delta P^{*+1} < 1.0 \quad \text{then} \quad D_h^{\text{NOZ}} = D_h \quad \text{and terminate the iteration}
\]  
(2-69)

6. Find the hydraulic diameter for next iteration:

\[
D_h^{*+1} = D_h^* + \Delta P^* \left| \frac{D_h^{*+1} - D_h^*}{\Delta \Delta P^* - \Delta \Delta P^{*+1}} \right|
\]  
(2-70)

7. Test if \( D_h^{*+1} \) is within the bounds.

\[
\begin{cases}
\text{Reset the values and return to step2} & \text{if} \quad D_h^{LOW} < D_h^{*+1} < D_h^{UP} \\
D_h^{*+1} = \frac{D_h^{LOW} + D_h^{UP}}{2} & \text{else}
\end{cases}
\]  
(2-71)
Because the form loss coefficient due to expansion and contraction in inlet orifice zone is given by user, the pressure drop in orifice zone can be obtained such as:

Mass flux for inlet orifice zone is obtained from the calculated hydraulic diameter:

\[ \dot{G}_{\text{INOZ}} = \frac{4 \cdot W_{\text{INOZ}}}{\pi \cdot D_{h}^{\text{INOZ}}} \]  

(2-72)

The pressure drop drop to form loss:

\[ \Delta P_{\text{loss}}^{\text{INOZ}} = F_{L5A} \frac{G_{\text{INOZ}} \cdot |G_{\text{INOZ}}|}{2\rho} \]  

(2-73)

The pressure at the bottom of active core region is:

\[ P_{\text{NODE},i} = P_{\text{BCOR}} - \Delta P_{\text{grav}}^{\text{INOZ}} - \Delta P_{\text{loss}}^{\text{INOZ}} - \Delta P_{\text{fric}}^{\text{INOZ}} \]  

(2-74)

The constant for calculation of the pressure distribution in active core region:

\[ \rho_{j,ol} = \frac{\rho_{j,i} + \rho_{j,i+1}}{2} \]  

(2-75)

where \( \rho_{j,ol} \) : average density for nodes \( i \) and \( i+1 \) in channel \( j \)

\[ \Delta P_{j,ol}^{\text{grav}} = \rho_{j,ol} \Delta Z_{j,ol} \]  

(2-76)

\[ \Delta P_{j,ol}^{\text{fric}} = f_{LFRIC} \frac{\Delta Z_{j,ol}}{D_{h}} \frac{G_{6i}}{|G_{6i}|} \frac{2\rho_{j,ol}}{2} \]  

(2-77)
\[ \Delta P_{m,ji} = \frac{G^2_{6j} - G^2_{6i}}{\rho_{j,ii} - \rho_{j,ji}} \] (2-78)

The pressure at node \( i+1 \) is:

\[ P_{6\text{NODE}_{i+1}} = P_{6\text{NODE}_{i}} - \Delta P_{j,di} - \Delta P_{j,di} - \Delta P_{m,ji} \] (2-79)

2.3.3. Upper Plenum Thermal-Hydraulics

The core region is divided into \( N_{6\text{CHAN}} \) parallel channels. These channels represent either fuel, blanket, or control rods. The flow rate for each channel is obtained by user specified flow fraction of the total flow through these channels.

\[ W_{6CT} = \sum_{j} W_{6\text{CHAN}_j} \] (2-80)

\[ E_{6\text{AVER}} = \sum_{j} \left( W_{6\text{CHAN}_j} \cdot E_{6\text{NODE}_j} \right) / W_{6CT} \] (2-81)

\[ T_{\text{AVER}} = \left( \sum_{j} T_{6\text{NODE}_j} \right) / N_{6\text{CHAN}} \] (2-82)

\[ Q_{\text{IN}} = \sum_{j} \left( W_{6\text{CHAN}_j} \cdot E_{6\text{NODE}_j} \right) \] (2-83)

The temperatures for cover gas, internal structure, thermal liner and vessel closure head can be found by solving the governing energy equations for hot pool region by iterative procedure:

1. Guess thermal liner temperature, \( T_{6,M2} \) same as hot pool sodium temperature:
\[ T_{6M2} = T_{6OUTL}; \quad T_{UP} = T_{6OUTL}; \quad T_{LOW} = -1. \]  

\[ E_{6BPUI} = E_{6BPUI}; \quad T_{6BPUI} = T(E_{6BPUI}) \]

2. Compute the temperatures for cover gas, internal structure, thermal liner from user-specified heat transfer coefficients and the assumed thermal liner temperature:

\[ T_{6CGAS} = T_{6M2} - U_{ALM2} (T_{6OUTL} - T_{6M2})/U_{AGM2} \]  

\[ T_{6M3} = (U_{AGM3} T_{6CGAS} + U_{AGM3} T_{6BPUI}) / 2 \cdot U_{AGM3} \]  

\[ T_{6M1} = (U_{ALM1} T_{6OUTL} + U_{AGM1} T_{6CGAS}) / (U_{ALM1} + U_{AGM1}) \]

3. Compute \( T_{6M2} \)

\[ T_{6M2}^* = T_{6CGAS} - \frac{U_{ALM1} (T_{6OUTL} - T_{6CGAS}) + U_{AGM1} (T_{6M1} - T_{6CGAS}) + U_{AGM3} (T_{6M3} - T_{6CGAS})}{U_{AGM2}} \]

4. If computed \( T_{6M2}^* \) is not equal to assumed \( T_{6M2} \), reset and iterate.

In order to calculate the pressure drop for outlet module, the core outlet pressure has to be found.

\[ P_{6OUTL} = P_{6CGAS} + \rho (T_{6OUTL}) g \cdot (Z_{6UPLN} + Z_{6ONOZ}) \]  

\[ P_{6TCOR} = P_{6OUTL} + \rho (T_{6OUTL}) g \cdot (Z_{6ONOZ} + Z_{6TCOR}) \]

where

\( P_{6OUTL} \) : IHX inlet pressure

\( P_{6TCOR} \) : core outlet pressure
2.3.4 Core Outlet Module Hydraulics

This subroutine calculates the pressure equalization loss coefficient at outlet module.

\[ W_{\text{INZ}_j} = W_{\text{TOT}} \cdot F_{\text{FLOW}_j} / N_{\text{ASSY}_j} \]  \hspace{1cm} (2-91)

\[ G_{\text{OUZ}_j} = W_{\text{INZ}_j} / (A_{\text{ROD}_j} \cdot N_{\text{AROD}_j}) \]  \hspace{1cm} (2-92)

where

- \( W_{\text{INZ}_j} \): flow rate per assembly in channel \( j \)
- \( G_{\text{OUZ}_j} \): mass flux per assembly in channel \( j \)

\[ \Delta P_{\text{grav}} = \rho \cdot g \cdot \Delta Z_{\text{OUZ}_j} \]  \hspace{1cm} (2-93)

\[ \Delta P_{\text{OUT}_{k\text{losj}}} = \frac{F_{\text{LSA}_j} \cdot G_{\text{OUZ}_j} \cdot |G_{\text{OUZ}_j}|}{2 \cdot \rho} \]  \hspace{1cm} (2-94)

where

- \( \Delta P_{\text{OUT}_{k\text{losj}}} \): pressure drop for outlet module zone in channel \( j \) due to contraction and expansion
- \( F_{\text{LSA}_j} \): k-loss factor for outlet module zone in channel \( j \) due to contraction and expansion

\[ \Delta P_{\varepsilon} = P_{6\text{NODE} \text{zone} - P_{6\text{TCOR}}} - \Delta P_{\text{grav}} - \Delta P_{\text{OUT}_{k\text{losj}}} \]  \hspace{1cm} (2-95)

\[ K_{\text{OUT}_j} = F_{\text{LSA}_j} = 2 \cdot \Delta P_{\varepsilon} \cdot \rho / (G_{\text{OUZ}_j} \cdot |G_{\text{OUZ}_j}|) \]  \hspace{1cm} (2-96)

where

- \( F_{\text{LSA}_j} \): k-loss factor for outlet module in channel \( j \) except k-loss due to expansion and contraction
2.4 Loop Hydraulics

2.4.1 Hydraulics for IHX

This subroutine solves the steady state pressure drop and/or k-loss factor for the IHX.

The pressure drop due to flow difference:

\[
\Delta P_{\text{flow}} = \left( \frac{1}{\rho_{\text{HX,0}}} - \frac{1}{\rho_{\text{HX,1}}} \right) \frac{W_{\text{HX}} |W_{\text{HX}}|}{A_{\text{HX}}^2} \quad (2-97)
\]

\[Re = \frac{W \cdot D_e}{A_x \cdot \mu} \quad (2-98)\]

\[f = f(Re) \quad (2-99)\]

The pressure drop due to wall friction:

\[
\Delta P_{\text{fric}} = f \frac{Ax W_{\text{HX}} |W_{\text{HX}}|}{D_e^2 \cdot 2 \cdot \rho \cdot A_{\text{HX}}^2} \quad (2-100)
\]

The pressure drop due to gravitation:

\[
\Delta P_{\text{grav}} = g \left( \rho_{\text{HX,1}} \cdot \sin \phi_{\text{HX,1}} \Delta x_{\text{in}} + \rho_{\text{HX,0}} \cdot \sin \phi_{\text{HX,0}} \Delta x_{\text{OUT}} + \sum_{i=1}^{N_{\text{NODE}}} \rho_i \cdot \sin \phi_i \Delta x_i \right) \quad (2-101)
\]

The pressure drop due to contraction or expansion at IHX inlet:

\[
\Delta P_{\text{loss,in}} = K_{\mu} \frac{W_{\text{HX}} |W_{\text{HX}}|}{2 \rho_{\text{in}} \cdot A_{\text{in}}^2} \quad (2-102)
\]

The pressure drop due to contraction or expansion at IHX outlet:
\[ \Delta P_{\text{loss, out}} = K_{\text{out}} \frac{W_{\text{HX}}}{\sqrt{W_{\text{HX}}}} \]  

The total pressure drop except the pressure drop due to k-loss factor inside IHX:

\[ \Delta P_{\text{SUM}} = \Delta P_{\text{flow}} + \Delta P_{\text{fie, ic}} + \Delta P_{\text{grav}} + \Delta P_{\text{loss, in}} + \Delta P_{\text{loss, out}} \]  

The total k-loss factor for IHX except k-loss due to contraction and expansion:

\[ K_{\text{HX}} = 2 \rho_{\text{HX}} (P_{1,P_{\text{HX}}} - \Delta P_{\text{SUM}}) \frac{A_{\text{HX}}^2}{W_{\text{HX}}^2} \]  

### 2.4.2 Hydraulics for Pipes

This subroutine solves the steady state flow equations for a pipe in the coolant loop. It is assumed that the diameter is constant, and the pipe wall is in thermal equilibrium with the coolant.

\[ \Delta x_{\text{node}} = \Delta x_{\text{pipe}} / N_{\text{NODE}} \]  

\[ \sin_{\text{SUM}} = \sum_{i} \sin \phi_{i} \]  

\[ E_{OD} = (\text{Roughness}) / D_{\epsilon} \]  

\[ f = f(Re,E_{OD}) \]

The total pressure drop in a pipe can be expressed in two different forms depend on locations. The pipe between IHX exit and pump inlet is not a real pipe and is used to minimize the modification of the SSC-L. Therefore, the pressure drop for the pipe between IHX exit and
pump inlet includes the pressure drop due to gravitation only. The density used in gravitational force calculation is assumed as the cold pool sodium density.

\[
\Delta P_{\text{drop}} = \rho_{\text{cold}} \cdot g \cdot \sin \theta \cdot \Delta x_{\text{node}} \quad \text{if pipe is between IHX exit and pump inlet} \tag{2-110}
\]

\[
\Delta P_{\text{drop}} = \left( f \cdot \frac{\Delta x_{\text{pipe}}}{D_e} + K \right) \frac{|W|}{2 \rho_{\text{inlet}} A_i^2} + \rho_{\text{inlet}} g \cdot \sin \theta \Delta x_{\text{node}} \quad \text{else} \tag{2-111}
\]

2.4.3 Pump

The pump rotating speed is determined by matching pump head and total hydraulic head. The required pressure rise across pump is obtained from:

\[
\Delta P_{pp} = \sum_{i=1}^{N_{\text{pipe}}} \Delta P_{\text{drop}_i} + P_{\text{PDRV}} + P_{\text{PDCV}} \tag{2-112}
\]

where \( \Delta P_{\text{drop}_i} \): pressure drop for pipe \( i \)

\( P_{\text{PDRV}} \): pressure drop from core inlet to IHX inlet

\( P_{\text{PDCV}} \): pressure drop in check valve

The pump head:

\[
H_{\text{pump}} = \frac{\Delta P_{pp}}{(\rho \cdot g)} \tag{2-113}
\]

\[
h = H_{\text{pump}} / H_r \tag{2-114}
\]

\[
\nu = \frac{(W_{\text{REF}} / \rho)}{Q_r} \tag{2-115}
\]

\[
\alpha = \Omega / \Omega_r \tag{2-116}
\]
The $\alpha$ is found based on the value of $h/v^2$ from pump homologous curve using root finding scheme and pump rotational speed is obtained from:

$$\Omega = \alpha \cdot \Omega_r$$  \hspace{1cm} (2-117)

### 2.4.4 Pressure Distribution of Pipes

This subroutine sets the pressure at the pipe end point.

$$P_{OUT,i} = P_{IN,i} - P_{DROP,i}$$  \hspace{1cm} (2-118)

where
- $P_{OUT,i}$: outlet pressure for pipe $i$ in primary loop
- $P_{IN,i}$: inlet pressure for pipe $i$ in primary loop (IHX inlet pressure)
- $P_{DROP,i}$: pressure drop in pipe $i$

For pipe 2 to NPIPE, the $P_{IN,i}$ is set to zero except the pipe after pump.

$$
\begin{cases}
    P_{IN,i} = \Delta P_{pump}^{rise} & \text{if } i \text{ = pipe index for the pipe after pump} \\
    P_{IN,i} = 0 & \text{else}
\end{cases}
$$  \hspace{1cm} (2-119)

Then, the pressure at a pipe inlet equals the sum of pressure at the previous pipe outlet and pressure drop due to any device (i.e., pump) between the pipes.

$$P_{IN,i} = P_{IN,i} + P_{OUT,i-1}$$  \hspace{1cm} \text{for } i = 2, \ldots, N\text{PIPE} \hspace{1cm} (2-120)$$

$$P_{OUT,i} = P_{IN,i} - P_{DROP,i}$$  \hspace{1cm} \text{for } i = 2, \ldots, N\text{PIPE} \hspace{1cm} (2-121)$$
2.4.5 Cold Pool Hydraulics

The sodium enthalpy in cold pool is assumed to the IHX exit enthalpy.

\[ h_{cp} = h_{Xout} \]  \hspace{1cm} (2-121)

The liquid level in cold pool is obtained from pressure difference between the cover gas pressure and the pump inlet pressure.

\[ Z_{cp} = Z_{Pin} + \frac{P_{Pin} - P_{gas}}{\rho_{Pin} \cdot g} \]  \hspace{1cm} (2-122)

Then, the cold pool sodium mass is obtained from the sodium level in cold pool by assuming that the cold pool can represented by two distinct regions with different cross-sectional area:

\[
M_{cp} = \begin{cases} 
V_{b-pmp} + A_{cldp-c} \cdot Z_{cldp-c} + A_{ovf} (Z_{cp} - Z_{xo}) & \text{if } Z_{cp} > Z_{xo} \\
V_{b-pmp} + A_{cldp-c} \cdot (Z_{cp} - Z_{Pin}) & \text{if } Z_{cp} \leq Z_{xo} 
\end{cases}
\]  \hspace{1cm} (2-123)
Fig. 2.1 Flowchart for Steady-State Calculation
Fig. 2.2  Steady state Conditions for an IHX Nodal Section
3. TRANSIENT MODELS

The dynamic response of the primary coolant in a pool-type LMR, particularly the hot pool concept like KALIMER, can be quite different from response in the loop-type LMR. The difference arises primarily from the lack of direct piping connections between components in the hot and cold pools. Even though there are free surfaces in the reactor vessel and pump tank of loop-type designs, the direct piping connections permit the use of basically a single momentum equation to characterize the coolant dynamics in the primary loop, except in a transient initiated by pipe rupture or similar asymmetric initiator.

In KALIMER, both hot and cold pools have free surfaces and there is direct mixing of the coolant with these open pools prior to entering the next component. At least two different flows would have to be modeled to characterize the coolant dynamics of the primary system. During steady-state the two flow rates can be obtained by a simple algebraic equation. During a transient, however, the flow from the pump to hot pool would respond to the pump head and losses in that circuit including losses in the core; the IHX flow would respond to the level difference between the two pools, as well as losses and gravity gains in the IHX. The gravity gain could be significant for low-flow conditions, particularly if the IHX gets overcooled due to a mismatch of primary and secondary flows. The flow chart for transient routine is in Fig. 3.1.

3.1 Flow Equations

Since the primary system of KALIMER has same number of pumps and IHXs, the first version of SSK-K has developed with constraint that the number of pumps has to be same as the number of IHXs. In SSC-K, the concept of flow paths \( N_{pam} \) is introduced and each flow path includes one pump and one IHX.

3.1.1 Intact System

For an intact system, volume-averaged momentum equations can be written as follows:
Pump Flow

\[
\frac{dW_p(k)}{dt} \sum_p \frac{L(k)}{A(k)} = P_p(k) - P_{Rin} - \sum_p \Delta P_{p,g}(k), \quad k = 1, \ldots, N_{path}
\]  

(3-1)

In above equation, the pump exit pressure, \( P_{po} \), is obtained from

\[ P_{po} = P_{pin} + \rho_{pin}gH \]  

(3-2)

where H is the pump head, obtained from the pump characteristics.

IHX Flow

\[
\frac{dW_{ix}(k)}{dt} \sum_x \frac{L(k)}{A(k)} = P_{xin} - P_{xo} - \sum_x \Delta P_{f,g}(k), \quad k = 1, \ldots, N_{path}
\]  

(3-3)

The IHX inlet and exit pressures, \( P_{xin} \) and \( P_{xo} \), are obtained from static balance as

\[ P_{xin} = P_{gut} + \rho_{gut}(Z_{HP} - Z_{xin}) \]  

(3-4)

\[ P_{xo} = P_{gut} + \rho_{gut}(Z_{CP} - Z_{xo}) \]  

(3-5)

The core inlet pressure, \( P_{Rin} \), is obtained from a complicated algebraic equation and the derivation will be discussed later.

3.1.2 Damaged System

In KALIMER, the pipe rupture can only happen in pump discharge line to reactor core. For the broken path, Eq. (3-1) has to be modified to:
An additional equation is needed to describe the flow downstream of the break:

\[
\frac{dW_p}{dt} \sum_{uob} L_A = P_{ro} - P_{bin} - \sum_{uob} \Delta P_f,\delta
\]

(3-6)

The inlet and outlet pressures at break location, \(P_{bin}\) and \(P_{bo}\), respectively, are calculated by break model. The break model in SSC-K is same as that in SSC-L. The external pressure for the break, which is needed to compute these pressures, is obtained from static balance as

\[
P_{ext} = P_{gas} + \rho_cg(Z_{CP} - Z_h)
\]

(3-8)

This pressure acts as the back pressure opposing the flow out of the break. The value of this pressure is much larger than that for loop-type design, which is generally equal to atmospheric pressure until the sodium in guard vessel covers the break location. This will make the pipe break in pool-type designs less severe relative to loop-type designs.

### 3.2 Pump Suction Pressure

Fig. 3.1 shows a schematic of SSC-K Modeling for KALIMER. As you may be noticed, there is a pipe after IHX which does not exist in KALIMER. This pipe is included to minimize the modification of loop type version of SSC-K. This pipe is used to make the elevation of IHX exit same as the elevation of pump inlet. The pump surge tank model in loop-type version of SSC is used as a basis of the cold pool model in KALIMER. Pump surge tank in a loop-type LMR has similar characteristics with cold pool in pool-type LMR in many aspects. Both components include two distinct regions. In one region, the sodium is present in lower part while the second region is filled with noncondensable gas on the top of the sodium. The sodium levels in both components are changing with mass balance between IHX exit flow and pump inlet flow. However, some differences exist between two components. First, cover gas in pump surge tank is separated by cover gas in vessel while cover gas in cold pool is in common with cover gas above hot pool. Second, enthalpy in pump surge tank is assumed to be same as enthalpy of IHX exit.
flow. This is a reasonable assumption for pump surge tank because of its small volume. However, it is not true in cold pool, which has relatively large sodium inventory. Therefore, energy equation is added in cold pool model to account the energy stored in sodium. And it is assumed that the entire pump inlet flow is from cold pool and no direct flow from IHX exit. The energy balance in cold pool will be discussed in later section.

As seen in Fig. 3.2, a few variables are newly defined to model a cold pool and their descriptions are as follows:

- V6BPMP: Volume below pump inlet
- Z6IHXP: Elevation change from pump suction to IHX exit
- A6IHXP: Average flow area from pump suction to IHX exit
- A6OVRF: Average flow area for overflow path
- B6CLDP: Sodium mass of cold pool
- E6CLDP: Sodium average enthalpy of cold pool
- T6CLDP: Sodium average temperature of cold pool
- D6CLDP: Sodium average density of cold pool

The pump inlet pressure is obtained by adding cover gas pressure with elevation head of cold pool:

\[ P_{pin} = P_{gas} + \rho \cdot g (Z_{CP} - Z_{pin}) \]  

(3-9)

3.3 Liquid Levels in Pools

The liquid levels in cold and hot pools can be obtained by mass balance at each pool. The total flow through all the IHXs and all the pumps can be determined from:

\[ W_{Xtot} = \sum_{k=1}^{N_{path}} W_X (k) \]  

(3-10)

and
Total sodium mass in cold pool is obtained by mass balance at the cold pool:

\[
\frac{d}{dt} (\rho V)_{CP} = W_{Xtot} - W_{Ptot} + W_{ovf} + W_{b}
\]  

(3-12)

Note that the break flow, \( W_b \), is zero for an intact system and the overflow from hot pool, \( W_{ovf} \), is zero if the hot pool level is below the top of thermal liner. Then, the cold pool level can be obtained from the sodium mass in cold pool by assuming that the cold pool can be represented by two distinct regions with different cross-sectional area:

\[
(\rho V)_{CP} = \begin{cases} 
\rho_{cp} \left[ V_{bpmp} + A_{HIXP} \cdot Z_{HIXP} + A_{ovf} \cdot (Z_{cp} - Z_{HIXP}) \right] & \text{if } (\rho V)_{CP} > \rho_{cp} \cdot (V_{bpmp} + A_{HIXP} \cdot Z_{HIXP}) \\
\rho_{cp} \left[ V_{bpmp} + A_{HIXP} \cdot Z_{cp} \right] & \text{if } (\rho V)_{CP} \leq \rho_{cp} \cdot (V_{bpmp} + A_{HIXP} \cdot Z_{HIXP}) 
\end{cases}
\]  

(3-13)

where

- \( V_{bpmp} \) : Cold pool volume below flow skirt
- \( A_{HIXP} \) : Average cold pool cross-sectional area between flow skirt bottom and IHX exit
- \( Z_{HIXP} \) : Height from flow skirt bottom to IHX exit
- \( A_{ovf} \) : Average cold pool cross-sectional area above IHX exit

The time rate change of sodium mass in hot pool is obtained by mass balance at the hot pool:

\[
A_{HP} \frac{d}{dt} (\rho Z)_{HP} = W_C - W_{Xtot} - W_{ovf}
\]  

(3-14)

Eq. (3-14) assumes that all the level changes likely to occur during the transient are confined to a constant cross-sectional area. When equations (3-12), (3-13) and (3-14) are solved
simultaneously with the flow equations, the sodium levels for hot and cold pool during the
transient can be obtained.

3.4 Reactor Internal Pressure

The reactor internal pressure, $P_{\text{RIN}}$, for both an intact and a damaged system is derived in
the following section.

3.4.1 Intact System

Mass conservation at core inlet yields

$$W_C = \sum_{k=1}^{N_{ch}} W_p(k)$$  \hspace{1cm} (3-15)

Differentiating both sides with time yields

$$\frac{dW_C}{dt} = \sum_{k=1}^{N_{ch}} \frac{dW_p(k)}{dt}$$  \hspace{1cm} (3-16)

The core flow can be expressed in terms of channel flows as

$$W_C = \sum_{j=1}^{N_{ch}} W_j$$  \hspace{1cm} (3-17)

where $N_{ch}$ represents the number of channels simulated in the core. Differentiating both sides
with time gives

$$\frac{dW_C}{dt} = \sum_{j=1}^{N_{ch}} \frac{dW_j}{dt}$$  \hspace{1cm} (3-18)

Time rate of core flow change for each channel can be written from momentum balance

3-6
Combining Eqs. (3-16), (3-18) and (3-19) gives

\[
\frac{dW_j}{dt} \left( \sum L/A \right)_j = P_{\text{Rin}} - P_{\text{Ro}} - \left( \sum \Delta P_{f,s} \right)_j
\]  

(3-19)

\[ P_{\text{Ro}} = P_g + \rho g (Z_{\text{HP}} - Z_{\text{Ro}}) . \]  

(3-20)

Substituting Eq. (3-1) into the left hand side of Eq. (3-21) gives

\[
\sum_{k=1}^{N_{\text{max}}} \frac{dW_p(k)}{dt} = \sum_j \left\{ \frac{P_{\text{Rin}} - P_{\text{Ro}} - \left( \sum \Delta P_{f,s} \right)_j}{\left( \sum L/A \right)_j} \right\}
\]  

(3-21)

Simplifying Eq. (3-22) yields the core inlet pressure as

\[
P_{\text{Rin}} = \frac{A+B}{C+D}
\]  

(3-23)

where

\[
A = \sum_j \left\{ \frac{P_{\text{Ro}} + \left( \sum \Delta P_{f,s} \right)_j}{\left( \sum L/A \right)_j} \right\}
\]  

(3-24)

\[
B = \sum_{k=1}^{N_{\text{max}}} \left[ \frac{P_{p_{\text{e}}}(k) - \sum_p \Delta P_{f,s}(k)}{\sum_p \{ L(k)/A(k) \}} \right]
\]  

(3-25)
3.4.2 Damaged System

In case of a pipe rupture in one of the pump discharge lines, mass conservation at core inlet has to account for the downstream flow of break to core.

\[ W_C = \sum_{k=1}^{N_{\text{brk}}} W_{P}(k) + W_{\text{deo}} \]  

(3-28)

Differentiating both sides with time yields

\[ \frac{dW_C}{dt} = \sum_{k=1}^{N_{\text{brk}}} \frac{dW_{P}(k)}{dt} + \frac{dW_{\text{deo}}}{dt} \]  

(3-29)

Combining Eqs. (3-19 and (3-29) gives

\[ \sum_{k=1}^{N_{\text{brk}}} \frac{dW_{P}(k)}{dt} + \frac{dW_{\text{deo}}}{dt} = \sum_{j} \left\{ \frac{P_{\text{in}} - P_{\text{eo}} - (\sum \Delta P_{f,e})_{j}}{(\sum L/A)_{j}} \right\} \]  

(3-30)

Substituting Eqs. (3-1) and (3-7) into the left hand side of Eq. (3-30) gives

\[ C = \sum_{j} \left\{ \frac{1}{(\sum L/A)_{j}} \right\} \]  

(3-26)

\[ D = \sum_{k=1}^{N_{\text{brk}}} \left[ \frac{1}{\sum_{P} \{L(k)/A(k)\}} \right] \]  

(3-27)
\[
\frac{P_{P_{\text{in}}}(k) - P_{R_{\text{in}}} - \sum_p \Delta P_{f,s}(k)}{\sum_p \frac{L(k)}{A(k)}} + \frac{P_{P_{\text{in}}}(k) - P_{R_{\text{in}}} - \sum_{d_{ob}} \Delta P_{f,s}(k)}{\sum_{d_{ob}} \frac{L(k)}{A(k)}} = \sum_j \left( P_{R_{\text{in}}} - P_{R_{o}} - \left( \sum \Delta P_{f,s} \right)_{i,j} \right). 
\] (3-31)

Simplifying Eq. (3-31) yields the core inlet pressure as

\[
P_{R_{\text{in}}} = \frac{A+B+C}{D+E+F}. 
\] (3-32)

where

\[
A = \sum_j \left( P_{R_{o}} + \left( \sum \Delta P_{f,s} \right)_{i,j} \right) \left( \sum \frac{L}{A} \right)_{i,j} 
\] (3-33)

\[
B = \sum_{k=1}^{N_{\text{net}}} \left[ P_{P_{\text{in}}}(k) - \sum_p \Delta P_{f,s}(k) \right] \left\{ \sum_p \frac{L(k)}{A(k)} \right\} \] (3-34)

\[
C = \frac{P_{P_{\text{in}}}(k) - \sum_{d_{ob}} \Delta P_{f,s}(k)}{\sum_{d_{ob}} \left\{ L(k)/A(k) \right\}} 
\] (3-35)

\[
D = \sum_j \left( \frac{1}{\sum \frac{L}{A}} \right)_{i,j} 
\] (3-36)

\[
E = \sum_{k=1}^{N_{\text{net}}} \left[ \frac{1}{\sum_p \left\{ L(k)/A(k) \right\}} \right] 
\] (3-37)
3.5 Energy Balance in Hot Pool

Thermal stratification can occur in the hot pool region if the entering coolant is colder than the existing hot pool coolant and the flow momentum is not large enough to overcome the negative buoyancy force. Since the fluid of hot pool enters IHXs, the temperature distribution of hot pool can alter the overall system response. Hence, it is necessary to predict the pool coolant temperature distribution with sufficient accuracy to determine the inlet temperature conditions for the IHXs and its contribution to the net buoyancy head.

During a normal reactor scram, the heat generation is reduced almost instantaneously while the coolant flow rate follows the pump coastdown. This mismatch between power and flow results in a situation where the core flow entering the hot pool is at a lower temperature than the temperature of the bulk pool sodium. This temperature difference leads to stratification when the decaying coolant momentum is insufficient.

The stratification of the core flow in the hot pool is represented by a two-zone model based on the model for mixing in the upper plenum of loop-type LMRs in SSC-L (Fig. 3.3). The hot pool is divided into two perfectly mixing zones determined by the maximum penetration distance of the core flow. This penetration distance is a function of the Froude number of the average core exit flow. The temperature of each zone is computed from energy balance considerations. The temperature of the upper portion, \( T_A \), will be relatively unchanged; in the lower region, however, \( T_B \) will be changed and somewhat between the core exit temperature and the temperature of upper zone due to active mixing with core exit flow as well as heat transfer with the upper zone. The temperature of upper zone is mainly affected by interfacial heat transfer. Full penetration is assumed for flow with positive buoyancy.

The two-zone model in SSC-L has some difficulties to maintain the mass and energy conservation in the hot pool because it does not account for the mass and energy change due to

\[
F = \frac{1}{\sum_{dol} \{L(k) / A(k)\}}
\]
the variation of penetration height. Therefore, the following equations for energy balance is adopted in SSC-K.

The non-conservative form of energy balance equations which determine the various temperatures in the hot pool are given below:

3.5.1 Lower Mixing Zone B:

Case 1: \( \frac{dz_j}{dt} > 0 \)

Mass conservation

\[
\frac{d}{dt}(\rho V)_B = \frac{dz_j}{dt} \rho_A A + W_C - f_B \sum_{k=1}^{N_{path}} W_{HX}(k)
\]  

(3-39)

Energy Conservation

\[
\frac{d}{dt}(\rho EV)_B = \frac{dz_j}{dt} \rho_A AE_A + W_C E_{Ro} - f_B \sum_{k=1}^{N_{path}} W_{HX} E_B
\]

\[- UA_{lm2}(T_B - T_{m2}) - UA_{lm1}(1-f)(T_B - T_{m1}) - hA_{lm}(T_B - T_A)\]

(3-40)

Expand derivative in energy equation for total mass and enthalpy:

\[
(\rho V)_B \frac{dE_B}{dt} + E_B \frac{d}{dt}(\rho V)_B = \frac{dz_j}{dt} \rho_A AE_A + W_C E_{Ro} - f_B \sum_{k=1}^{N_{path}} W_{HX} E_B
\]

\[- UA_{lm2}(T_B - T_{m2}) - UA_{lm1}(1-f)(T_B - T_{m1}) - hA_{lm}(T_B - T_A)\]

(3-41)

Combine above equation with mass conservation equation and rearrange the nonconservative form of energy equation:
\[ \rho_B V_B \frac{dE_B}{dt} = \frac{dz_j}{dt} \rho_A A(E_A - E_B) + W_C(E_{\text{ho}} - E_B) \]
\[ - U_A m_2 (T_B - T_{m_2}) - U_A m_1 (1 - f) (T_B - T_{m_1}) - h_A b (T_B - T_A) \] (3-42)

**Case 2:** \( \frac{dz_j}{dt} < 0 \)

**Mass conservation**
\[ \frac{d}{dt} (\rho V) = \frac{dz_j}{dt} \rho_B A + W_C + \sum_{k=1}^{N_{\text{path}}} W_{\text{HX}} (k) \] (3-43)

**Energy Conservation**
\[ \frac{d}{dt} (\rho E V) = \frac{dz_j}{dt} \rho_B A E_B + W_C E_{\text{ho}} - \sum_{k=1}^{N_{\text{path}}} W_{\text{HX}} E_B \]
\[ - U_A m_2 (T_B - T_{m_2}) - U_A m_1 (1 - f) (T_B - T_{m_1}) - h_A b (T_B - T_A) \] (3-44)

Expand derivative in energy equation for total mass and enthalpy:
\[ (\rho V) \frac{dE_B}{dt} + E_B \frac{d}{dt} (\rho V) = \frac{dz_j}{dt} \rho_B A E_B + W_C E_{\text{ho}} - \sum_{k=1}^{N_{\text{path}}} W_{\text{HX}} E_B \]
\[ - U_A m_2 (T_B - T_{m_2}) - U_A m_1 (1 - f) (T_B - T_{m_1}) - h_A b (T_B - T_A) \] (3-45)

Combine above equation with mass conservation equation and rearrange the nonconservative form of energy equation:
\[ \rho_B V_B \frac{dE_B}{dt} = W_C (E_{\text{ho}} - E_B) \]
\[ - U_A m_2 (T_B - T_{m_2}) - U_A m_1 (1 - f) (T_B - T_{m_1}) - h_A b (T_B - T_A) \] (3-46)

3-12
3.5.2 Upper Mixing Zone A:

Case 1: \( \frac{dz_j}{dt} > 0 \)

Mass conservation

\[
\frac{d}{dt}(\rho V)_A = -\frac{dz_j}{dt} \rho_A A - \int A \sum_{k=1}^{n_{pack}} W_{Hx}(k) - W_{off}
\]  

(3-47)

Energy Conservation

\[
\frac{d}{dt}(\rho EV)_A = -\frac{dz_j}{dt} \rho_A AE_A - \int A \sum_{k=1}^{n_{pack}} W_{Hx}E_A - W_{off}E_A
\]

\[-UA_{m2}(T_A - T_{m2}) - UA_{m1}f(T_A - T_{m1}) - UA_{g}(T_A - T_g) + hA_{be}(T_B - T_A)\]

Expand derivative in energy equation for total mass and enthalpy:

\[
(\rho V)_A \frac{dE_A}{dt} + E_A \frac{d}{dt}(\rho V)_A = -\frac{dz_j}{dt} \rho_A AE_A - \int A \sum_{k=1}^{n_{pack}} W_{Hx}E_A - W_{off}E_A
\]

\[-UA_{m2}(T_A - T_{m2}) - UA_{m1}f(T_A - T_{m1}) - UA_{g}(T_A - T_g) + hA_{be}(T_B - T_A)\]

(3-49)

Combine above equation with mass conservation equation and rearrange the nonconservative form of energy equation:

\[
(\rho V)_A \frac{dE_A}{dt} = -UA_{m2}(T_A - T_{m2}) - UA_{m1}f(T_A - T_{m1})
\]

\[-UA_{g}(T_A - T_g) + hA_{be}(T_B - T_A)\]

(3-50)

Case 2: \( \frac{dz_j}{dt} < 0 \)
Mass conservation

\[
\frac{d}{dt}(\rho V)_A = -\frac{dz_j}{dt} \rho_B A - f_A \sum_{k=1}^{N_{path}} W_{int}^k(k) - W_{orf}
\]  \hspace{1cm} (3-51)

Energy Conservation

\[
\frac{d}{dt}(\rho EV)_A = -\frac{dz_j}{dt} \rho_B AE_B - f_A \sum_{k=1}^{N_{path}} W_{int}^k E_A - W_{orf} E_A
\]
\[
- U A_{sm2} (T_A - T_{m2}) - U A_{sm1} f(T_A - T_{m1}) - U A_{kg} (T_A - T_g) + h A_{bo} (T_B - T_A)
\]  \hspace{1cm} (3-52)

Expand derivative in energy equation for total mass and enthalpy:

\[
(\rho V)_A \frac{dE_A}{dt} + E_A \frac{d}{dt} (\rho V)_A = -\frac{dz_j}{dt} \rho_B AE_B - f_A \sum_{k=1}^{N_{path}} W_{int}^k E_A - W_{orf} E_A
\]
\[
- U A_{sm2} (T_A - T_{m2}) - U A_{sm1} f(T_A - T_{m1}) - U A_{kg} (T_A - T_g) + h A_{bo} (T_B - T_A)
\]  \hspace{1cm} (3-53)

Combine above equation with mass conservation equation and rearrange the nonconservative form of energy equation:

\[
(\rho V)_A \frac{dE_A}{dt} = -\frac{dz_j}{dt} \rho_B A(E_B - E_A) - U A_{sm2} (T_A - T_{m2})
\]
\[
- U A_{sm1} f (T_A - T_{m1}) - U A_{kg} (T_A - T_g) + h A_{bo} (T_B - T_A)
\]  \hspace{1cm} (3-54)

3.5.3 Other Temperatures in Hot Pool

Upper internal structure (metal m1):

\[
M_{m1} C_{m1} \frac{dT_{m1}}{dt} = U A_{sm1} [f T_A + (1-f)T_B - T_{m1}] - U A_{sm1} (T_{m1} - T_g)
\]  \hspace{1cm} (3-55)
Barrier (metal m2):

\[ M_{m2} C_{m2} \frac{dT_{m2}}{dt} = U A_{km2} \left( \frac{A_{cm2} T_A + A_{bm2} T_B}{A_{km2}} - T_{m2} \right) - U A_{cm2} (T_{m2} - T_{CP}) \]  \hspace{1cm} (3-56)

\( U_{km2} \) is not very sensitive to changes in sodium temperature, and so this equation is derived assuming \( U_{km2} = U_{am2} \).

Roof (metal m3):

\[ M_{m3} C_{m3} \frac{dT_{m3}}{dt} = U A_{gm3} (T_g - T_{m3}) \]  \hspace{1cm} (3-57)

The heat transfer from the roof to the ambient has been neglected.

Cover gas:

\[ M_{g} C_{g} \frac{dT_g}{dt} = U A_{kg} (T_A - T_g) - U A_{tg} (T_g - T_{CP}) + U A_{gm1} (T_{m1} - T_g) - U A_{gm3} (T_g - T_{m3}) \]  \hspace{1cm} (3-58)

The auxiliary equations required by the above governing equations are

\[ A_{ba} = \pi D^2 / 4 \]  \hspace{1cm} (3-59)

\[ f = 1 - z_j(t) / (Z_{HP} - Z_{HR}) \]  \hspace{1cm} (3-60)

### 3.6 Energy Balance in Cold Pool

Currently, perfect mixing of the IHX flow with the cold pool sodium is assumed. Energy balance equation for cold pool is derived as:
Mass Conservation

\[
\frac{d}{dt}(\rho V)_{cp} = \sum_{N_{push}} W_{HIX} - \sum_{N_{push}} W_{pmp} + W_{off} + \sum_{N_{push}} W_{brk}
\] (3-61)

Energy Conservation

\[
\frac{d}{dt}(\rho hV)_{cp} = \sum_{N_{push}} W_{HIX} h_{HIX} - \sum_{N_{push}} W_{pmp} h_{cp} + W_{off} h_{hp} + \sum_{N_{push}} W_{brk} h_{brk}
\] (3-62)

Expand derivative in energy equation for total mass and enthalpy:

\[
(\rho V)_{cp} \frac{dh_{cp}}{dt} + h_{cp} \frac{d}{dt}(\rho V)_{cp} = \sum_{N_{push}} W_{HIX} h_{HIX}
\]

\[-h_{cp} \sum_{N_{push}} W_{pmp} + W_{off} h_{hp} + \sum_{N_{push}} W_{brk} h_{brk}
\] (3-63)

Combine above equation with mass conservation equation:

\[
(\rho V)_{cp} \frac{dh_{cp}}{dt} + h_{cp} \left( \sum_{N_{push}} W_{HIX} - \sum_{N_{push}} W_{pmp} + W_{off} \right)
\]

\[= \sum_{N_{push}} W_{HIX} h_{HIX} - h_{cp} \sum_{N_{push}} W_{pmp} + W_{off} h_{hp} + \sum_{N_{push}} W_{brk} h_{brk}
\] (3-64)

Rearrange the nonconservative form of energy equation:

\[
(\rho V)_{cp} \frac{dh_{cp}}{dt} = \sum_{N_{push}} W_{HIX} h_{HIX} - h_{cp} \sum_{N_{push}} W_{HIX}
\]

\[+ W_{off} h_{hp} - W_{off} h_{cp} + \sum_{N_{push}} W_{brk} h_{brk} - h_{cp} \sum_{N_{push}} W_{brk}
\] (3-65)

Above equation can be expressed into two different equations depend on the direction of break flow.
\[(\rho V)_{cp} \frac{dh_{cp}}{dt} = \]
\[
\left\{ \begin{array}{l}
\sum_{N_{pul}} W_{HX} h_{HX} - h_{cp} \sum_{N_{pul}} W_{HX} + W_{of} (h_{hp} - h_{cp}) \\
\quad + \sum_{N_{pul}} W_{brk} h_{brk} - h_{cp} \sum_{N_{pul}} W_{brk} & \text{if } W_{brk} > 0 \\
\sum_{N_{pul}} W_{HX} h_{HX} - h_{cp} \sum_{N_{pul}} W_{HX} + W_{of} (h_{hp} - h_{cp}) & \text{if } W_{brk} \leq 0
\end{array} \right. \]

(3-66)

Discretize above equation in time:

\[h_{cp}^{t+\Delta t} - h_{cp}^t = \]
\[
\frac{\Delta t}{(\rho V)_{cp}} \left[ \sum_{N_{pul}} W_{HX} h_{HX} - h_{cp}^{t+\Delta t} \sum_{N_{pul}} W_{HX} + W_{of} h_{hp} \\
- W_{of} h_{cp}^{t+\Delta t} + \sum_{N_{pul}} W_{brk} h_{brk} - h_{cp}^{t+\Delta t} \sum_{N_{pul}} W_{brk} \right] & \text{if } W_{brk} > 0
\]
\[
\frac{\Delta t}{(\rho V)_{cp}} \left[ \sum_{N_{pul}} W_{HX} h_{HX} - h_{cp}^{t+\Delta t} \sum_{N_{pul}} W_{HX} \\
+ W_{of} h_{hp} - W_{of} h_{cp}^{t+\Delta t} \right] & \text{if } W_{brk} \leq 0
\]

(3-67)

\[h_{cp}^{t+\Delta t} \left\{ 1 + \frac{\Delta t}{(\rho V)_{cp}} \left( \sum_{N_{pul}} W_{HX} + W_{of} + \sum_{N_{pul}} W_{brk} \right) \right\} \]
\[= h_{cp}^t + \frac{\Delta t}{(\rho V)_{cp}} \left\{ \sum_{N_{pul}} W_{HX} h_{HX} + W_{of} h_{hp} + \sum_{N_{pul}} W_{brk} h_{brk} \right\} & \text{if } W_{brk} > 0
\]
\[h_{cp}^{t+\Delta t} \left\{ 1 + \frac{\Delta t}{(\rho V)_{cp}} \left( \sum_{N_{pul}} W_{HX} + W_{of} \right) \right\} \]
\[= h_{cp}^t + \frac{\Delta t}{(\rho V)_{cp}} \left\{ \sum_{N_{pul}} W_{HX} h_{HX} + W_{of} h_{hp} \right\} & \text{if } W_{brk} \leq 0
\]

(3-68)
Solve for $h'_{cp}^m$:

$$h'_{cp}^m = \frac{h'_{cp} + \frac{\Delta t}{(\rho V)_{cp}} \left( \sum_{\text{push}} W_{\text{HILX}} h_{\text{HILX}} + W_{\text{off}} h_{\text{sp}} + \sum_{\text{push}} W_{\text{brk}} h_{\text{brk}} \right)}{1 + \frac{\Delta t}{(\rho V)_{cp}} \left( \sum_{\text{push}} W_{\text{HILX}} + W_{\text{off}} + \sum_{\text{push}} W_{\text{brk}} \right)}$$

if $W_{\text{brk}} > 0$

$$h'_{cp}^m = \frac{h'_{cp} + \frac{\Delta t}{(\rho V)_{cp}} \left( \sum_{\text{push}} W_{\text{HILX}} h_{\text{HILX}} + W_{\text{off}} h_{\text{sp}} \right)}{1 + \frac{\Delta t}{(\rho V)_{cp}} \left( \sum_{\text{push}} W_{\text{HILX}} + W_{\text{off}} \right)}$$

if $W_{\text{brk}} \leq 0$

(3-69)

Lower structures (metal m4):

$$(MC)_{net} \frac{dT_{net}}{dt} = UA_{net} (T_{cp} - T_{net})$$

(3-70)

It should be noted that the heat transfer between structures and cold pool sodium is ignored in current version of SSC-K. The above equation will be adopted in later version.
### Table 3-1 Code Modification List

<table>
<thead>
<tr>
<th>Subroutine Name</th>
<th>Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRDR9R</td>
<td>Inconsistent subroutine arguments: GENRD</td>
</tr>
</tbody>
</table>
| DCODNC          | Inconsistent data type with subroutine argument.  
• IVLU been set to real(8) from integer |
| END1T           | Inlet/Outlet enthalpy of pipe segment in cold pool has been changed |
| EQIV1T          | No pump surge tank option  
• head due to liquid level to zero  
• matrix element for head due to liquid level to zero  
• pump speed change rate to zero  
• liquid level change rate to zero  
Bypass flow calculation has been corrected  
Integrated values related to pool model has been changed |
| EQIV2T          | No pump surge tank option  
• head due to liquid level to zero  
• matrix element for head due to liquid level to zero  
• pump speed change rate to zero  
• liquid level change rate to zero |
| ERRMSG          | 2nd argument of EXIT9U to 8 characters |
| FLOW1T          | No pump surge tank option has been added |
| FLOW2T          | No pump surge tank option has been added |
| GENRD           | Inconsistent data type with subroutine argument.  
• IVLU been set to real(8) from integer |
| GVSL1T          | External pressure for break flow calculation |
| HEAD1T          | Discontinuity in pump head homologous curve removed |
| HYDR1S          | Pressure drop calculations corrected |
| IHX1T           | LOHS actuation at specified time by user |
| INIT1T          | Initialization for no pump surge tank case  
• pump inlet pres. to vessel outlet pres.  
• head due to liquid level to zero  
Initialization for cold pool variables  
• Cold pool sodium mass  
• Pump inlet pressure  
Cover gas volume calculation  
Cold pool enthalpy calculation |
| INIT2T          | Initialization for no pump surge tank case  
• Pump inlet pres. to preceeding pipe outlet pres.  
• Head due to liquid level to zero |
| INTG1T          | Inconsistent data type with subroutine argument.  
• IVLU been set to real(8) from integer |
Table 3-1  Code Modification List (continued)

<table>
<thead>
<tr>
<th>Subroutine Name</th>
<th>Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISETHM</td>
<td>Character variables can not be set to real variables directly.</td>
</tr>
<tr>
<td></td>
<td>• Character variables are set to real variables using write statement.</td>
</tr>
<tr>
<td>LOOP1T</td>
<td>Cold pool enthalpy calculation</td>
</tr>
<tr>
<td>NSKIP</td>
<td>Inconsistent data type with subroutine argument.</td>
</tr>
<tr>
<td></td>
<td>• IVLU been set to real(8) from integer.</td>
</tr>
<tr>
<td>PBAL9S</td>
<td>ERR9U arguments been changed</td>
</tr>
<tr>
<td></td>
<td>• sequence of arguments has been changed</td>
</tr>
<tr>
<td>PIPE1S</td>
<td>Enthalpy and pressure drop calculation routine for cold pool added</td>
</tr>
<tr>
<td>PIPEW1T</td>
<td>Pressure drop calculation routine for cold pool added</td>
</tr>
<tr>
<td>PRUP6T</td>
<td>Calculation for IHX inlet pressure been corrected</td>
</tr>
<tr>
<td>PUMP1S</td>
<td>Discontinuity of head homologous curve been corrected</td>
</tr>
<tr>
<td>PUMP1T</td>
<td>Discontinuity of head homologous curve been corrected</td>
</tr>
<tr>
<td></td>
<td>EMP coastdown at specified time</td>
</tr>
<tr>
<td></td>
<td>No enthalpy rise across EMP assumed</td>
</tr>
<tr>
<td>READ1R</td>
<td>GENRD arguments been changed : 19 places</td>
</tr>
<tr>
<td></td>
<td>• 4th arg.: integer(id2) to real(d2)</td>
</tr>
<tr>
<td>READ7R</td>
<td>GENRD arguments been changed : 43 places</td>
</tr>
<tr>
<td></td>
<td>• 4th arg.: integer(id2) to real(d2)</td>
</tr>
<tr>
<td>READ8R</td>
<td>GENRD arguments been changed : 1 place</td>
</tr>
<tr>
<td></td>
<td>• 4th arg.: integer(id2) to real(d2)</td>
</tr>
<tr>
<td></td>
<td>GENRD arguments been changed : 1 place</td>
</tr>
<tr>
<td></td>
<td>• 3rd arg.: real(dum) to integer(idum)</td>
</tr>
<tr>
<td></td>
<td>• 5th arg.: real(dum) to first real array element[a(1)]</td>
</tr>
<tr>
<td></td>
<td>• 6th arg.: real(dum) to first int array element[ia(1)]</td>
</tr>
<tr>
<td>READ9R</td>
<td>int. array for data containment[ia(1)] been included</td>
</tr>
<tr>
<td></td>
<td>GENRD arguments been changed : 7 places</td>
</tr>
<tr>
<td></td>
<td>• 4th arg.: integer(id2) to real(d2)</td>
</tr>
<tr>
<td>READ9T</td>
<td>equivalence statement (A(1),IA(1)) been removed</td>
</tr>
<tr>
<td></td>
<td>GENRD arguments been changed : 1 place</td>
</tr>
<tr>
<td></td>
<td>• 3rd arg.: real(dum) to integer(idum)</td>
</tr>
<tr>
<td></td>
<td>• 5th arg.: real(dum) to first real array element[a(1)]</td>
</tr>
<tr>
<td></td>
<td>• 6th arg.: real(dum) to first int array element[ia(1)]</td>
</tr>
<tr>
<td></td>
<td>GENRD arguments been changed : 3 places</td>
</tr>
<tr>
<td></td>
<td>• 4th arg.: integer(id2) to real(d2)</td>
</tr>
<tr>
<td></td>
<td>error message for excess of max. table length been removed</td>
</tr>
<tr>
<td>READHM</td>
<td>Character variables can not be set to real variables directly.</td>
</tr>
<tr>
<td></td>
<td>• Character variables are set to real variables using write statement.</td>
</tr>
<tr>
<td>REPEAT</td>
<td>Inconsistent data type with subroutine argument.</td>
</tr>
<tr>
<td></td>
<td>• IVLU been set to real(8) from integer.</td>
</tr>
<tr>
<td>Subroutine Name</td>
<td>Changes</td>
</tr>
<tr>
<td>----------------</td>
<td>---------</td>
</tr>
<tr>
<td>RES1S</td>
<td>Steady state calculation for cold pool</td>
</tr>
<tr>
<td></td>
<td>No pump surge tank option has been added</td>
</tr>
<tr>
<td></td>
<td>• liquid level in pump tank to zero</td>
</tr>
<tr>
<td></td>
<td>• pump inlet pressure to vessel outlet pres.</td>
</tr>
<tr>
<td></td>
<td>• liquid level change rate to zero</td>
</tr>
<tr>
<td>RES1T</td>
<td>Cold pool option added</td>
</tr>
<tr>
<td></td>
<td>• Time derivative of cold pool sodium mass</td>
</tr>
<tr>
<td></td>
<td>• Cold pool level calculation</td>
</tr>
<tr>
<td></td>
<td>• Pump inlet pressure</td>
</tr>
<tr>
<td>RES2S</td>
<td>No pump surge tank option</td>
</tr>
<tr>
<td></td>
<td>• gas mass in surge tank to zero</td>
</tr>
<tr>
<td></td>
<td>• liquid level in surge tank to zero</td>
</tr>
<tr>
<td>RES2T</td>
<td>No pump surge tank option</td>
</tr>
<tr>
<td></td>
<td>• liquid level in pump tank to zero</td>
</tr>
<tr>
<td></td>
<td>• pump inlet pressure to vessel outlet pres.</td>
</tr>
<tr>
<td></td>
<td>• liquid level change rate to zero</td>
</tr>
<tr>
<td>RITE6U</td>
<td>int. variables HY, HI been defined</td>
</tr>
<tr>
<td></td>
<td>definition for character STRING1 been changed</td>
</tr>
<tr>
<td>UPLS6T</td>
<td>• Overflow model added</td>
</tr>
<tr>
<td></td>
<td>• Mass, energy equations changed to include overflow effect</td>
</tr>
<tr>
<td></td>
<td>• Time derivative of enthalpy difference due to overflow modified</td>
</tr>
<tr>
<td>VERR9T</td>
<td>Dimension for character NAME been changed to character*6</td>
</tr>
<tr>
<td>VESL1T</td>
<td>Overflow rate calculation</td>
</tr>
<tr>
<td></td>
<td>Cover gas volume</td>
</tr>
<tr>
<td>VRFY9T</td>
<td>character NC been defined</td>
</tr>
<tr>
<td></td>
<td>VERR9T arguments been changed : 11 places</td>
</tr>
<tr>
<td></td>
<td>• 4th arg.: integer(+0) to character(NC)</td>
</tr>
<tr>
<td></td>
<td>VERR9T arguments been changed : 1 place</td>
</tr>
<tr>
<td></td>
<td>• 4th arg.: null character to character(NC)</td>
</tr>
<tr>
<td>WIMPLT</td>
<td>Cover gas volume calculation</td>
</tr>
</tbody>
</table>
Fig. 3.1  Flowchart for Transient Calculation
Fig. 3.2 Schematic of SSC-K Modeling for KALIMER
Fig. 3.3 Two Mixing Zone Model for Hot Pool
4. INTERMEDIATE HEAT EXCHANGER

4.1 Pool Type IHX

The intermediate heat exchangers (IHX) physically separate the radioactive primary coolant from the non-radioactive intermediate coolant while at the same time thermally connecting the two circuits in order to transfer the core heat to the steam generator. The IHX in pool type LMFBR is identical in function, and similar in design, to that in loop type design. The only difference arises from the different configuration in the primary system, where the IHX draws coolant from an open hot pool and discharges to another open cold pool. The liquid levels in the hot and cold pools reflect the hydraulic flow resistance through the IHXs. The liquid level difference in the KALIMER is about 5 m under normal operation. The low differential level requires the IHX to have a low pressure drop on the primary side. The main concern with a low pressure drop in the IHXs is its effect on flow distribution. Poor flow distribution can adversely affect operational reliability by causing temperature distributions and resultant thermal stress that could exceed design allowances.

Most of IHX in LMFBRs are of similar design. The IHX design of KALIMER is vertical, counter flow, shell-and-tube heat exchangers with basically straight tubes as shown in Fig. 4.1. Primary sodium flows downward on the shell side and exits at the bottom, with transferring heat to secondary coolant in the tubes. The secondary coolant flows in the tubes. The pressure losses in the primary side are limited as discussed above, it may be advantageous to send primary flow through the tubes to ensure good flow distribution. The higher pressure in the secondary side is to assure no radioactive coolant enters the secondary circuit in the event of a leak in any of the heat transfer tubes.

Principal differences in IHXs between the loop and pool systems appear at the entrance and exit flow nozzles. Tube bundle is mounted to allow for differential thermal expansion between the tubes and the shell. To accomplish this, the lower tube sheet is allowed to float and, therefore, is supported by the tube bundle. The tubes are supported by the upper tube sheet.
4.2 Heat Transfer Model

The IHX model of SSC-K is essentially unchanged from that of SSC-L. The energy equations are written using nodal heat balance with the donor-cell differencing scheme. Figure 3-2 is a nodal diagram for thermal model under counterflow arrangement. The active heat transfer tubes are modeled by one representative tube in the figure. The active heat transfer tube is divided into same axial distance by user specified number. Axial heat conduction in the metal wall is assumed negligible. As shown in Fig. 4.2, the IHX is modeled by four radial nodes, secondary coolant, tube metal, primary coolant and shell wall. Material properties and heat transfer coefficients are evaluated locally by specifying the material as user input. The tube and shell wall nodes lie in the mid-plane between the fluid nodal interfaces, giving rise to a staggered nodal arrangement.

The coolant equations are derived using the nodal heat balance method. It is assumed that ideal mixing plenums at the inlet and outlet of each coolant stream. The time dependent governing equations for thermal transportation of each section are described below.

1) Primary inlet plenum

\[ \rho_{in} V_{in} \frac{d}{dt} (e_p) = W_p (e_p - e_{p_in}) \] (4-1)

where

\[ e_{p_in} = e(T_{p_in}) \quad \text{and} \quad e_p = e(T_{p_in}) \] (4-2)

\( V_{in} \) is the stagnant sodium volume in the primary inlet plenum, and \( \rho_{in} \) is the average sodium density in the inlet plenum. Considering the fraction of flow bypassing the active heat transfer region, \( \beta_p \), we have the following equation from mass conservation.

\[ W_p' = (1 - \beta_p) W_p \] (4-3)

1) Primary outlet plenum
\[ \rho_{\text{out}} V_{\text{out}} \frac{d}{dt}(e_{\text{out}}) = W_p e_{\text{pv}} + \beta_p W_p e_{\text{pb}} - W_p e_{\text{pav}} \] (4-4)

\( V_{\text{out}} \) is the sodium volume in the primary outlet plenum and \( \rho_{\text{out}} \) is the average sodium density in the outlet plenum.

3) Primary bypass plenum

\[ \rho_{\text{pb}} V_{\text{pb}} \frac{d}{dt}(e_{\text{pb}}) = \beta_p W_p (e_{\text{pav}} - e_{\text{pb}}) \] (4-5)

Similar equations can be written for the inlet, outlet plenums and downcomer on the secondary side.

4) Active heat transfer region

For primary coolant

\[ \rho V_p \frac{d}{dt}(e_{\text{pav}}) = W_p (e_{\text{pav}} - e_{\text{pav}}) - U_{pt} A_{pt} (T_{\text{pav}} - T_{\text{pt}}) - U_{psh} A_{psh} (T_{\text{pav}} - T_{\text{sh}}) \] (4-6)

For secondary side coolant

\[ \rho V_s \frac{d}{dt}(e_{\text{sav}}) = W_s (e_{\text{sav}} - e_{\text{sav}}) + U_s A_s (T_{\text{sav}} - T_{\text{siav}}) \] (4-7)

For tube wall

\[ M_i C_i \frac{d}{dt}(T_{\text{ti}}) = U_{pt} A_{pt} (T_{\text{pav}} - T_{\text{pt}}) - U_s A_s (T_{\text{sav}} - T_{\text{siav}}) \] (4-8)

For shell wall

\[ M_{sh} C_{sh} \frac{d}{dt}(T_{\text{sh}}) = U_{psh} A_{psh} (T_{\text{pav}} - T_{\text{sh}}) \] (4-9)
In the above equations, $V_p$ and $V_s$ are the control volumes between interfaces $i$ and $i+1$ on the primary and secondary sides, respectively. $A_{pt}$, $A_{st}$ and $A_{ps}$ are the areas per length $\Delta x$ for heat transfer between primary coolant and tube wall, between secondary fluid and tube wall, and between primary coolant and shell wall, respectively, defined as

$$A_{pt} = \pi D_2 n_t \Delta x$$  \hspace{1cm} (4-10)
$$A_{st} = \pi D_1 n_s \Delta x$$  \hspace{1cm} (4-11)
$$A_{ps} = A_{sh} \Delta x / L$$  \hspace{1cm} (4-12)

where $n_t$ is number of active heat transfer tubes and $A_{sh}$ is the shell heat transfer area given by user input. $D_1$ and $D_2$ are the IHX tube inner and outer diameters, respectively, and $L$ is the length of the active heat transfer region.

In above equations, $U_{pt}$, $U_{st}$, and $U_{ps}$ represent the overall heat transfer coefficient between primary coolant and tube wall, between secondary fluid and tube wall, and between primary coolant and shell wall, respectively. Those are defined based on the thermal resistance concept as:

$$\frac{1}{U_{pt}} = \frac{1}{h_{film,p}} + r_{wall,p} + \frac{1}{h_{foul,p}}$$  \hspace{1cm} (4-13)
$$\frac{1}{U_{st}} = \frac{1}{h_{film,s}} + r_{wall,s} + \frac{1}{h_{foul,s}}$$  \hspace{1cm} (4-14)
$$\frac{1}{U_{ps}} = \frac{1}{h_{film,p}}$$  \hspace{1cm} (4-15)

where the film heat transfer coefficients are calculated in terms of Nusselt number $Nu$, which is obtained from the embedded correlations in SSC-K. Fouling is a time-dependent phenomenon, and the fouling resistances of $1/h_{foul,p}$ and $1/h_{foul,s}$ are provided as a user input quantity for the primary and secondary sided walls, respectively.

4-4
\[ h_{\text{film},p} = \frac{Nu_{pt} k_p}{D_{h,p}} \quad (4-16) \]
\[ h_{\text{film},s} = \frac{Nu_{st} k_s}{D_{t}} \quad (4-17) \]

The wall thermal resistance terms are defined by dividing the tube wall thickness equally between primary and secondary sides. The temperature of tube, \( T_t \), is defined at the midpoint of wall thickness.

\[ r_{\text{wall},p} = \frac{D_{t}}{2k_t} \ln\left(\frac{2D_t}{(D_t + D_s)}\right) \quad (4-18) \]
\[ r_{\text{wall},s} = \frac{D_{t}}{2k_t} \ln\left(\frac{(D_t + D_s)}{2D_t}\right) \quad (4-19) \]

where \( k_t \) is a thermal conductivity of tube wall which is calculated internally by specifying the material as input.

The overall heat transfer coefficients \( U_{pt} \) and \( U_{st} \) are dependent on material and flow properties, which are functions of temperature. Those are evaluated at each nodal section along with the temperatures. Referring to Fig. 4.2, for each \( i \), \( k_t \) is evaluated at \( i \) on the tube wall node whereas all other variables \( (k_p, k_s, Nu_{pt}, Nu_{st}) \) are evaluated at the midpoint between the fluid nodal interfaces \( i \) and \((i+1)\).

If a flow area on primary side of IHX is not provided as a user input, SSC-K calculates it by the following equation. The pitch-to-diameter \( P/D_2 \) is taken to be as the average value in case the pitch is not uniform throughout the tube bundle.

\[ A_p = n_t \frac{\pi D_t^2}{4} \left[ \frac{2\sqrt{3}}{\pi} \left( \frac{P}{D_2} \right)^2 - 1 \right] \quad (4-20) \]
Then, the hydraulic diameter of primary side is calculated as follows:

\[ D_{h,p} = \frac{4A_p}{n_t\pi D_2} \]  

(4-21)

The Reynolds number for the primary side and internal tube is defined as, respectively.

\[ Re_p = \frac{W_p D_{h,p}}{A_p \mu_p} \]  

(4-22)

\[ Re_i = \frac{W_i D_i}{A_i \mu_i} \]  

(4-23)

where, the flow area through the tubes is given as

\[ A_i = n_t \frac{\pi D_i^2}{4} \]  

(4-24)

4.3 Pressure Losses Model

Figure 4-1 shows the flow paths of KALIMER IHX. Primary coolant flows downward in the active heat transfer region and exits at the bottom of the tube unit. The secondary (intermediate) coolant flows down the central downcomer into the bottom header (inlet plenum region) where it turns upward to present a counterflow arrangement in the heat transfer region. In all cases, the primary flow is downward, and this helps to simplify the formulation. The sum of pressure losses on both primary and secondary sides of the IHX is expressed as follows:

\[ (\Delta P_{t,g})_{IHX} = \text{(acceleration loss)} + \text{(frictional loss)} + \text{(gravity loss or gain)} + \text{(inlet loss)} + \text{(exit loss)} + \text{(contraction/expansion losses)} + \text{(other losses)} \]

Note that a negative value obtained for gravity loss indicates a gain. The user should be cautious when specifying the value of \( \Delta P_{IHX} \) if known, to ensure that it does not include the
gravity term. The SSC-K code adds on the gravity term to give the final $\Delta P_{\text{HIX}}$ for the hydraulic calculations.

For the primary side, the pressure losses are calculated as

$$
(\Delta p_{f,g})_{\text{HIX,p}} = \frac{W_p}{A_p} \left( \frac{1}{\rho_f} - \frac{1}{\rho_e} \right) + \frac{1}{2} \frac{W_p}{D_{v,p} A_p} \int f \frac{\rho}{\rho} dx + \Delta p_g \\
+ k_{p,\text{in}} \left( \frac{W_p}{(\rho A^2)_{\text{in}}} \right) + k_{p,\text{out}} \left( \frac{W_p}{(\rho A^2)_{\text{out}}} \right) + k_p \left( \frac{W_p}{\bar{\rho} A^2} \right)
$$

(4-25)

where

$$
\Delta p_g = g(\rho \sin \alpha \Delta x)_{\text{inlet plenum}} + g \int_{0}^{L} \rho \sin \alpha dx + g(\rho \sin \alpha \Delta x)_{\text{outlet plenum}}
$$

(4-26)

$$
W_p' = (1 - \beta_p) W_p
$$

(4-3)

$$
\bar{\rho} = \frac{\rho_{\text{in}} + \rho_{\text{out}}}{2}
$$

(4-27)

where $k_{p,\text{in}}$ and $k_{p,\text{out}}$ represent loss coefficients for expansion and contraction of flow, respectively, i.e., from the plenum to pipe or reverse direction. It also include inlet plenum losses due to turning, flow distribution, etc. $k_p$ is an uncertainty absorber that is either calculated during steady state if $\Delta P_{\text{HIX,p}}$ is provided by user input. Once determined or known, the value of $k_p$ remains constant throughout the transient. This is useful parameter especially to overcome the difficulty of determining accurately all the losses in the complex internal geometry of the IHX.

Similarly, for the secondary side of IHX,

$$
(\Delta p_{f,g})_{\text{HIX,s}} = \frac{W_s^2}{A_s^2} \left( \frac{1}{\rho_e} - \frac{1}{\rho_s} \right) + \frac{1}{2} \frac{W_s}{D_{v,s} A_s^2} \int f \frac{\rho}{\rho} dx + \Delta p_g \\
+ k_{s,\text{in}} \left( \frac{W_s}{(\rho A^2)_{\text{in}}} \right) + k_{s,\text{out}} \left( \frac{W_s}{(\rho A^2)_{\text{out}}} \right) + \Delta p_{c,s} + k_s \left( \frac{W_s}{1} \right) (\bar{\rho} A^2)
$$

(4-28)
\[ \Delta p_g = g(\rho \sin \alpha \Delta x)_{\text{downcomer}} + g(\rho \sin \alpha \Delta x)_{\text{inlet plenum}} \]
\[ + g \int_{\text{h}}^{\text{v}} \rho \sin \alpha \text{d}x + g(\rho \sin \alpha \Delta x)_{\text{outlet plenum}} \]  
(4-29)

\[ \Delta p_{ce} = k_{s} \frac{W_{i}W_{f}}{(\rho A_{n}^{2})_{\text{hube in}}} + k_{s} \frac{W_{i}W_{f}}{(\rho A_{n}^{2})_{\text{hube out}}} \]  
(4-30)

where \( k_{s} \) is the uncertainty absorber for the secondary side. The friction factor \( f \) in above equations is a function of Reynold number and the relative roughness of the channel. The same approach is used in the formulation of the hydraulics in the sodium side of the IHX.

### 4.4 Liquid Levels in Pools

During steady state, the level difference between hot and cold pools supports the net losses occurring in the IHX, thereby maintaining flow through it. A high level difference would be necessary to drive flow through a high pressure drop unit. During transient conditions, reduction in IHX losses will tend to increase flow through it. However, this will also reduce the level difference driving the flow. This competition between two opposing forces determining the dynamic state of levels and flow through the IHX. During flow coastdown transients, the levels approach each other, implying a net increase of cold pool mass at the expense of the hot pool. When the levels restabilize under low flow conditions, the level difference once again maintains the IHX losses.

If the IHX is overcooled due to very high intermediate flow, the resulting gravity head in the unit, available at much higher densities, is sufficient to overcome all frictional and losses. The levels then cross each other while the flow is maintained positive.

Mass balance at the cold pool gives

\[ A_{cp} \frac{d\left(\rho_{c} Z_{cp}\right)}{dt} = W_{\text{HIX}} - W_{\text{core}} + W_{\text{bypass}} + W_{\text{break}} \]  
(4-31)
Note that $W_b$, the break flow, is zero for an intact loop. $Z_{cp}$ in Eq. (4-31) is calculated based on the assumption that all the level changes likely to occur during a transient are confined to a constant cross-section area, $A_{60VRF}$ in Fig. 1.1.

Mass balance in the hot pool gives

$$A_{bp} \frac{d(\rho_h Z_{bp})}{dt} = W_{core} - W_{HX}$$

(4-32)

When equations (4-31) and (4-32) are solved simultaneously with the flow equations, the results yield levels of cold pool ($Z_{cp}$) and hot pool ($Z_{bp}$) during the transient.
Fig. 4.1 Flow Paths of KALIMER IHX
Fig. 4.2 Nodal Diagram for Thermal Balance
5. ELECTROMAGNETIC PUMP

The electromagnetic (EM) pump is modeled as a component. There are two pump choices available in the SSC-K code: centrifugal pump which was originally imbedded into the SSC-L, and an electromagnetic pump. Model description for the centrifugal pump is presented in the SSC-L code manual. In the SSC-K, an electromagnetic pump model is introduced for the KALIMER design.

5.1 Pump Models

The KALIMER design contains motor-generators on the primary pumps to extend the coastdown times of these EM pumps. Combination of EM pumps and motor-generators is included in SSC-K to handle this configuration. In the current KALIMER design a synchronous motor is running all of the time during normal operation, but the power to the EM Pump does not go through the motor as long as the normal pump power is available. If normal pump power is lost, then the motor becomes a generator, and a switch is thrown automatically to supply voltage from the motor-generator to the pump. The pump coastdown rate is then determined by the inertia of the motor. The motor is designed such that it will initially supply 60% of nominal voltage to the pump. Thus, when normal power is lost and the motor-generator power is switched on there is a sudden drop in pump head and flow followed by a gradual coastdown.

Pump Head

The pump head is correlated with an expression of the form

\[ \bar{H} = (\bar{V}/\bar{f})^{1.5} h_s (\bar{W}/\bar{f}) - L_f \bar{W}^2 \]  

where

\[ \bar{H} = \frac{H}{H_r} \]  

\[ \bar{V} = \frac{V}{V_r} \]
\[ \bar{f} = \frac{f}{f_r} \quad (5-4) \]

\[ \bar{w} = \frac{w}{w_r} \quad (5-5) \]

- \( H \) = pump head
- \( H_r \) = rated head
- \( V \) = pump voltage
- \( V_r \) = rated voltage
- \( f \) = frequency
- \( f_r \) = rated frequency
- \( w \) = mass flow rate
- \( w_r \) = rated mass flow rate
- \( L_f \) = friction loss coefficient and
- \( h_n \) is a head curve correlated as

\[ h_n (\bar{w}/\bar{f}) = \sum_{j=1}^{4} a_j (\bar{w}/\bar{f})^{j-1} \quad (5-6) \]

with the coefficients \( a_j \) determined by a least-squares fit to the data.

**Pump Efficiency**

The pump efficiency, \( \varepsilon_t \), is correlated as

\[ \varepsilon_t = F(V) \ G(\bar{w}/\bar{f}) \varepsilon_{tr} \quad (5-7) \]

with

\[ F(V) = \sum_{j=1}^{7} b_j \ V^{j-1} \quad (5-8) \]

\[ G(\bar{w}/\bar{f}) = \begin{cases} 0.01 & \text{if } \bar{w}/\bar{f} \geq 5 \\ \sum_{j=1}^{9} c_j (\bar{w}/\bar{f})^{j-1} & \text{if } \bar{w}/\bar{f} < 5 \end{cases} \quad (5-9) \]

and \( \varepsilon_{tr} \) = rated efficiency
**Pump Voltage**

Before the cut-over to the motor-generator, the pump voltage is assumed to be constant at its rated value. Also, the frequency is constant at its rated value. Immediately after cut-over, the voltage drops to a fraction, \( V_{fr} \), of its initial value. Then the voltage is proportional to the square of the frequency, so after cut-over the voltage is

\[
\overline{V} = V_{fr} f^2
\]  
(5-10)

where

\[
V_{fr} = 0.6
\]  
(5-11)

**Motor Speed**

The equation for the motor speed, \( s \), is

\[
\frac{ds}{dt} = - \frac{(\tau_p + \tau_t)}{I}
\]  
(5-12)

where

- \( \tau_p \) = pump torque
- \( \tau_t \) = friction loss
- \( I \) = moment of inertia

Note that the motor speed and the pump frequency are the same:

\[
f = s
\]  
(5-13)

The pump torque is given by

\[
\tau_p = \frac{Hw}{\varepsilon_j \rho s}
\]  
(5-14)

where

\( \rho \) = liquid density

The friction loss in the motor is assumed to have the form
\[ \tau_i = \tau_r L_m s \]  

(5-15)

where \( L_m \) is a loss coefficient and \( \tau_r \), the rated torque.

5.2 Correlations to Pump Data

Experimental data has been fit by a least-squares fitting program to give the parameters listed in Table 5-1 for use in equations 5-6, 5-8, and 5-9. Also a value of .07592 is used for \( L_r \) in equation 5-1.

<table>
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<th>( a_j )</th>
<th>( b_j )</th>
<th>( c_j )</th>
</tr>
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<td>-.148</td>
<td>0.</td>
</tr>
<tr>
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<td>.996</td>
<td>7.110</td>
<td>-51.235</td>
</tr>
<tr>
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<td>-15.972</td>
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<td>4</td>
<td>6.056</td>
<td>9.942</td>
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<tr>
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<td>12.024</td>
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</tr>
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<td>-</td>
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6. PASSIVE DECAY HEAT REMOVAL SYSTEM

6.1 Introduction

PSDRS (Passive Safety Decay Heat Removal System) is a heat removal feature in the KALIMER design which is characterized to cool the containment outer vessel with atmospheric air in passive manner. Fig. 6.1 exhibits the schematic of PSDRS. Atmospheric air comes in from the inlets located top of the containment, and flows down through the annulus gap between the air divider and the concrete wall. Then, it turns back upward passing through the other annulus gap between the containment outer surface and the air divider, and, finally, flows out through the stack with raised temperature by energy gained from cooling of the containment vessel. The air flow rate is determined from various parameters. Air temperature difference between two annulus channels, flow path or pressure drop of an orifice placed for flow control, friction exerted on the surfaces are main parameters affecting the flow rate.

It is important that the air divider should be made of high heat resistance material to maximize the temperature difference between the inner and outer channels. The gap between the reactor vessel and the containment vessel is filled with helium gas and thus radiation heat transfer prevails due to high temperature of these walls.

The significance of PSDRS in the KALIMER design is that it plays a role of the only heat removal system under total loss of heat sink accident. For this reason, its function is crucial to prevent the core damage, so that performance analysis as well as realistic modeling of the system may be a key issue to provide essential knowledge for safety evaluation of the KALIMER design.

6.2 PSDRS Modeling

6.2.1 Basic Assumptions

- Temperature in a wall is represented with one temperature except the air divider as shown in Fig. 6.1, because the wall thicknesses are thinner than those of gaps between them by roughly factor of 3 and more over the thermal resistances of the gaps are also relatively much higher. The air divider, however, is made of material with high thermal
resistance to reduce conduction across it.

- Air flow is calculated under assumption of quasi steady state, due to much smaller time constant than those of the walls. Therefore, it is assumed that air temperature varies axially along the flow channels.

- All walls and air channels are modeled with an equal mesh size which locates the same elevation in the axial direction. The axial heat conduction is ignored.

6.2.2 Governing Equations

**Reactor vessel**

The energy balance is set up using heat transfers from sodium or helium gas to the reactor vessel depending on the sodium level, and between reactor vessel inner and containment outer surfaces, e.g.

\[
m_w c_w \frac{dT}{dt} = h_{NW1} A_{NW1} (T_N - T_{W1}) + h_{W12} A_{W12} (T_{W2} - T_{W1})
\]

where,

- \(m_w\), \(c_w\) : mass and specific heat for the reactor vessel
- \(T_N\), \(T_{W1}\), \(T_{W2}\) : temperatures of coolant or cover gas, reactor vessel, and containment vessel, respectively
- \(h_{NW1}\) : heat transfer coef. between the inner surface of the reactor vessel and the coolant or cover gas
- \(A_{NW1}\), \(A_{W12}\) : corresponding heat transfer areas to the heat transfer coefficients
- \(h_{W12}\) : heat transfer coef. between the reactor vessel and the containment vessel

\[
\frac{1}{h_{W12}} = \frac{R_{w1}}{2} + \frac{1}{h_{CV12} + \varepsilon_{12} \sigma (T_{W1} + T_{W2}) (T_{W1}^2 + T_{W2}^2)} + \frac{R_{w2}}{2}
\]

The approximation is made that \(R_{w1}\) and \(R_{w2}\) are lumped in with \(h_{CV12}\), so

\[
h_{W12} = h_{CV12} + \varepsilon_{12} \sigma (T_{W1} + T_{W2}) (T_{W1}^2 + T_{W2}^2)
\]
where

\[ \varepsilon_{12} = \frac{1}{1 + \frac{1}{\varepsilon_{RV}} - \frac{1}{\varepsilon_{GV}}} \] (6-4)

and

\[ h_{CV12} = \text{user-supplied convective heat transfer coefficient, RV to GV} \]

(see 'User Manual')

\[ \varepsilon_{RV} = \text{emissivity of the reactor vessel wall} \]

\[ \varepsilon_{GV1} = \text{emissivity of the guard vessel inner surface} \]

\[ \sigma = \text{Stefan-Boltzmann Constant} \]

\[ R_{W1} = \frac{G_{RV}}{k_{RV}} \]

\[ R_{W2} = \frac{G_{GV}}{k_{GV}} \]

\[ G_{RV} = \text{thickness of the reactor vessel} \]

\[ G_{GV} = \text{thickness of the guard vessel} \]

\[ k_{RV} = \text{thermal conductivity of guard vessel} \]

\[ k_{GV} = \text{thermal conductivity of reactor vessel} \]

**Containment vessel**

The containment temperature is determined by such terms as heat transfer from the reactor vessel, convection heat transfer to the up-flowing air, and radiation heat transfer directly to the inner surface of the air divider. Thus, the balance equation is led to

\[ m_{w2}c_{w2} \frac{dT_{w2}}{dt} = h_{w12}A_{w12}(T_{w1} - T_{w2}) + h_{w23}A_{w23}(T_{w3} - T_{w2}) + h_{w2a}A_{w2a}(T_{a1} - T_{w2}) \] (6-5)

The definitions of the coefficients used in this equation are the same notations as used in Eq. (6-1). However, \( h_{2a} \) denotes the heat transfer coefficient between the containment and down-flowing air, and \( A_{2a} \) is the outer surface area of the containment. \( T_{a1} \) is temperature of the up-flowing air. The heat transfer coefficient \( h_{23} \) is given by

\[ \frac{1}{h_{w23}} = \frac{R_{w2}}{2} + \frac{1}{\varepsilon_{23} \sigma (T_{w2} + T_{w3})(T_{w2}^2 + T_{w3}^2)} \] (6-6)
$R_{w2}$ is neglected, so

$$h_{w23} = \varepsilon_{23} \sigma (T_{w2} + T_{w3})(T_{w2}^2 + T_{w3}^2)$$

(6-7)

where

$$\varepsilon_{23} = \frac{1}{1 + \frac{1}{\varepsilon_{GVO}} - 1}$$

(6-8)

and

$\varepsilon_{GVO} =$ emissivity of the guard vessel outer surface

$\varepsilon_{Di} =$ emissivity of the air divider inner surface

$$\frac{1}{h_{w2a}} = \frac{R_{w2}}{2} + \frac{1}{h_{a1}}$$

(6-9)

again $R_{w2}$ is neglected, so

$$h_{w2a} = h_{a1}$$

(6-10)

where the air heat transfer coefficient is

$$h_{a1} = \frac{k_a}{D_{h1}} N_{u1}$$

(6-11)

$k_a =$ air thermal conductivity

$D_{h1} =$ hydraulic diameter between the guard vessel and the air divider

$N_{u1} =$ Nusselt number

$$N_{u1} = C_1 \text{Re}_i c_2 P_{rl}^{0.4} \quad \text{if} \quad \text{Re}_i \geq \text{Re}_c$$

$$C_3 \quad \text{if} \quad \text{Re}_i < \text{Re}_c$$

(6-12)

$$\text{Re}_i = \frac{D_{h1} w_i}{\rho a1 \mu a1}$$

(6-13)
\( w_a \) = air flow rate  
\( \rho a \) = air density  
\( \mu a \) = air viscosity  
\( \text{Pr}_1 \) = Prandtl number  
\( C_1, C_2, C_3 \) = user supplied correlation coefficients  
\( C_1 \sim 0.023 \)  
\( C_2 \sim 0.8 \)  
\( C_3 \sim 3-8 \)

**Inner and outer surfaces of the air divider**

Energy balance equation in the inner and outer surfaces of the air divider are given in similar manner and thus, it becomes

\[ m_{w3}c_{w3} \frac{dT_{w3}}{dt} = h_{w34}A_{w34}(T_{w4} - T_{w3}) + h_{w2a}A_{w2a}(T_{w2} - T_{w3}) + h_{w3a}A_{w3a}(T_{a1} - T_{w3}) \]  \hspace{1cm} (6-14)

\[ m_{w4}c_{w4} \frac{dT_{w4}}{dt} = h_{w45}A_{w45}(T_{w5} - T_{w4}) + h_{w3a}A_{w3a}(T_{w3} - T_{w4}) + h_{w4a}A_{w4a}(T_{a2} - T_{w4}) \]  \hspace{1cm} (6-15)

Here, \( T_{a2} \) represents temperature of the down-flowing air and heat transfer coefficients are given by

\[ h_{w3a} = h_{a1} \]  \hspace{1cm} (6-16)

\[ h_{w4a} = h_{a2} \]  \hspace{1cm} (6-17)

\[ \frac{1}{h_{w5a}} = R_{w5} + \frac{1}{h_{2a}} \]  \hspace{1cm} (6-18)

or

\[ h_{w5a} = \frac{h_{2a}}{1 + R_{w5}h_{2a}} \]  \hspace{1cm} (6-19)
Concrete wall

\[ h_{a2} = \frac{k_{a2}}{D_{w2}} Nu_z \]  \hspace{1cm} (6-20)

Temperatures of the up- and down-flowing air channels

The balance equations in the up- and down-flowing air channels are given as following equations, based on the assumptions described earlier.

\[ w_a c_a \frac{dT_{a1}}{dz} = h_{w2} A_{w2} (T_{w2}(z) - T_{a1}(z)) + h_{w3} A_{w3} (T_{w3}(z) - T_{a1}(z)) \]  \hspace{1cm} (6-22)

and

\[ w_a c_a \frac{dT_{a2}}{dz} = h_{w4} A_{w4} (T_{w4}(z) - T_{a2}(z)) + h_{w5} A_{w5} (T_{w5}(z) - T_{a2}(z)) \]  \hspace{1cm} (6-23)

Where, \( W_a \) denotes air flow rate and \( C_a \) does specific heat of air.

Calculation of air flow rate

Air flow rate is determined from gravitational force balance between down- and up-flowing air channels, and flow resistance along those channels. e.g.

\[ \Delta p_g = \int \rho g dz = g \{ \rho_{in} \Delta z_{in} - \rho_{stock} \Delta z_{stock} + \sum_j \rho_{a2}(j) \Delta z_j - \sum_j \rho_{a3}(j) \Delta z_j - \rho_{in} (z_{st} - z_{in}) \} \]  \hspace{1cm} (6-24)

and
\[ \Delta p_{\text{loss}} = \sum \frac{w^2}{2 \rho_a A_a^2} \left( \frac{L}{D_h} + k_{of} \right) \]  

(6-25)

where, \((Z_{in} - Z_{in})\) is the elevation difference between the inlet and stack, \(\bar{\rho}_a(j)\) represents air density in \(j\)th node, and \(K_{of}\) is defined as a form loss coefficient due to the geometry or orifice.

The friction factor is calculated as

\[
f = \begin{cases} 
A_f \, \text{Re}^b & \text{if } \text{Re} \geq \text{Re}_t \\
\frac{A_{fl}}{\text{Re}} & \text{if } \text{Re} < \text{Re}_t
\end{cases}
\]  

(6-26)

where

\[
\text{Re} = \text{Reynolds number} = \frac{D_h \, W_a}{\mu_a \, A_a}
\]

\(\mu_a\) = viscosity

\(A_f\) = user-supplied turbulent friction factor coefficient (see 'User Manual')

\(b\) = user-supplied coefficient (see 'User Manual')

and

\(A_{fl}\) = user-supplied laminar friction factor coefficient

The value of \(\text{Re}_t\), the Reynolds number for the transition from turbulent to laminar, is calculated by the code to make the friction factor continuous at the transition point.

\[
A_f \, \text{Re}_t^b = \frac{A_f}{\text{Re}_t}
\]  

(6-27)

or

\[
\text{Re}_t = \frac{A_{fl}^{1-b}}{A_f}
\]  

(6-28)

6-7
6.2.3 Solution Method

Schematic of solving the governing equations are presented in Fig. 6.2. Non-linear differential equations from Eqs. (6-1) to (6-5) are solved using Runge-Kutta Method [6-1], while Eqs. (6-6) and (6-7) can be solved with typical solution method of linear differential equation, if the axial wall temperature variations inside a node are ignored. The final solutions of these ordinary differential equations have a form of

\[ T_{ai}(z') = T_{ai}' + (T_{ai}(0) - T_{ai}') e^{-\lambda_i z'} \]  

(6-29)

where, \( i = 1,2 \), which correspond to up- and down-flowing channels, respectively.

\[ z' = z - z_j \]  

(6-30)

\[ T_{ai}' = f_2 T_{w2j} + f_3 T_{w3j} \]  

(6-31)

\[ f_2 = \frac{h_{w2a} A_{w2a}}{h_{w2a} A_{w2a} + h_{w3a} A_{w3a}} \]  

(6-32)

\[ f_3 = 1 - f_2 \]  

(6-33)

\[ \lambda_i = \frac{h_{w2a} A_{w2a} + h_{w3a} A_{w3a}}{w_a C_a} \]  

(6-34)

and above definitions for \( T_{ai}(z') \) is similar.

Since the temperature, \( T_{ai}(0) \), in Eq. (6-29) is defined at each node interface, so that a node temperature can be obtained by averaging the temperature profile within the length inside a node. Thus, the average value is calculated as
For the air temperature calculation, the balance Eqs. (6-24) and (6-25) becomes an algebraic equation. Thus, air temperature can be calculated straightforward once all coefficients are known.

\[
T_{nj} = \frac{\int_0^{\Delta z} T_{nj}(z') dz'}{\Delta z}
\]  \hspace{1cm} (6-35)

6.3 PSDRS Program

Program ‘PSDRS’ consists of group-wised input variables. User should note that the sequence of input variables must be consecutive, otherwise there will be a problem to read the input. Error indication is not enough to find errors in the input lists easily at the present time and thus users should make sure of the card number and the number of input variables in a card. User also notes that units of all physical quantities should be given in SI units. Top view of the KALIMER PSDRS is shown in Fig. 6.3.
Fig. 6.1 PSDRS Model
Fig. 6.2 Flowchart of PSDRS Program
Fig. 6.3  Top View of KALIMER PSDRS
7. REACTIVITY MODELS

7.1 Introduction

One of the important KALIMER design features is inherent shutdown, which refers to the tendency of the reactor to transitions to a much lower power level whenever temperatures rise significantly. There are several reactivity feedbacks important in the inherent shutdown response for the metal cores, and the core is designed to provide strong, inherent, negative reactivity feedback with rising temperature. This feature, combined with the heat removal capability of the PSDRS, makes the KALIMER capable of safely withstanding severe undercooling or overpower accidents, even without scram.

Only when a major off-normal condition is encountered, combined with a postulated failure of the Plant Protective System (PPS), can serious accident consequences be predicted. The inherent shutdown characteristic must be tested against various postulated challenges if it is to be credited in the licensing arena.

The Super System Code (SSC), developed at BNL for analyzing LMR transients, was selected as a basis for the development of KALIMER safety analysis code SSC-K. Since the SSC code was used for the preparation of the PSAR for CRBRP which did not rely on the passive safety features including reactivity feedback effects, there exist only limited reactivity models within the code.

The objectives of the current task are (i) to develop a version of SSC-K code which has the capability of analyzing the inherent safety characteristics of the metal core, (ii) to gain experiences of the safety analysis for the unprotected accidents, and (iii) to identify action items for the further development of the reactivity, component and system models.

Reactivity feedback models have been developed for the SSC-K code in order to account for the effects due to Doppler, sodium density/void, fuel axial expansion, core radial expansion and control rod driveline expansion. These models will be used to establish a working version of the SSC-K code which is essential for the development of component and system models as the
Attempts have been made for the application of the models in order to gain insight on the inherent safety characteristic under the postulated unprotected accident conditions. Reactivity models developed are not for actually generating a safety analysis results of KALIMER design but for the preparation of the further modeling efforts when the reactivity coefficients can be generated through a detailed neutronics calculation.

Efforts also have been made for the identification of the limitations and of the further modeling needs for the current version of the code through the preliminary safety analysis.

7.2 Reactor Kinetics

Nuclear reactor kinetics models predict the time behavior of the neutron population in a reactor core induced by changes in reactor multiplication. Diffusion model is capable of describing the time behavior of a nuclear reactor, provided the effects of delayed neutrons are included. However, such a model is too detailed for practical implementation in reactor kinetics analysis due to excessive computation requirements.

Point reactor kinetics approximations can be used more effectively for fast reactors than for thermal reactors because the neutron flux is more nearly separable in space and time for fast reactors. Fast reactor safety codes to date have therefore generally employed point kinetics, however, the reactivity feedback terms due to reactor temperature variations and material motion generally contain spatial effects.

7.2.1 Point Kinetics Equations

The total heat generation per unit volume $P(r, t)$ is given as

$$P(r, t) = P_f(r, t) + P_d(r, t)$$

where $P_f(r, t)$ is the heat generation rate per unit volume due to nuclear fission and $P_d(r, t)$ is the decay heat generation rate per unit volume.
While the spatial power distribution in a reactor core is of interest in the steady-state operation of the plant, the temporal power distribution is of utmost importance in day-to-day plant operation, reactor stability studies, and safety. The time-dependent portion of the fission power contribution is calculated by solving the space-averaged, one-energy group reactor kinetics equations. The one-energy group assumption is reasonable, particularly for a fast reactor. The space-averaged model is quite adequate since the core of an LMFBR responds, due to the relative smallness of the core and the large neutron migration area, more uniformly than a light water reactor core to changes in reactivity.

The point-kinetics equations may be expressed as

\[
\frac{dN}{dt} = \frac{\rho - \beta_r}{\Lambda} N + \sum_{i=1}^{6} \lambda_i C_i \tag{7-2}
\]

\[
\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} N - \lambda_i C_i \quad (i = 1, 2, ..., 6) \tag{7-3}
\]

where

- \( N \) = neutron density (neutrons/m\(^3\)),
- \( t \) = time(s),
- \( \rho \) = reactivity (\( \Delta k / k \)),
- \( \beta_r \) = effective delayed neutron fraction = \( \sum_i \beta_i \),
- \( \Lambda \) = prompt neutron generation time(s)
  = prompt neutron lifetime / multiplication factor \( k \),
- \( \lambda_i \) = decay constant for the \( i \)-th delayed neutron group(s\(^-1\)),
- \( C_i \) = density of the \( i \)-th effective delayed neutron precursor (precursors/m\(^3\)),
- \( \beta_i \) = effective delayed neutron fraction for the \( i \)-the group.

It should be noted that for a particular isotopic composition of a reactor, a single set of \( \lambda_i \) and \( \beta_i \) values is obtained and utilized in the kinetics equations.

It is convenient to rewrite Eqs. (7-2) and (7-3) in a normalized form by defining the normalized neutron density, \( n(t) \) and concentration of the \( i \)-th group precursor, \( c_i(t) \), as
\[ n(t) = \frac{N(t)}{N(0)} \quad \text{and} \quad c_i(t) = \frac{C_i(t)}{C_i(0)} \]

Prior to the reactivity change, the derivative \( dC_i / dt \) in Eq. (7-3) is zero and

\[ C_i(0) = \frac{\beta_i}{\lambda_i \Lambda} N(0) \]

By replacing \( N(t) \) and \( C_i(t) \) with \( n(t) \) and \( c_i(t) \), respectively, Eqs. (7-2) and (7-3) become

\[ \frac{dn}{dt} = \frac{\rho - \beta_r}{\Lambda} n + \frac{1}{\Lambda} \sum_{i=1}^{6} \lambda_i c_i \quad (7-4) \]

\[ \frac{dc_i}{dt} = \lambda_i (n - c_i) \quad (i = 1, 2, \ldots, 6) \quad (7-5) \]

Perhaps the most serious approximation involved in the point reactor kinetics equations involves the assumption that the flux can be adequately represented by a single, time-independent spatial mode. When changes in core composition are sufficiently slow, as in fuel depletion or fission-product poisoning studies, one can perform an instantaneous steady-state criticality calculation of the shape function. For rapidly varying transients in which spatial effects are important, one is usually forced to solve the time-dependent neutron diffusion equation directly.

### 7.2.2 Prompt Jump Approximation

The direct integration of these equations requires very small timestep sizes due to the small numerical value of the generation time \( \Lambda \). To assure numerical stability and accuracy, step sizes of approximately \((100 \text{ to } 1000) \cdot \Lambda \) are required. Typically, \( \Lambda \) is about \(= 6 \times 10^{-7} \text{s} \), therefore, the step sizes of the order of \(0.00006 \text{ to } 0.00006 \text{s} \) would be required.

The simplest way to circumvent this problem is to utilize the prompt jump approximation (PJA). This approximation makes use of the very fact that \( \Lambda \) is extremely small. By assuming the \( \Lambda \) approaches zero, the product \( \Lambda (dn / dt) \) in Eq. (7-4) also approaches zero. It is also noted that for small values of reactivity, the rate of change of neutron density is sufficiently slow that
\( \frac{dn}{dt} \) is negligible compared to the two terms on the right hand side of Eq. (7-4). Thus, \( n \) may be directly solved for as

\[
n = \frac{1}{\beta_r - \rho} \sum \lambda_i c_i
\]  

(7-6)

This means that any disturbance in the reactivity \( \rho \) will be instantaneously reflected in the neutron density \( n \) jumps immediately to some initial level dependent on the size of the reactivity insertion.

Since \( \frac{dn}{dt} \) was assumed to be zero, the PJA is in excellent agreement (to within < 0.1\%) with the exact solution for values of \( \rho \) less than +50 cents. It should be noted that this approximation gets even closer to the exact solution when the prompt neutron generation time is smaller.

The main drawback of using the PJA is the fact that agreement to the exact solution diminishes as \( \rho \) approaches \( \beta_r \). It can be seen from Eq. (7-6) that \( n \) is discontinuous at \( \rho = \beta_r \). To provide for these cases where \( \rho \) approaches \( \beta_r \) (or more conservatively, when \( \rho > 50 \) cents) an optional numerical method is included in SSC-K which solves the equations exactly.

7.2.3 Kagnove Method

To provide an exact solution to Eqs. (7-4) and (7-5), without integrating them directly, the method proposed by Kaganove was used in SSC. Here, Eqs. (7-5) are solved for \( c_i \) in terms of \( \frac{dc_i}{dt} \) and substituted into Eq. (7-4) such that

\[
\frac{dn}{dt} = \frac{\rho n}{\Lambda} - \frac{1}{\Lambda} \sum \beta_i \frac{dc_i}{dt}
\]  

(7-7)

The assumption is then made that over any integration step \( (\Delta t) \), the normalized power \( (n) \) and reactivity \( (\rho) \) may be represented by second-order polynomials. Thus,

\[
n(t) = n_o + n_t t + n_t^2 t^2 ; 0 \leq t \leq \Delta t,
\]  

(7-8)

\[
\rho(t) = \rho_o + \rho_t t + \rho_t^2 t^2 ; 0 \leq t \leq \Delta t,
\]  

(7-9)
where

\[ n_0 = \text{value of } n \text{ at the end of previous timestep} \]
\[ \rho_0 = \text{value of } \rho \text{ at the end of previous timestep} \]
and \( n_1, n_2, \rho_1, \rho_2 \) are constants to be evaluated.

Eq. (7-5) is now integrated in a straightforward manner:

\[
\int d[c_i(\mu)e^{i\mu}] = \int \lambda e^{i\mu} n(\mu) d\mu.
\]

Then

\[
c_i(t) = c_{i0}e^{-\lambda t} + \lambda e^{-\lambda t} \int e^{2\mu} n(\mu) d\mu
\]

where

\[ c_{i0} = c(t) \big|_{t=0} \]

Making use of Eq. (7-8), Eq. (7-10) becomes

\[
c_i(t) = c_{i0}e^{-\lambda t} + n_0(1 - e^{-\lambda t}) + \frac{n_1}{\lambda_1} (\lambda_1 t - 1 + e^{-\lambda_1 t})
\]

\[ + \frac{n_2}{\lambda_2^2} (\lambda_2^2 t^2 - 2\lambda_2 t - 2(1 - e^{-\lambda_2 t})) \]

Likewise, Eq. (7-7) becomes

\[
n(t) - n(0) = \frac{1}{\Lambda} \int \rho(\mu) n(\mu) d\mu \left[ \frac{1}{\mu} \sum \frac{\beta_i}{\lambda_i} [c_i(t) - c_{i0}] \right]
\]

Upon substituting Eqs. (7-8) and (7-9) into Equation (7-12), one obtains
\[ n_i(t) + n_s t^2 = \frac{1}{\Lambda} (\rho_0 n_i t + \rho_0 n \frac{t^2}{2} + \rho_0 n \frac{t^3}{3} + \rho_0 n^2 \frac{t^2}{2} + \rho_0 n \frac{t^3}{3}) + \rho_0 n^2 \frac{t^4}{4} + \rho_0 n \frac{t^3}{3} + \rho_0 n \frac{t^4}{4} + \rho_0 n^2 \frac{t^5}{5} - \frac{1}{\Lambda} \sum_i \frac{B_i}{\lambda_i} [c_i(t) - c_{o_i}] \] 

(7-13)

The boundary conditions are then imposed that integral Eq. (7-13) be satisfied at the midpoint and end of the step (i.e., at \( t = \Delta t/2 \) and \( t = \Delta t \)).

Thus, Eq. (7-13) yields two equations in the unknown \( n_i \) and \( n_s \). With the assumption that during any given timestep, the power and reactivity are functions of time only (i.e., decoupled), the solution in SSC will proceed as follows.

(a) using the predicted value of reactivity at \( t = \Delta t \) and two previous values, the two constants \( \rho_i \) and \( \rho_s \) in Eq. (7-9) are calculated;
(b) using Eq. (7-13) solved at \( \Delta t/2 \) and \( \Delta t \), the constants \( n_i \) and \( n_s \) are calculated;
(c) the predicted power may then be calculated using Eq. (7-8).

### 7.3 Reactivity Effects

Values for reactivity effects are required both for transient safety analysis and for control requirements during normal operation. Reactivity effects of importance in fast reactor design and safety include the Doppler effect, effects of sodium density changes or loss of sodium, effects of dimensional changes in core geometry, and long-term reactivity loss from fuel burnup.

The total reactivity at a given time, \( \rho(t) \), is the sum of as applied reactivity, \( \rho_a(t) \) e.g., control rod movement, plus the sum of the various reactivity feedback contributions, \( \rho(0) \):

\[ \rho(t) = \rho_a(t) + \sum \rho_i(t) \] 

(7-14)

As indicated in Fig. 7.1, the total reactivity is then incorporated into the point-kinetics model and used in the evaluation of the normalized time dependent factor for the fission and gamma heating. It should also be noted that the reactivity effects are inherently space-dependent. This is not only due to the fact that the temperatures vary spatially, but even for the same
temperatures the magnitude of the effect will depend on the location within the reactor. Since the point-kinetics equations suppress any spatial dependence, an appropriately weighted spatial integration of the evaluated local reactivity feedback effects must be performed.

In the following sections, models for various reactivity feedback effects are discussed. For the reactivity effects of dimensional changes in core geometry, fuel axial expansion, core radial expansion and control rod driveline expansion are considered.

Due to the unavailability of reactivity coefficients for KALIMER core designs at the present time, test runs have been performed for the SSC-K representation of the KALIMER for the preliminary verification of the reactivity models and for the better understanding of the reactor response under unprotected accident conditions.

7.3.1 Doppler Effect

It is important to have a prompt negative reactivity feedback that reverses a power transient if the reactor becomes prompt critical. Mechanical action by control rods is too slow after prompt criticality is reached. A prompt negative feedback is particularly important for fast reactors because two mechanisms, fuel compaction and sodium loss, have the potential to make the reactor superprompt critical.

The Doppler effect is the most important and reliable prompt negative reactivity effect in current thermal and fast reactor designs which utilize high fertile U238 material concentrations. Probably one of the better understood reactivity phenomena, the Doppler effect is due to the increased kinetic motion of the fuel atoms, as measured by an increase in fuel temperature, resulting in the broadening of cross-section resonances and increased resonance absorption.

The Doppler reactivity comes predominantly from the capture of low-energy neutrons. Ceramic-fueled reactors, due to the presence of oxygen or carbon in the fuel, have a soft enough neutron spectrum to have a large Doppler effect. The high density metal reactor, having no moderator in the fuel matrix, yields the hard neutron spectrum, and the flux in the principal Doppler resonance region (0.1 - 10 keV) is appreciably less than for the ceramic fueled reactor. Consequently, both oxide and carbide fueled fast reactors possess much higher Doppler
coefficients than metal fueled reactors. This represents one of the important advantages of ceramic over metal fuel.

7.3.1.1 Hard Spectrum Case

The Doppler coefficient, \( \frac{dk}{dT} \), is defined as the change in multiplication factor, \( k \), associated with an arbitrary change in the absolute fuel temperature, \( T \). For a reactor with hard neutron spectrum, such as a metal-fueled fast reactor, the theory for the effective Doppler cross section indicates that \( \frac{dk}{dT} \) should vary as \( 1/T^{3/2} \), i.e.,

\[
\frac{dk}{dt} = \frac{\alpha_{DOP}}{T^{3/2}}
\]  

(7-15)

where \( \alpha_{DOP} \) is the Doppler constant which is independent of temperature.

Eq. (7-15) may be integrated to yield

\[
k - k_0 = 2 \alpha_{DOP} \left( \frac{1}{\sqrt{T_0}} - \frac{1}{\sqrt{T}} \right)
\]

(7-16)

where \( T_0 \) and \( T \) represent two different fuel temperatures and \( k_0 \) and \( k \) are the resulting multiplication factors. Rigorously, reactivity is defined as

\[
\rho = \frac{k - 1}{k}
\]

and changes in reactivity, \( \Delta \rho \), as

\[
\Delta \rho = \rho - \rho_0 = \frac{k - k_0}{k k_0}
\]

For small reactivity changes, the Doppler effect is of the order of \( 10^{-4} \). With \( k \approx 1 \),

\[
\Delta \rho \approx k - k_0
\]
and the change in reactivity due to the Doppler effect $\Delta\rho^{\text{DOP}}$, can be written as

$$\Delta\rho^{\text{DOP}} = 2 \alpha^{\text{DOP}} \left( \frac{1}{\sqrt{T_0}} - \frac{1}{\sqrt{T}} \right)$$  \hspace{1cm} (7-17)

By definition, the reactivities are referenced to zero at steady state conditions, that is, $k_0 = 1$ and $\rho_0 = 0$, and the Doppler reactivity can be rewritten as

$$\rho^{\text{DOP}} = 2 \alpha^{\text{DOP}} \left( \frac{1}{\sqrt{T_0}} - \frac{1}{\sqrt{T}} \right)$$  \hspace{1cm} (7-18)

This equation may be applied locally or regionally depending on how the temperatures and Doppler constant are defined. Specifically, in discrete notation, the local Doppler reactivity, $\rho_{jk}^{\text{DOP}}$ is

$$\rho_{jk}^{\text{DOP}} = 2 \alpha_{jk}^{\text{DOP}} \left( \frac{1}{\sqrt{T_{0,jk}}} - \frac{1}{\sqrt{T_{jk}}} \right)$$  \hspace{1cm} (7-19)

where

- $K$ = index of fuel channel
- $J$ = index of the axial level along the fuel channel
- $\alpha_{jk}^{\text{DOP}}$ = the node-weighted Doppler constant for position $JK$
- $T_{0,jk}$ = the reference fuel temperature at position $JK$
- $T_{jk}$ = the effective local temperature at position $JK$

The effective fuel temperature can be taken to be the volume-averaged fuel temperature which is defined as

$$T_{jk} = \frac{\sum V_{jk} T_{jk}}{\sum V_{jk}}$$  \hspace{1cm} (7-20)

where $V_{jk}$ is the fuel volume in channel $K$, axial slice $J$, between radial mesh $I$ and $I-1$. 

7-10
and \( T_{jK} \) is the local fuel temperature at this position. Figures 7.3 and 7.4 show the SSC-K representations of reactor core subassemblies and radial node within a fuel rod, respectively.

It should be noted that the Doppler constant in Eq. (7-19) is shown to be a space-dependent variable. Although \( \alpha_{jK}^{\text{DOP}} \) will be a constant with respect to fuel temperature, there will be spatial variations due to different fuel types (e.g., enrichment, pin size, volume fractions of structural material, coolant, and fuel) and different sodium density. In the present model, \( \alpha_{jK}^{\text{DOP}} \) will be a space-dependent parameter supplied by the user. Thus, the first concern relating to fuel type can be directly addressed.

The sodium density dependences is actually a neutron spectrum dependence- the harder the spectrum, the smaller the Doppler effect since there are less neutrons in the resonance range. The less sodium present, owing to density decreases or voids, implies a harder spectrum. To treat this effect, an effective isothermal sodium void fraction, \( X_{jK}^{Na} \), is defined

\[
X_{jK}^{Na} = \frac{\rho_{0,jK}^{Na} - \rho_{jK}^{Na}}{\rho_{0,jK}^{Na}}
\]

where \( \rho_{jK}^{Na} \) is the local, time-dependent sodium density at position \( jK \), and \( \rho_{0,jK}^{Na} \) is the local reference sodium density. Thus, if \( \beta_{jK}^{\text{DOP}} \) and \( \Omega_{jK}^{\text{DOP}} \) are the Doppler constants with and without sodium present, respectively, then the net Doppler constant can be approximated by

\[
\alpha_{jK}^{\text{DOP}} = \beta_{jK}^{\text{DOP}} (1 - X_{jK}^{Na}) + \Omega_{jK}^{\text{DOP}} X_{jK}^{Na}
\]

To obtain an overall Doppler reactivity, \( \rho^{\text{DOP}} \), for use in the point - Kinetics equation, a summation of Eq. (7-19) must be performed. Thus

\[
\rho^{\text{DOP}} = \sum_{jK} \rho_{jK}^{\text{DOP}} = 2 \sum_{jK} \alpha_{jK}^{\text{DOP}} \left( \frac{1}{\sqrt{T_{0,jK}}} - \frac{1}{\sqrt{T_{jK}}} \right)
\]

The value of the Doppler constants, \( \beta_{jK}^{\text{DOP}} \) and \( \Omega_{jK}^{\text{DOP}} \) for each position \( jK \), must be supplied by the user in units of reactivity \( \Delta k / k \) for that mesh.

7.3.1.2 Soft Spectrum Case
Since the Doppler coefficient is found to vary with $1/T$ in an oxide-fueled fast reactor, this coefficient can be defined as

$$\frac{dk}{dT} = \frac{\alpha_{Dop}}{T}$$  \hspace{1cm} (7-24)

where $\alpha_{Dop}$ is a temperature independent Doppler constant.

For a uniform change in fuel temperature from $T_o$ and $T$, Eq. (7-24) may be integrated to yield

$$k - k_o = \alpha_{Dop} \ln\left(\frac{T}{T_o}\right)$$  \hspace{1cm} (7-25)

where $k$ and $k_o$ are resulting multiplication factors.

For small reactivity changes with $k \approx 1$, the Doppler reactivity effect can be calculated as

$$\rho_{Dop} = \alpha_{Dop} \ln\left(\frac{T}{T_o}\right)$$  \hspace{1cm} (7-26)

which can be applied locally and rewritten as

$$\rho_{jk}^{Dop} = \alpha_{jk}^{Dop} \ln\left(\frac{T_{jk}}{T_{o,jk}}\right)$$  \hspace{1cm} (7-27)

To obtain an overall Doppler reactivity, $\rho_{Dop}$, for use in the point kinetics equation, a summation of Eq. (7-27) must be performed. Thus,

$$\rho_{jk}^{Dop} = \sum_{jk} \rho_{jk}^{Dop} = \sum_{jk} \alpha_{jk}^{Dop} \ln\left(\frac{T_{jk}}{T_{o,jk}}\right)$$  \hspace{1cm} (7-28)

where $\alpha_{jk}^{Dop}$ is also defined by Eq. (7-22).

Input requirements for the calculation of Doppler reactivity are $\beta_{jk}^{Dop}$ and $\Omega_{jk}^{Dop}$ in $\Delta k / k$.
7.3.1.3 Other Models

ARIES code also calculates the Doppler reactivity coefficient by the Eq. (7-28) with temperatures in Rankines.

SASSYS code calculates the Doppler feedback reactivity, $\rho^{DOP}$, based on summation, over fuel axial nodes in all channels, the contribution for a node which is based on a mass weighted average fuel temperature, as well as on how much fuel and sodium are currently present in the node:

$$
\rho^{DOP} = \sum_{J,K} \rho_{JK}^{DOP}
$$

$$
= \sum_{J,K} W_{JK} \frac{m_{f JK}}{m_{f 0}} \left\{ \Omega_{K}^{DOP} + (\beta_{K}^{DOP} - \Omega_{K}^{DOP}) \frac{\rho_{JK}}{\rho_{JK 0}} \right\} \ln \left( \frac{T_{JK}}{T_{JK 0}} \right) \tag{7-29}
$$

where

$W_{JK}$ = Doppler weighting factor for axial node J in channel K.

normalized for each channel

$\beta_{K}^{DOP}$ = Doppler coefficient for channel K with all sodium present

$\Omega_{K}^{DOP}$ = Doppler coefficient for channel K with no sodium present

$m_{f JK}$ = fuel mass of the node JK

$m_{f 0}^{JK}$ = initial steady-state mass of fuel in the node JK

$\rho_{JK}$ = average density of sodium in the node JK

$\rho_{JK 0}$ = initial steady-state density of sodium in the node JK

$T_{JK}$ = average temperature of fuel in the node JK

$T_{JK 0}$ = initial steady-state temperature of fuel in the node JK

The valves for the unvoided and voided Doppler coefficient, $\beta_{K}^{DOP}$ and $\Omega_{K}^{DOP}$, for each channel, as well as the weighting factors are supplied by the user, based on neutronics calculations or experimental measurements.
7.3.2 Sodium Density Effect

The loss of sodium from a large fast reactor can result in a large positive reactivity effect. Sodium might be expelled from the core in the unlikely event of an unprotected transient, in which sodium boiling results from undercooling the reactor. This condition presents an important safety problem for an LMFBR, a problem not present in thermal reactors.

The sodium loss reactivity effect is exceedingly space-dependent. Sodium loss from the center of the core yields a highly positive reactivity effect, and sodium loss from near the edge gives a negative effect. The density decreases affect the reactivity of the reactor through two competing effects: increased leakage, which adds negative reactivity and is important away from the center of the core, and spectral hardening due to a decrease in the macroscopic sodium scattering cross-section which adds positive reactivity. The net effect depends primarily upon the location in the reactor.

In modeling this effect, both sodium density changes and voiding can be treated in a similar fashion. Basically, what is required along with the spatial sodium density distribution is a table of space-dependent sodium reactivity worths. The sodium density will be determined internally by SSC from knowledge of the sodium temperature distribution. However, the reactivity worths are user supplied.

There are several ways to present this reactivity effect depending on the form in which the reactivity worth data are known. For application in SSC, the following equation, which can treat either sodium density or voiding reactivity effects, is used

\[ \rho_{na} = \sum_{jk} \beta_{jk} M_{jk} \]  

(7-30)

where \( \rho_{na} \) is the overall sodium void reactivity coefficient for use in the point-kinetics equation, \( \beta_{jk} \) is the sodium reactivity worth in axial slice J, channel K, in units of reactivity per unit mass of sodium voided in segment JK, and is defined as

\[ M_{jk} = \left( \rho_{\nu,jk}^{NT} - \rho_{\nu,jk}^{V} \right) V_{jk}^{NT} \]  

(7-31)
where $\rho_{\text{oh}}^{\text{Na}}$ is the local sodium density at reference temperature, $\rho_{\text{av}}^{\text{Na}}$ is the local average, time-dependent sodium density and $V_{\text{av}}^{\text{Na}}$ is the local coolant volume in segment JK.

Input requirements for the calculation of sodium void reactivity according to the Eq. (7-30) are the mesh weighted sodium void reactivity coefficients $\beta_{\text{av}}^{\text{Na}}$ in $\Delta k / k$ per kg of sodium effectively voided.

The sodium void reactivity may also be calculated based on the changes in sodium temperatures as

$$\rho_{\text{Na}}^{\text{Na}} = \sum_{\text{K}} \beta_{\text{av}}^{\text{Na}} \ast (T_{\text{av}}^{\text{Na}} - T_{\text{av}}^{\text{Na}})$$

(7-32)

where $\beta_{\text{av}}^{\text{Na}}$ is the sodium void reactivity coefficient in $\Delta k / k$ per K, $T_{\text{av}}^{\text{Na}}$ is the sodium temperature at axial node J of channel K, and $T_{\text{av}}^{\text{Na}}$ is the initial steady state sodium temperature at axial node J of channel K.

The ARIES code computes the sodium void reactivity as

$$\rho_{\text{Na}}^{\text{Na}} = \sum_{\text{K}} \alpha_{\text{av}}^{\text{Na}} \beta_{\text{av}}^{\text{Na}} \ast (T_{\text{av}}^{\text{Na}} - T_{\text{av}}^{\text{Na}})$$

(7-33)

where $\alpha_{\text{av}}^{\text{Na}}$ is the sodium volumetric expansion coefficient in $^\circ \text{F}^{-1}$, $\beta_{\text{av}}^{\text{Na}}$ is the sodium void reactivity coefficient in $\Delta k / k$ and $T_{\text{av}}^{\text{Na}}$ and $T_{\text{av}}^{\text{Na}}$ are sodium temperatures in $^\circ \text{F}$

The sodium voiding model in SASSYS-1 and SAS4A is a multiple-bubble slug ejection model. The main purposes of this model are to predict the rate and extent of voiding for the voiding reactivity calculations and to predict the heat removal from the cladding surface after the onset of voiding for the fuel and cladding temperature calculations.

7.3.3 Axial Expansion Effect

A role of axial expansion of fuel in the normal solid fuel pin geometry is to provide a prompt negative reactivity feedback at the start of a power transient. This mechanism is the principal prompt negative feedback available in a metal-fueled fast reactor. Doppler feedback is
also available for the metal-fueled system, but it is relatively small due to the hard neutron spectrum. For a ceramic-fueled reactor, lack of structural integrity due to cracking in high burnup fuel renders the axial expansion mechanism somewhat unreliable so that more dependence is placed on the Doppler effect for a prompt negative feedback.

The fuel axial expansion increases the core height as temperatures rise, and changes the reactivity of the system by increasing the neutron leakage. The result is a rapid negative feedback contribution from an increase in fuel temperature, or a rapid positive feedback in response to a decrease in fuel temperature. The axial leakage changes only a little with axial fuel expansion, but the radial leakage does increase, thereby producing a negative reactivity effect, which can be shown as follows.

The criticality factor can be expressed as

\[ k = k_{\infty} P_{\text{ne}} = k_{\infty} e^{-a_1 L} \]  

(7-34)

where \( k \) is the product of the criticality factor for an infinite reactor, \( k_{\infty} \), and the fast neutron nonleakage probability, \( e^{-a_1 L} \). For a cylindrical core,

\[ k = k_{\infty} e^{-a_1 L} = k_{\infty} e^{-\mu_2 M^2} \]  

(7-35)

Now let us suppose that fuel expands axially as a result of increasing fuel temperature during the rise to full power or in a power transient. Radial fuel expansion may increase fuel pin diameters slightly but will have relatively little effect on radial expansion of the core. Bulk radial core expansion is governed primarily by the structure and hence, the coolant temperatures, together with the influence of the radial restraint system. Hence, the primary core expansion from increased fuel temperature is in the axial direction.

According to conventional reactor theory, the migration area varies with transport and total cross sections as

\[ M^2 = \frac{1}{\Sigma_t} \sum_{i} \frac{1}{N^2} \]  

7-16
where $\sum_{r}$ and $\sum_{t}$ are effective transport and total cross sections that provide the correct nonleakage probability. $N$ is the number density of fuel and structure atoms.

For a fixed number of fuel and structure atoms,

$$N \propto \frac{1}{V} \propto \frac{1}{R^2Z}$$

where $V = $ volume of the core

$R = $ core radius

and $Z = $ core height

Thus $M^2 \propto R^4Z^2$, but now $Z$ is the only dimension in $V$ that changes during axial fuel expansion. Hence, the criticality factor can be presented in terms of the only parameter that is varying, $Z$, as

$$k = k_e e^{-G_i z^2 / r^2} e^{-G_2 z^2 / r^2} = k_e e^{-G_1} e^{-G_2 z^2}$$  \hspace{1cm} (7-36)

This result indicates that the axial leakage does not change with axial fuel expansion, but that the radial leakage does increase, thereby producing a negative reactivity effect.

An upper limit to the magnitude of this effect is obtained if it is assumed that the fuel pellets are free to move within the clad. However, the actual mechanisms for expansion are difficult to model, especially for ceramic fuel. Fuel pellet cracking or friction between the pellet surface and inner clad wall will reduce the expansion significantly. On the other hand, if the fuel pellets are not stacked in perfect contact within the clad, then there may be negative fuel expansion if the fuel pellets settle. Physics calculations for CRBRP indicate a maximum overall reactivity of -.18 $\xi$ /mil of fuel axial expansion. The range of this effect is quoted to be +.025 $\xi$ /mil to -.18 $\xi$ /mil owing to the uncertainties involved in the expansion mechanism.

The lack of strong Doppler coefficient for metal fuels, which is caused by the characteristic hard neutron spectrum, has historically been compensated for by the presence of a reliable axial expansion coefficient. The ternary U-Pu-Zr fuel swells out to contact the HT9 cladding material.
around 2-3% atom burnup. After the fuel-clad lockup occurs, the fuel thermally expands according to the thermal expansion of the clad material. This is because the strength of metal fuel is very limited, and thus its expansion is dominated by the clad expansion. Experiments have shown that a 4% axial elongation is possible in the 1.9 to 5.3% burnup range.

The reactivity effect due to the thermal expansion usually decreases with the increase in reactor core size.

There are three models in the SSC-K code available for the evaluation of fuel axial reactivity coefficient. Free fuel expansion model, which gives the upper limit to the axial expansion reactivity, assumes that the fuel expands freely in the axial direction, and fuel-cladding contact is ignored. Uncertainties in the axial reactivity coefficient are accounted for by the uncertainty factor, and this is the original model present in the SSC-L code.

Force balance controlled expansion model assumes that the fuel is in contact with the clad, which is the most likely state for the metal-fueled core since the fuel is in an unlocked state only briefly. The fuel elongation is calculated by using an average strain, weighted with Young's modulus.

Another model is the one for ARIES code, which is based upon the fuel and clad temperature variations. Axial expansion may be optionally calculated based upon clad temperatures for conservative analyses of postulated accident conditions.

The simple model of the SASSYS code is based on a few assumptions. During the transient, if the cladding expands faster than the fuel, then the fuel-cladding gap opens, and the fuel can expand freely in the axial direction. If the fuel expands faster than the cladding, then the fuel binds with the cladding, and the axial expansion is determined by balancing the axial forces between the fuel and cladding.

7.3.3.1 Free Fuel Expansion Model

The reactivity due to fuel axial expansion, $\rho^{ax}$ is based on a model which parallels the treatment of sodium density reactivity effects:
\[ \rho^{\text{ax}} = \sum_{JK} C_{JK} N^*_{JK} \]  
(7-37)

where \( C_{JK} \) is the user-supplied fuel reactivity worth in axial slice \( J \), channel \( K \), in units of reactivity, \( \Delta k/k \), per unit mass of fuel effectively voided from segment \( JK \), and \( N^*_{JK} \) is the effective mass of fuel voided in segment \( JK \).

An expression for the evaluation of \( N^*_{JK} \) is derived based on the logic that as the fuel temperature increases, the fuel expands axially according to

\[ Z_{JK} = [1 + \alpha (T_{JK} - T_{0JK})] Z_{0JK} \]  
(7-38)

where \( \alpha \) is the linear fuel expansion coefficient in units of \( \text{cm/cm K} \) and \( T_{JK} \) is volume-averaged fuel temperature. To conserve mass, an axial increase in the fuel length implies a decrease in the fuel density \( \rho_{JK} \), which can be expressed as

\[ \rho_{0JK} Z_{0JK} = \rho_{JK} Z_{JK} \]  
(7-39)

or

\[ \rho_{0JK} - \rho_{JK} = \rho_{0JK} \left[ \frac{\alpha(T_{JK} - T_{0JK})}{1 + \alpha(T_{JK} - T_{0JK})} \right] \]  
(7-40)

The difference in density times the original fuel volume, \( V_{0JK} \), will give the amount of fuel voided from location \( JK \), \( N_{JK} \),

\[ N_{JK} = (\rho_{0JK} - \rho_{JK}) V_{0JK} \rho_{0JK} \left[ \frac{\alpha(T_{JK} - T_{0JK})}{1 + \alpha(T_{JK} - T_{0JK})} \right] \]  
(7-41)

The effective amount of fuel voided from location \( JK \), \( N^*_{JK} \), and the resulting net reactivity effect associated with fuel axial expansion are given as

\[ N^*_{JK} = e N_{JK} \]  
(7-42)
\[ \rho^{ax} = e \sum_k C_{jk} N_{jk} \quad (7-43) \]

where \( e \) is a user-supplied constant that accounts for the fact that the present model does not account for the uncertainties associated with the mode of fuel expansion and does not explicitly evaluate the increase in reactivity because the fuel that was calculated to be voided from location \( JK \) actually causes a net increase in axial fuel height, reducing leakage. A recommended upper limit for \( e \) is given to be 0.3 for oxide fuels.

For the calculation of fuel axial expansion reactivity, a user needs to supply \( C_{jk} \), the fuel reactivity worth in axial slice \( J \), channel \( K \), in units of reactivity \((\Delta k/k)\) per kg of fuel effectively voided from segment \( JK \).

### 7.3.3.2 Force Balance Controlled Expansion Model

This model assumes that the fuel is locked and expands with clad. The reactivity worth is determined from the difference between the initial fuel length and the elongated length at any given time.

The axial expansion reactivity coefficient \( \frac{dk}{dz} \) is defined as

\[ \frac{dk}{dz} = \alpha^{ax} \quad (7-44) \]

where \( \alpha^{ax} \) is an axial expansion constant in units of \( \Delta k \). This equation may be integrated to yield

\[ \rho^{ax} = \alpha^{ax} \ln \left( \frac{z}{z_0} \right) \quad (7-45) \]

In discrete notation

\[ \rho^{ax} = \sum_k \rho_k^{ax} = \sum_k \alpha_k^{ax} \ln \left( \frac{z_k}{z_{0k}} \right) \quad (7-46) \]

where
\( \alpha_{K}^{\text{ax}} \) is an axial expansion constant for channel \( K \) in units of \( \Delta k \)

\( z_{k} \) = the elongated axial length of channel \( K \)

\( z_{0k} \) = the axial length of channel \( K \) at reference temperature \( T_{0} \)

By definition, the effective strain \( (\Delta l/l) \) of \( K \)-th channel, \( \xi_{k} \), can be expressed as

\[
\xi_{k} = \frac{z_{k} - z_{0k}}{z_{0k}}
\]  

(7-47)

and rewritten as

\[
\bar{\alpha}(T) = \alpha_{0} + \alpha_{1}T
\]

(7-48)

The effective strain of channel \( K \) can be calculated by using an average strain, weighted with Young’s modulus as

\[
\xi_{k} = \frac{1}{z_{0k}} \sum_{j} z_{0,Jk} \xi_{jk}
\]

\[
= \frac{1}{z_{0k}} \sum_{j} z_{0,Jk} \left( \xi_{f}\frac{Y_{f}A_{f}}{Y_{f}A_{f} + Y_{c}A_{c}} + \xi_{c}\frac{Y_{c}A_{c}}{Y_{f}A_{f} + Y_{c}A_{c}} \right)_{JK}
\]

(7-49)

where

- \( K \) = index of channel
- \( J \) = index of the axial position along the channel
- \( z_{0,Jk} \) = the axial length of segment \( JK \) at reference temperature
- \( Y \) = Young’s modulus
- \( A \) = Nominal cross-sectional area

and subscripts \( f \) and \( c \) represent fuel and clad, respectively.
The strains of fuel and clad can be obtained from

\[ \varepsilon_{jk}^{f} = \alpha^{f} (T_{jk}^{f} - T_{0,jk}) \] (7-50)

\[ \varepsilon_{jk}^{c} = \alpha^{c} (T_{jk}^{c} - T_{0,jk}) \] (7-51)

where

- \( \alpha^{f} \) = the thermal expansion coefficient of the fuel
- \( \alpha^{c} \) = the thermal expansion coefficient of the clad
- \( T_{jk}^{f} \) = the average temperature of fuel in segment \( JK \)
- \( T_{jk}^{c} \) = the average temperature of clad in segment \( JK \)
- \( T_{0,jk} \) = the reference temperature

Input requirements for this model are as follows:
- \( \alpha^{f} \) = the thermal expansion coefficient of the fuel
- \( \alpha^{c} \) = the thermal expansion coefficient of the clad
- \( Y \) = Young's modulus for fuel and clad
- \( \alpha_{x}^{Ak} \) = axial expansion constant in units of \( \Delta k \)

\( \alpha^{f} \) and \( \alpha^{c} \) are currently calculated in subroutine TEXP, while \( Y \) and \( \alpha_{x}^{Ak} \) are provided in subroutine GROW5T of SSC-K.

### 7.3.3.3 Other Models

ARIES code adopts a fuel-clad expansion model as

\[ \rho_{x}^{Ak} = \sum_{jk} \left[ \alpha^{C} \rho_{x}^{C} (T_{0,jk}^{n} - T_{0,jk}^{C}) + \alpha^{F} \rho_{x}^{F} (T_{0,jk}^{F} - T_{0,jk}^{x}) \right] \] (7-52)

where

- \( \alpha^{C} \) = the cladding linear expansion coefficient in \( ^{\circ} \text{F}^{-1} \)
- \( \alpha^{F} \) = the fuel linear expansion coefficient in \( ^{\circ} \text{F}^{-1} \)
- \( \rho_{x}^{C} \) = the cladding axial expansion reactivity coefficient in \( \Delta k \)
- \( \rho_{x}^{F} \) = the fuel axial expansion reactivity coefficient in \( \Delta k \)

Axial fuel expansion can also be calculated based on cladding temperature as
\[ \rho^{\Delta k} = \sum_{jk}(\alpha^c_\rho^{c} + \alpha^c_\rho^{p}) (T^{n_0}_{jk} - T^{n_0}_{0jk}) \]  

(7-53)

Usually, Eq. (7-52) is used when analyzing undercooling events and Eq. (7-53) is used for conservative analyses of transient overpower events.

It is assumed in SASSYS code that before the start of the transient, a combination of fuel cracking, fuel re-structuring, and stress relaxation cause the gap between the fuel and the cladding to close, but there is little contact force between the fuel and cladding. During the transient, if the cladding expands faster than the fuel, then the fuel-cladding gap opens, and the fuel can expand freely in the axial direction. If the fuel expands faster than the cladding, then the fuel binds with the cladding, and the axial expansion is determined by balancing the axial forces between the fuel and cladding. Slip between fuel and cladding is ignored in this case.

The reactivity calculation is based on the user-supplied local fuel reactivity worth, in units of reactivity, \( \Delta k/k \), per unit mass of fuel effectively voided from the segment.

### 7.3.4 Radial Expansion Effect

#### 7.3.4.1 SSC-K Model

Radial fuel expansion due to increasing fuel temperature may increase fuel pin diameters slightly but will have relatively little effect on radial expansion of the core. Bulk radial core expansion is governed primarily by the structure and, hence, the coolant temperatures, together with the influence of the radial restraint system.

The core assemblies are held by their nosepieces in the receptacles, and by the load pads near the top of the assemblies which are surrounded by a core restraint ring attached to the core barrel, as shown in Fig. 7.6. The separation of the assemblies is maintained by an intermediate plane of load pads at an elevation above the active core. The intermediate load pads above the core are not restrained by a former ring attached to the core barrel. Thus, the core assemblies are free to bow as dictated by temperature differences and their metallurgical condition.

The radial dimension of the core is largely determined by the assembly spacing. This spacing is
determined by the grid plate below the core and by two sets of load pads above the core.

The radial expansion reactivity coefficient, \( \frac{dk}{dr} \), can be defined as

\[
\frac{dk}{dr} = \frac{\alpha^r}{r}
\]  

(7-54)

where \( \alpha^r \) is a radial expansion constant in units of \( \Delta k \). This equation may be integrated to yield

\[
\rho^r = \alpha^r \ln\left(\frac{r}{r_0}\right)
\]  

(7-55)

where

- \( r \) = the radial dimension of core at transient temperature
- \( r_0 \) = the initial steady-state radial dimension of core

By definition, the effective strain (\( \Delta l/l \)), \( \xi \), can be expressed as

\[
\xi = \frac{r - r^0}{r^0}
\]

and rewritten as

\[
\frac{r}{r^0} = 1 + \xi
\]

Thus

\[
\rho^r = \alpha^r \ln(1 + \xi)
\]  

(7-56)

The coefficients \( \alpha^r \), for radial expansion effect, were calculated assuming a uniform increase over the core radius. However, the above core load pad (ACLP) responds to core exit sodium temperature while the grid plate (GP) responds to the core inlet temperature. This causes non-uniform expansion and the worth for each component must be weighted. From geometrical considerations, the split is \( W_{\text{LP}} \) for ACLP and \( W_{\text{GP}} \) for GP. Hence, the radial expansion reactivity can be calculated as

\[
\rho^r = \alpha^r \ln(1 + W_{\text{LP}} \xi_{\text{LP}} + W_{\text{GP}} \xi_{\text{GP}})
\]  

(7-57)
where
\[ W_{LP} = \text{geometrical weighting factor for the ACLP} \]
\[ W_{GP} = \text{geometrical weighting factor for the GP} \]

The strain of the ACLP can be calculated as
\[ \xi_{LP} = \sum_K N^K \xi_{LP}^K \quad (7.58) \]

where
\[ K = \text{index of the fuel channel} \]
\[ N^K = \text{number of subassemblies in K-th channel across core radius layout} \]

as shown in Fig. 7.6
\[ \xi_{LP}^K = \text{strain } (\Delta r / r) \text{ for ACLP of channel } K \]

The strains of the ACLP and the GP for channel K can be obtained as
\[ \xi_{LP}^K = \alpha_{LP} (T_{\text{avg}}^K - T_0^K) \quad (7.59) \]
\[ \xi_{GP}^K = \alpha_{GP} (T_{GP}^K - T_0^{GP}) \quad (7.60) \]

where
\[ \alpha_{LP} = \text{the thermal expansion coefficient of the ACLP} \]
\[ \alpha_{GP} = \text{the thermal expansion coefficient of the GP} \]
\[ T_0^K = \text{the initial steady state temperature of the ACLP at K-th channel} \]
\[ T_{\text{avg}}^K = \text{the volume-averaged temperature of the ACLP at K-th channel} \]
\[ T_{GP}^K = \text{the initial steady state temperature of the GP} \]
\[ T_0^{GP} = \text{the temperature of the GP} \].

### 7.3.4.2 Other Models

The ARIES code computes the thermal expansion reactivity coefficient as a sum of contributions from the fuel axial expansion, core radial expansion, and bowing effects. A Global radial expansion reactivity coefficient is utilized for the core radial expansion effect.
Two radial expansion feedback models are available in SASSYS-1: a simple model and a more detailed model.

The simple model assumes that

1. The reactivity feedback is determined solely by thermal expansions of the grid support plate and load pad region, with all regions having the same thermal expansion coefficient.
2. The displacement of the core mid-plane is sufficient to estimate the reactivity feedback from the radial core expansion.
3. All of the subassembly load pads are in contact throughout the transients.

The equations actually used in SASSYS are

\[ \rho \Delta \psi = C_{rc} [\Delta T_{in} + \frac{XMC}{\Delta T_{slp}} (\Delta T_{slp} - \Delta T_s)] \]  

(7-61)

where

- \( C_{rc} \) = coefficient, \$/K
- \( \Delta T_{in} \) = changes in coolant inlet temperature
- \( XMC \) = distance from nozzle support point to core mid-plane
- \( XMC \) = distance from nozzle support point to above ACLP
- \( \Delta T_{slp} \) = changes in average structure temperature at ACLP

This model was not explicitly set up to account for subassembly bowing or flowering of the core, but the user can set arbitrary values for \( C_{rc} \) and \( XMC/XMC \). Therefore, if the bowing reactivity effect is proportional to \( \Delta T_{slp} \) or the \( \Delta T_{slp} - \Delta T_s \), then bowing reactivity can be accounted for by adjusting \( C_{rc} \) and \( XMC/XAC \).

The simple model, however, does not explicitly account for subassembly bowing, and is not capable of calculating changes in core loading conditions during the course of a transient. In a more detailed model, rather than maintaining the cylindrical shape associated with a uniform core dilation, an axial profile of core radius is calculated. During a transient, the changes in the axial profile are used in conjunction with a worth curve for radial core expansion, such as the one obtained with NUBOW-3D code, to yield the reactivity feedback.
7.3.5 Control Rod Driveline Expansion Effect

Thermal expansion of the drives due to a rise in core outlet temperature will cause the control rods to be inserted further into the core, providing a negative reactivity component. On the other hand, if the control rod drives are supported on the vessel head, and if the core is supported by the vessel walls, then heating the vessel walls will either lower the core or raise the control rod drive supports, leading to a positive reactivity component. The effect of vessel expansion needs to be analyzed carefully for the KALIMER design which adopts PSDRS.

A simple one node treatment is used for calculating the temperature of the control rod drives.

\[ M_c \cdot C^c \frac{dT_c}{dt} = h_o A_o (T'^{o}_{\infty} - T_c) \]  

where

- \( M_c \) = mass of the control rod drives, kg
- \( C^c \) = specific heat of the control rod drives, J/kg K
- \( T_c \) = control rod drive temperature, K
- \( t \) = time, sec
- \( h_o \) = heat transfer coefficient between coolant and control rod drive, W/m² K
- \( A_o \) = heat transfer area, m²
- \( T'^{o}_{\infty} \) = coolant temperature in the upper plenum region, K

In finite difference equation form, the above equation becomes

\[ M_c \cdot C^c \frac{T_c(t) - T_c(t - \Delta t)}{\Delta t} = h_o A_o \frac{(T'^{o}_{\infty}(t) - T_c(t))}{1 + d_o} \]  

or

\[ T_c(t) = \frac{T_c(t - \Delta t) + d_o T'^{o}_{\infty}(t)}{1 + d_o} \]

where

\[ d_o = \frac{\Delta t h_o A_o}{M_c} \]
\[ Z_\omega = Z_\omega^0 \left\{ 1 + \alpha_\omega T_\omega(t) - \frac{H(t)}{H(t)} T_\omega(t) \right\} \]

- \( Z_\omega(t) \) = penetration height into upper mixing plenum of average core exit flow, m
- \( H(t) \) = height of sodium in upper mixing plenum above top of core, m
- \( T_\omega(t) \) = temperature of sodium in upper mixing zone of upper outlet plenum, K
- \( T_\omega(t) \) = temperature of sodium in lower mixing zone of upper outlet plenum, K

For calculation of \( T_{\omega}(t) \), two-zone mixing model of SSC-K is used during transient. However, a single-zone perfect mixing model is used at steady state, and the control rod drives and coolant in the upper plenum region are assumed to be in thermal equilibrium. That is,

\[ T_{\omega}(0) = T_i \]

where \( T_i \) is the vessel sodium outlet temperature in K.

At steady state, the length of control rod drive can be calculated as

\[ Z_\omega = Z_\omega^0 \left\{ 1 + \alpha_\omega(T_\omega(0)) \ast (T_\omega(0) - T_{\omega}^0) \right\} \]

where
- \( Z_\omega^0 \) = steady state length of control rod drive immersed in sodium, m
- \( Z_{\omega}^0 \) = reference length of control rod drive immersed in sodium, m
- \( H_{\omega} \) = reference height of sodium in upper mixing plenum above top of core, m
- \( \alpha_\omega \) = linear coefficient of thermal expansion for control rod drive, m/m K
- \( T_{\omega}^0 \) = reference control rod drive temperature, K

Expansion of the control rod drive from the steady state length can be expressed as

\[ \Delta Z_\omega = Z_\omega \ast \alpha_\omega(T_\omega(t)) \ast (T_\omega(t) - T_{\omega}^0) \]

For vessel expansion,

\[ M_{\omega} C_\omega \frac{dT_{\omega}}{dt} = h_{\omega} A_{\omega}(T_{\omega}^\infty - T_{\omega}) \]

7-28
where

\[ M_{\text{vs}} = \text{mass of the reactor vessel, kg} \]

\[ C_{p}^{\text{vs}} = \text{specific heat of the reactor vessel, J/kg K} \]

\[ T_{\text{vs}} = \text{temperature of the reactor vessel, K} \]

\[ t = \text{time, sec} \]

\[ h_{\text{vs}} = \text{heat transfer coefficient between the coolant and the reactor vessel, W/m}^2\text{K} \]

\[ A_{\text{vs}} = \text{heat transfer area, m}^2 \]

\[ T_{\text{Na}}^{\text{vs}} = \text{coolant temperature adjacent to the reactor vessel, K} \]

Above equation can be solved for the reactor vessel temperature \( T_{\text{vs}} \) as

\[
T_{\text{vs}}(t) = \frac{T_{\text{Na}}^{\text{vs}}(t - \Delta t) + d_{\text{vs}} T_{\text{Na}}^{\text{vs}}(t)}{1 + d_{\text{vs}}} \tag{7-68}
\]

where

\[
d_{\text{vs}} = \frac{\Delta t h_{\text{vs}} A_{\text{vs}}}{M_{\text{vs}} C_{p}^{\text{vs}}} \]

\[ T_{\text{Na}}^{\text{vs}}(t) \simeq T_{\text{Na}}^{\text{upu}}(t) \]

\[ = \text{mean coolant temperature in upper region of bypass, K} \]

\[ T_{\text{vs}}(0) = T_{\text{Na}}^{\text{vs}}(0) \]

The vessel height at steady state can be calculated as

\[
Z_{\text{vs}}^{0} = Z_{\text{vs}}^{\text{ref}} \{1 + \alpha_{\text{vs}} (T_{\text{vs}}(0)) (T_{\text{vs}}(0) - T_{\text{vs}}^{\text{ref}}) \} \tag{7-69}
\]

where

\[ Z_{\text{vs}}^{0} = \text{reactor vessel height at steady state, m} \]

\[ Z_{\text{vs}}^{\text{ref}} = \text{reference vessel height, m} \]

\[ \approx \text{reference sodium level from bottom of reactor vessel, m} \]

\[ \alpha_{\text{vs}} = \text{linear coefficient of thermal expansion for reactor vessel, m/m K} \]

\[ T_{\text{vs}}^{\text{ref}} = \text{reference reactor vessel temperature, K} \]

Expansion of the reactor vessel from the steady state height can be expressed as
\[
\Delta Z_u = Z_u^0 + \alpha_u (T_u(t) \ast \{T_u(t) - T_u^0\})
\]  

(7-70)

Thus the effective control rod driveline expansion can be calculated as

\[
\Delta Z = \Delta Z_u - \Delta Z_u^\prime
\]

(7-71)

Reactivity for control rod driveline expansion is calculated as

\[
\rho_{CR}^{^\ast \ast} = C_{CR}^{^\ast \ast} \Delta Z
\]

(7-72)

where \( C_{CR}^{^\ast \ast} \) is the user-supplied coefficient for control rod driveline expansion in \( \Delta k/k \) per m.

Control rod driveline expansion model of the SASSYS-1 code is similar to the one described above.

7.4 Input Requirements for Reactivity Feedback Models

For the generation of the reactivity coefficients by the core design group of the KALIMER design team, descriptions of each model with the definition of the reactivity coefficient are summarized below. Discussions with the core design group for the SSC-K reactivity feedback models will be based on the following descriptions which will be included in the Design Data Request for the Safety Analysis.

7.4.1 Doppler Effect

Reactivity coefficients need to be provided for one of the models described below or for any other model suggested by the core design.

Model 1

\[
K\rho_{DOP}^{^\ast \ast} = \sum_{jk} \rho_{DOP}^{^\ast \ast} = 2 \sum_{jk} \alpha_{DOP}^{^\ast \ast} \left( \frac{1}{\sqrt{T_{0,jk}}} - \frac{1}{\sqrt{T_{jk}}} \right)
\]

(7-73)

\[
\alpha_{DOP}^{^\ast \ast} = \beta_{DOP}^{^\ast \ast} (1 - X_{jk}^{\ast \ast}) + \Omega_{DOP}^{^\ast \ast} X_{jk}^{\ast \ast}
\]

(7-74)

where
\( K \) = index of the fuel channel

\( J \) = index of the axial level along the fuel channel

\( T_{JK} \) = the initial steady state fuel temperature at position \( JK \)

\( T_{JK} \) = the effective local temperature at position \( JK \)

\( X_{JK}^{Na} \) = an effective isothermal sodium void fraction

**Input Requirements:**

\( \beta_{JK}^{Dop} \) = Doppler coefficient with Na present for node \( JK \), \( \Delta k / k \)

\( \Omega_{JK}^{Dop} \) = Doppler coefficient without Na present for node \( JK \), \( \Delta k / k \)

Typically, twelve axial nodes are used for the entire length of the fuel rod: two for lower blanket or shielding, six for active fuel, and four for upper gas plenum.

**Model 2**

\[
\rho^{Dop} = \sum_{JK} \rho_{JK}^{Dop} = \sum_{JK} \alpha_{JK}^{Dop} \ln \left( \frac{T_{JK}}{T_{JKo}} \right)
\]

\[
\rho^{Dop} = \beta_{JK}^{Dop} (1 - X_{JK}^{Na}) + \Omega_{JK}^{Dop} X_{JK}^{Na}
\]

**Input Requirements:**

\( \beta_{JK}^{Dop} \) = Doppler coefficient with Na present for node \( JK \), \( \Delta k / k \)

\( \Omega_{JK}^{Dop} \) = Doppler coefficient without Na present for node \( JK \), \( \Delta k / k \)

**Model 3**

\[
\rho^{Dop} = \sum_{JK} \rho_{JK}^{Dop}
\]

\[
= \sum_{JK} W_{JK} \frac{m_{fJK}}{m_{fJK0}} \left( \Omega_{JK}^{Dop} + (\beta_{JK}^{Dop} - \Omega_{JK}^{Dop}) \frac{\bar{P}_{JK}}{\bar{P}_{JK0}} \right) \ln \left( \frac{T_{JK}}{T_{JKo}} \right)
\]

where

\( m_{fJK} \) = fuel mass of the node \( JK \)
\[ m_{JK}^{0} = \text{initial steady-state mass of fuel in the node } JK \]
\[ \rho_{JK} = \text{average density of sodium in the node } JK \]
\[ \rho_{JK0} = \text{initial steady-state density of sodium in the node } JK \]
\[ T_{JK} = \text{average temperature of fuel in the node } JK \]
\[ T_{JK0} = \text{initial steady-state temperature of fuel in the node } JK \]

**Input Requirements:**

\[ W_{JK} = \text{Doppler weighting factor for node } JK, \text{ normalized for each channel} \]
\[ \beta_{K}^{\text{Dop}} = \text{Doppler coefficient for channel } K \text{ with all sodium present} \]
\[ \Omega_{K}^{\text{Dop}} = \text{Doppler coefficient for channel } K \text{ with no sodium present} \]

### 7.4.2 Sodium Density Effect

Reactivity coefficients need to be provided for one of the models described below or for any other model suggested by the core design.

**Model 1**

\[ \rho_{Na}^{K} = \sum_{JK} \beta_{JK} M_{JK} \quad (7-78) \]

where \( M_{JK} \) is the effective mass of sodium voided in the segment \( JK \).

**Input Requirements:**

\[ \beta_{JK} = \text{sodium void reactivity coefficient for axial slice } J \text{ of channel} \]

**Model 2**

\[ \rho_{Na}^{K} = \sum_{JK} \beta_{JK} * (T_{JK}^{Na} - T_{0JK}^{Na}) \quad (7-79) \]
Input Requirements:

\[ \beta_{jk} = \text{sodium void reactivity coefficient for the axial slice J of channel K}, \]
\[ \Delta k / k / K \]

Model 3

\[ \rho^{Na} = \sum_{jk} \alpha^{Na} \beta_{jk} * (T_{jk}^{Na} - T_{o,jk}^{Na}) \]  \hspace{1cm} (7-80)

Input Requirements:

\[ \alpha^{Na} = \text{sodium volumetric expansion coefficient in } ^{\circ}\text{F} \cdot 1 \]
\[ \beta_{jk} = \text{sodium void reactivity coefficient for the node JK in } \Delta k / k \]

7.4.3 Axial Expansion Effect

Reactivity coefficients need to be provided for one of the models described below or for any other model suggested by the core design.

Model 1

\[ \rho^{Ax} = e \sum_{jk} C_{jk} N_{jk} \]  \hspace{1cm} (7-81)

where \( N_{jk} \) is the mass of fuel voided from segment JK.

Input Requirements:

\[ e = \text{a user-supplied constant that accounts for the uncertainties associated with the mode of fuel expansion} \]
\[ C_{jk} = \text{fuel reactivity worth in axial slice, } J, \text{ channel } K, \text{ in } \Delta k / k \text{ per unit mass fuel effectively voided from segment JK} \]

**Model 2**

\[ \rho^{AX} = \sum_k \rho_k^{AX} = \sum_k \alpha_k^{AX} \ln \left( \frac{z_k}{z_{ok}} \right) \]  

(7-82)

where

- \( z_k \) = the elongated axial fuel length of channel K
- \( z_{ok} \) = the axial fuel length of channel K at reference temperature \( T_o \)

**Input Requirements:**

\[ \alpha_k^{AX} = \text{an axial expansion reactivity coefficient for channel K in units of } \Delta k \]

**Model 3**

\[ \rho^{AX} = \sum_{JK} \left[ \alpha^c \rho^c_{jk} (T_{jk} - T_{0,jk}) + \alpha^f \rho^f_{jk} (T_{jk} - T_{0,jk}) \right] \]  

(7-83)

**Input Requirements:**

\[ \alpha^c = \text{the cladding linear expansion coefficient in } \text{K}^{-1} \]
\[ \alpha^f = \text{the fuel linear expansion coefficient in } \text{K}^{-1} \]
\[ \rho^c_{jk} = \text{the cladding axial expansion reactivity coefficient in } \Delta k \]
\[ \rho^f_{jk} = \text{the fuel axial expansion reactivity coefficient in } \Delta k \]

### 7.4.4 Radial Expansion Effect

Reactivity coefficients need to be provided for one of the models described below or for any other model suggested by the core design.

**Model 1**

\[ \rho^R = \alpha^R \ln \left( 1 + \frac{W_{LP} \xi_{LP}}{W_{GP} \xi_{GP}} \right) \]  

(7-84)
where $\xi_{LP}$ and $\xi_{GP}$ are the strains of Above Core Load Pad (ACLP) and Grid Plate (GP), respectively.

**Input Requirements:**

\[ \alpha^R = \text{the radial expansion reactivity coefficient in units of } \Delta k \]
\[ W_{LP} = \text{geometrical weighting factor for the ACLP} \]
\[ W_{GP} = \text{geometrical weighting factor for the GP} \]

**Model 2**

\[
\rho^{\text{AR}} = C_n [\Delta T_m + \frac{XMC}{XAC} (\Delta T_{SLP} - \Delta T_m)] \quad (7-85)
\]

where

\[ \Delta T_m = \text{changes in coolant inlet temperature} \]
\[ XMC = \text{distance from GP to core mid-place} \]
\[ XAC = \text{distance from GP to ACLP} \]
\[ \Delta T_{SLP} = \text{changes in average structure temperature at ACLP} \]

**Input Requirements:**

\[ C_n = \text{the radial expansion reactivity coefficient, } $/K \]

**7.4.5 Control Rod Driveline Expansion Effect**

Reactivity coefficients need to be provided for the model described below or for any other model suggested by the core design.

\[
\rho^{CR} = C^{CR} (\Delta Z_{cr} - \Delta Z_{av}) \quad (7-86)
\]

where $\Delta Z_{cr}$ and $\Delta Z_{av}$ are the changes in CRDL and reactor vessel height, respectively.

**Input Requirements:**

\[ C^{CR} = \text{CRDL expansion reactivity coefficient in } \Delta k / k \text{ per m} \]
7.5 Flowcharts

Figure 7.9 shows the modularized structure of the reactivity feedback subroutines of SSC-K. Each box contains subroutine names, which are underlined, and a brief description of their functions. All subroutines shown in the figure are implemented into the SSC-K code except for GEM5T which will be developed for the analysis of gas expansion modules in the core.

7.6 GEM Model

Gas Expansion Modules (GEMs) are added to KALIMER core in order to supplement the negative reactivity feedback that develops once the primary pump has been tripped. When the pumps trip and the pressure drops, the sodium within the GEMs at the active core elevation is displaced by Helium gas, thus increasing the leakage of neutrons from the core and subtracting about [TBD] cents of reactivity, assuming all 6 GEMs function properly.

The GEM is essentially an empty hexagonal cross section duct, sealed at the top, open at the bottom and connected to the high pressure in the inlet plenum of the core as shown in Fig. 7.7. When the pumps are at full flow, the plenum pressure compresses the gas in the GEM cavity. When the flow decreases, the trapped Helium expands and drops the sodium level into the core region. As a result, fewer neutrons are scattered back into the core region. The reactivity effect increases as the gas expands into the core and remains constant once the gas liquid interface drops below the core region.

The objective of this study is to develop a simple model for the analysis of the reactivity effects introduced by the GEM, and to identify the areas of further improvement.

7.6.1 Current GEM Model

In order to calculate the sodium level in the GEM, the following equations are solved. As shown in Fig. 7.8, the total length of GEM is occupied by the Helium gas and primary sodium as

\[ h_s + h_i = h_t \]  

(7-87)
where

\[ h_g = \text{axial length of Helium gas in GEM, m} \]
\[ h_i = \text{axial length of sodium in GEM, m} \]
\[ h_t = \text{total axial length of GEM, m} \]

Since there is no sodium flow through the GEM, the pressure of sodium at the core inlet plenum can be expressed as

\[ P_g + \rho g h_i = P_i \quad (7-88) \]

where

\[ P_g = \text{GEM gas pressure, Pa} \]
\[ P_i = \text{pressure of sodium at core inlet plenum, Pa} \]
\[ = (\text{pressure of sodium at bottom of core}) \]
\[ - (\text{gravitational pressure drop along the orifice inlet zone}) \]
\[ \rho = \text{average density of sodium in GEM, kg/m}^3 \]
\[ g = \text{gravity, m/s}^2 \]

The equation of state for ideal gas is applied for the Helium gas in the GEM as

\[ P_g A h_g = \left( \frac{M_g}{W_g} \right) R T_g \quad (7-89) \]

where

\[ A = \text{cross sectional area of GEM, m}^2 \]
\[ M_g = \text{mass of Helium gas in GEM, kg} \]
\[ W_g = \text{molecular weight of Helium gas, kg/mole} \]
\[ R = \text{universal gas constant, J/K mole} \]
\[ T_g = \text{temperature of Helium gas in GEM, K} \]

Unknowns in the Eqs. (7-87) to (7-89) are \( h_g, h_i, \) and \( P_g \).
The average density of sodium in GEM, $\rho$, is assumed to be the density corresponding to the average temperature of sodium in adjacent subassemblies.

The gas temperature, $T_g$, closely follows the GEM duct temperature which is determined by considering the heat transfer between the neighboring subassemblies and the GEM. For simplicity, the gas temperature is assumed to be the average of the temperatures of duct walls of adjacent subassemblies.

Equations (7-87) to (7-89) can be rearranged to give a quadratic equation for the axial length of Helium gas in GEM, $h_g$, which is calculated at each time step. The worth of the GEMs when the sodium level is equal to, or greater than, the top of the core is zero. When the level reaches the bottom of the core, the maximum worth of GEM is inserted. Intermediate values of reactivity are interpolated linearly from the sodium level in the GEMs.

Subroutine GEM5T of SSC-K code has been developed to calculate the level of sodium inside GEM and the negative reactivity inserted. GEM5T is called by REAC5T which drives the overall reactivity calculations.

7.6.2 GEM Model Improvement

A GEM model, which will be used for the analysis of LOF accident, has been developed for SSC-K code, and reasonable results have been obtained through test runs. Due to the lack of detailed design data, including dimensions, sodium levels at various operating regimes, mass of Helium gas inside GEM, and GEM reactivity worth as a function of sodium level, a simplified model was developed first in order to study the effectiveness of GEM under LOF accident conditions.

Following are the items which need further work for the current GEM model:

- Currently the sodium density inside the GEM is assumed to be the axial average of the neighboring channels. Sensitivity study is needed to investigate the effect of sodium density on the sodium level. If needed, the GEM model will be modified so that the axial sodium density is calculated considering inter-assembly heat transfer.
The temperature of the GEM gas is assumed to the average of the structural temperature of neighboring channels. Improvement of the current GEM model can be achieved by calculating the GEM gas temperature as

\[ c_p \, M_e \, \frac{dT_e}{dt} = Q \]  

(7-90)

where

\[ c_p = \text{Specific heat of GEM gas, J/kg*K} \]
\[ Q = \text{Heat from conduction from neighboring channels, watts} \]

In addition to the model improvement described above, more detailed design data are essential for the analysis of GEM effect.

- GEM worth curve: sodium level vs reactivity
- Sodium level at various operating regimes
- Mass of GEM gas

The effect of primary pump coastdown can be investigated and generate the requirements for the coastdown.
Fig. 7.1 Overall Scheme for Calculating Total Reactor Core Power
Fig. 7.2 Components of Reactivity Feedback Effect
Fig. 7.3 Schematic of Core Layout for Reactivity Model Development
<table>
<thead>
<tr>
<th>Driver Fuel</th>
<th>Internal Blanket</th>
<th>Radial Blanket</th>
<th>Control</th>
<th>Reflector</th>
<th>Shield IVS</th>
<th>Hot Fuel</th>
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<td></td>
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</tr>
<tr>
<td>Active Region</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower Shielding</td>
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<td></td>
</tr>
</tbody>
</table>

Fig. 7.4  SSC-K Representation of Core Subassemblies
Fig. 7.5  SSC-K Representation of Fuel Rod
Fig. 7.6 Typical Core Restraint System
Fig. 7.7 GEM Operation Scheme
Fig. 7.8  Schematic for GEM Model Development
Fig. 7.9  Flow Diagram of Reactivity Feedback Calculation for SSC-K
8. CONSTITUTIVE LAWS AND CORRELATIONS

A number of constitutive laws and correlations are required in order to execute the SSC code. The collection or part of these data may be overwritten by the user. This section describes collections of data that have been approached based on providing the best available data into the code. The entire has been incorporated so far. All of the correlations and numerical values used are in SI units.

8.1 Constitutive Laws

The required thermo-physical and transport properties for all of the materials of interest are provided for in the form of correlations. Reasonable values for the coefficients in these correlations are provided in SI units. These values may be changed by the user through input cards. Various constitutive laws are grouped according to materials.

8.1.1 SSC-L Properties

8.1.1.1 Core and Blanket Fuel

**Thermal Conductivity (W/m K)**

The thermal conductivity of mixed oxide [8-1] core (UO₂-20 w/o PuO₂) and blanket (oxide) materials is given by the following relation:

\[
K(T, P) = \frac{k_5(1 - P)}{1 + (k_4 + k_3 P)P} \frac{1}{k_1 + k_2 T^3 + k_4 T^2}
\]  

(8-1)

Where typical values for \(k_0, k_1, k_2, k_3, k_4\) and \(k_5\) are noted in Table 8-1, and \(P\) is the fractional porosity (= 1 - fractional density).

**Specific Heat Capacity (J/ kg K)**
The specific heat capacity of mixed-oxide [8-2] core and blanket materials is given by the following relations:

\[ c_p(T) = c_0 \left[ 1 + c_1 T + c_2 T^2 + c_3 T^3 + \frac{c_6}{T^2} \right] \]  
for  \( T < T_1 \)  \( (8-2) \)

\[ c_p(T) = c_p(T_1) + \frac{c_p(T_2) - c_p(T_1)}{T_2 - T_1} (T - T_1) \]  
for  \( T_1 < T \leq T_2 \)  \( (8-3) \)

\[ c_p(T) = c_4 + c_5 T \]  
for  \( T > T_2 \)  \( (8-4) \)

where values of various parameters are noted in Table 8-1, and

\[ c_p(T_1) = c_0 \left[ 1 + c_1 T_1 + c_2 T_1^2 + c_3 T_1^3 \right] \]  \( (8-5) \)

and

\[ c_p(T_2) = c_4 + c_5 T_2 \]  \( (8-6) \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fuel material</th>
<th>Blanket material</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_0 )</td>
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<td>113.3</td>
</tr>
<tr>
<td>( k_1 )</td>
<td>0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>( k_2 )</td>
<td>0.02935</td>
<td>0.02935</td>
</tr>
<tr>
<td>( k_3 )</td>
<td>6.600*10^{-13}</td>
<td>6.60*10^{-13}</td>
</tr>
<tr>
<td>( k_4 )</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( k_5 )</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>P</td>
<td>input</td>
<td>input</td>
</tr>
<tr>
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<td>194.319</td>
</tr>
<tr>
<td>( C_1 )</td>
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<td>1.3557*10^{-3}</td>
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<tr>
<td>( C_2 )</td>
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<td>-9.3301*10^{-7}</td>
</tr>
<tr>
<td>( C_3 )</td>
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<td>2.4482*10^{-10}</td>
</tr>
<tr>
<td>( C_4 )</td>
<td>502.951</td>
<td>502.951</td>
</tr>
<tr>
<td>( C_5 )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( C_6 )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( T_1 )</td>
<td>3020.0</td>
<td>3020.0</td>
</tr>
<tr>
<td>( T_2 )</td>
<td>3060.0</td>
<td>3060.0</td>
</tr>
</tbody>
</table>
Coefficient of Thermal Expansion (m/m K)

The average linear coefficient of thermal expansion from \( T_0 \) to \( T \) for core and blanket materials is represented by the following equation [8-3, 8-4]:

\[
\alpha(T) = \alpha_0 + \alpha_1 T \quad \text{for} \quad T \leq T_3
\] (8-7)

For higher temperatures, the average linear coefficient of thermal expansion is given by the following relation:

\[
\alpha(T) = \alpha_2 \quad \text{for} \quad T \geq T_4
\] (8-8)

For intermediate temperatures,

\[
\alpha(T) = \alpha(T_3) + \left[ \frac{\alpha(T_3) - \alpha(T_4)}{T_4 - T_3} \right] (T - T_3) \quad \text{for} \quad T_3 < T < T_4
\] (8-9)

where

\[
\alpha(T_3) = \alpha_0 + \alpha_1 T_3
\] (8-10)

\[
\alpha(T_4) = \alpha_2
\] (8-11)

and other parameters are noted in Table 8-2

Density (kg/m\(^3\))

The core and blanket fuel materials density is given by the following set of correlations:

\[
\rho(T, P) = \frac{\rho_0(1 - P)}{\left[ 1 + \alpha(T)(T - T_0) \right]^3} \quad \text{for} \quad T_0 \leq T \leq T_3
\] (8-12)
\[ \rho(T, P) = \rho(T_3, P) + \frac{\rho(T_4, P) - \rho(T_3, P)}{T_4 - T_3} (T - T_3) \quad \text{for} \quad T_3 < T \leq T_4 \quad (8-13) \]

\[ \rho(T, P) = \frac{\rho_1}{\left[1 + \alpha(T)(T - T_4)\right]^3} \quad \text{for} \quad T > T_4 \quad (8-14) \]

where \( P \) is the fractional porosity. The above correlations imply that (a) the core fuel density for different restructured regions have the same temperature dependence below fuel solidus temperature \( (T_3) \), and (b) the molten fuel density, i.e., density beyond its liquids temperature \( (T_4) \), does not depend upon its pre-molten fractional density. The following two equations are noted for the sake of clarity:

\[ \rho(T_3, P) = \frac{\rho_0(1 - P)}{\left[1 + \alpha(T_3)(T_3 - T_0)\right]^3} \quad (8-15) \]

\[ \rho(T_4, P) = \rho_1 \quad (8-16) \]

The average linear coefficient of thermal expansion is already noted above; other parameters are noted in Table 8-2.

**Table 8-2**

Parameters in Fuel Coefficient of Thermal Expansion, Density and Emissivity Correlations

<table>
<thead>
<tr>
<th>parameter</th>
<th>Fuel material</th>
<th>Blanket material</th>
</tr>
</thead>
<tbody>
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<td>( a_0 )</td>
<td>( 5.706 \times 10^{-6} )</td>
<td>( 5.7506 \times 10^{-6} )</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>( 2.997 \times 10^{-9} )</td>
<td>( 2.997 \times 10^{-9} )</td>
</tr>
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<td>( a_2 )</td>
<td>( 3.1 \times 10^{-5} )</td>
<td>( 3.1 \times 10^{-5} )</td>
</tr>
<tr>
<td>( T_0 )</td>
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<td>( 295.4 )</td>
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<tr>
<td>( T_3 )</td>
<td>( 3020.0 )</td>
<td>( 3020.0 )</td>
</tr>
<tr>
<td>( T_4 )</td>
<td>( 3060.0 )</td>
<td>( 3060.0 )</td>
</tr>
<tr>
<td>( \rho_0 )</td>
<td>( 11.04 \times 10^3 )</td>
<td>( 10.0 \times 10^3 )</td>
</tr>
<tr>
<td>( \rho_1 )</td>
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<td>( 8.744 \times 10^3 )</td>
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<td>input</td>
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<tr>
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<td>0.75</td>
</tr>
<tr>
<td>( e_1 )</td>
<td>( 5 \times 10^{-5} )</td>
<td>( 5 \times 10^{-5} )</td>
</tr>
<tr>
<td>( T_5 )</td>
<td>400.0</td>
<td>400.0</td>
</tr>
</tbody>
</table>
**Emissivity (Dimensionless)**

The core and blanket material emissivity [8-5] is given by the following correlations:

\[ e = e_0 \quad \text{for} \quad T \leq T_s \]  
\[ e = e_0 + e_1 (T - T_s) \quad \text{for} \quad T > T_s \]  

(8-17) and (8-18)

where \( e_0, e_1 \) and \( T_s \) are given in Table 8-2.

### 8.1.1.2 Cladding and Structural Materials

For stainless steel, the default material for cladding and structure, the thermal conductivity (W/m-k) [8-6], specific heat (J/kg K) [8-6], and the average linear coefficient of thermal expansion (m/m-K) [8-7], are represented by polynomial fits of data. These equations, for temperatures up to melting point, are given by the following:

\[ k(T) = k_0 + k_1 T + k_2 T^2 + k_3 T^3 \]  
\[ c_p(T) = c_{p0} + c_{p1} T + c_{p2} T^2 + c_{p3} T^3 \]  
\[ \alpha(T) = \alpha_0 + \alpha_1 T + \alpha_2 T^2 \]  

(8-19) and (8-20) and (8-21)

where values for various parameters for both cladding and structural materials are noted in Table 8-3. The structural or cladding material density is related to the average thermal coefficient of linear expansion as follows:

\[ \frac{\rho(T)}{\rho_0} = \frac{1}{[1 + \alpha(T)(T - T_0)]^3} \]  

(8-22)
where \( \rho_0 \) is the density at temperature \( T_0 \).

The cladding and structural emissivity [8-8] are given by the following relations:

\[
e = e_0 \quad \text{for } T \leq T_i
\]

and

\[
e = e_0 + e_1 (T - T_i) \quad \text{for } T > T_i
\]  

(8-23)

(8-24)

where values for \( e_0 \), \( e_1 \) and \( T_i \) are also noted in Table 8-3.

<table>
<thead>
<tr>
<th>Parameter</th>
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8.1.2 Constitutive Laws for SSC-K

8.1.2.1 Metal Fuel Properties

Original SSC-L code has a collection of thermo-physical and transport properties for
selected materials, however, additional properties are necessary for materials which will be used for KALIMER design. Table shows properties which are provided in the SSC-K code:
E denotes properties which are in the original code, and N denotes newly added properties.

<table>
<thead>
<tr>
<th></th>
<th>UO$_2$-2O w/o PuO$_2$</th>
<th>U-Zr-Pu</th>
<th>Stainless steel</th>
<th>HT9</th>
<th>Modified Subroutines</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$, W/m K</td>
<td>E</td>
<td>N</td>
<td>E</td>
<td>N</td>
<td>gama5s, gama5t, stem5s</td>
</tr>
<tr>
<td>$C_p$, J/kg K</td>
<td>E</td>
<td>N</td>
<td>E</td>
<td></td>
<td>prop5t</td>
</tr>
<tr>
<td>$\alpha$, m/m K</td>
<td>E</td>
<td>N</td>
<td>E</td>
<td>N</td>
<td>alfa5s, prop5t</td>
</tr>
<tr>
<td>$\rho$, kg/m$^3$</td>
<td>E</td>
<td>N</td>
<td>E</td>
<td>N</td>
<td>prop5t</td>
</tr>
<tr>
<td>E</td>
<td>E</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Detailed description of changes is summarized below:

- Equations with fixed coefficients are inserted in the subroutines, and input parameters are dummies.
- For general material types, input requirements and block data need to be modified.

**Thermal Conductivity**

<table>
<thead>
<tr>
<th>Material (ID)</th>
<th>Parameter</th>
<th>Subroutine</th>
<th>Thermal Conductivity Parameter</th>
<th>Subroutine</th>
<th>Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanket (40-49)</td>
<td>C4K0 ~ C4K → C5KF</td>
<td>CALC7R</td>
<td>COND5K</td>
<td>GAMA5S GAMA5T STEM5S</td>
<td>MOX → U-Pu-Z</td>
</tr>
<tr>
<td>Fuel (50-59)</td>
<td>C5K0 ~ C5K → C5KF</td>
<td>-</td>
<td>COND5K</td>
<td>GAMA5S GAMA5T STEM5S</td>
<td>MOX → U-Pu-Z</td>
</tr>
<tr>
<td>Clad (60-69)</td>
<td>C6K0 ~ C6K → C6KF</td>
<td>-</td>
<td>COND6K</td>
<td>GAMA5S GAMA5T STEM5S</td>
<td>SS → HT9</td>
</tr>
<tr>
<td>Structure (70-79)</td>
<td>C7K0 ~ C7K → C7KF</td>
<td>-</td>
<td>COND7K</td>
<td>GAMA5T STEM5S</td>
<td>SS → HT9</td>
</tr>
</tbody>
</table>

8-7
## Specific Heat Capacity

<table>
<thead>
<tr>
<th>Material (ID)</th>
<th>Input Parameter</th>
<th>Subroutine</th>
<th>Specific heat Parameter</th>
<th>Subroutine</th>
<th>Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanket (40-49)</td>
<td>C4C0, C4CT2 → C5CF</td>
<td>CALC7R</td>
<td>HCAP5C</td>
<td>PROP5T</td>
<td>MOX → U-Pu-Z</td>
</tr>
<tr>
<td>Fuel (50-59)</td>
<td>C5C0, C5CT2 → C5CF</td>
<td>&quot;</td>
<td>HCAP5C</td>
<td>PROP5T</td>
<td>MOX → U-Pu-Z</td>
</tr>
<tr>
<td>Clad (60-69)</td>
<td>C6C0 ~ C6C → C6CF</td>
<td>&quot;</td>
<td>HCAP6C</td>
<td>PROP5T</td>
<td>(SS → HT9)</td>
</tr>
<tr>
<td>Structure (70-79)</td>
<td>C7C0 ~ C7C → C7CF</td>
<td>&quot;</td>
<td>HCAP7C</td>
<td>PROP5T</td>
<td>(SS → HT9)</td>
</tr>
</tbody>
</table>

## Thermal Expansion Coefficient

<table>
<thead>
<tr>
<th>Material (ID)</th>
<th>Input Parameter</th>
<th>Subroutine</th>
<th>Thermal expansion coefficient Parameter</th>
<th>Subroutine</th>
<th>Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanket (40-49)</td>
<td>C4A0, C4AT2 → C5AF</td>
<td>CALC7R</td>
<td>ALFA5A</td>
<td>ALFA5S, PROP5T, GROW5T</td>
<td>MOX → U-Pu-Z</td>
</tr>
<tr>
<td>Fuel (50-59)</td>
<td>C5A0, C5AT2 → C5AF</td>
<td>&quot;</td>
<td>ALFA5A</td>
<td>ALFA5S, PROP5T, GROW5T</td>
<td>MOX → U-Pu-Z</td>
</tr>
<tr>
<td>Clad (60-69)</td>
<td>C6A0, C6AT1 → C6AF</td>
<td>&quot;</td>
<td>ALFA6A</td>
<td>ALFA5S, PROP5T, GROW5T</td>
<td>SS → HT9</td>
</tr>
<tr>
<td>Structure (70-79)</td>
<td>C7A0 ~ C7A → C7AF</td>
<td>&quot;</td>
<td>ALFA7A</td>
<td>ALFA5S, PROP5T</td>
<td>SS → HT9</td>
</tr>
</tbody>
</table>

- Note that functions TEXFUEL and TEXCLAD, which were used in subroutine GROW5T for fuel rod expansion, have been replaced by the relations given in subroutines ALFA5S and PROP5T.
Density

<table>
<thead>
<tr>
<th>Material (ID)</th>
<th>Parameter</th>
<th>Subroutine</th>
<th>Parameter</th>
<th>Subroutine</th>
<th>Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanket (40-49)</td>
<td>C4D0 ~ C4D</td>
<td>CALC7R</td>
<td>DENS5D</td>
<td>PROP5T</td>
<td>MOX → U-Pu-Z</td>
</tr>
<tr>
<td></td>
<td>C5D0 ~ C5D</td>
<td>C5DF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel (50-59)</td>
<td></td>
<td></td>
<td>DENS5D</td>
<td>PROP5T</td>
<td>MOX → U-Pu-Z</td>
</tr>
<tr>
<td>Clad (60-69)</td>
<td>C6D0</td>
<td></td>
<td>DENS6D</td>
<td>PROP5T</td>
<td>SS → HT9</td>
</tr>
<tr>
<td></td>
<td>C6DF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure (70-79)</td>
<td>C7DT0</td>
<td></td>
<td>DENS7D</td>
<td>PROP5T</td>
<td>SS → HT9</td>
</tr>
<tr>
<td></td>
<td>C7D0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C7DF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thermal Conductivity of U-Zr-Pu Alloys (Unirradiated) [8-9]

\[
 k_0 = A + BT + CT^2
\]  
(8-25)

where

\[
k_0 = \text{thermal conductivity, W/m K}
\]

\[
A = 17.5 \left[ \frac{1 - 2.23W_z}{1 + 1.61W_z} - 2.62W_p \right]
\]  
(8-26)

\[
B = 1.54 \times 10^{-2} \left[ \frac{1 + 0.061W_z + 0.90W_p}{1 + 1.61W_z} \right]
\]  
(8-27)

\[
C = 9.38 \times 10^{-5} (1 - 2.70W_p)
\]  
(8-28)

\[
W_z = \text{Zr weight fraction}
\]

\[
W_p = \text{Pu weight fraction}
\]

and

\[
T = \text{temperature, K}
\]

For design calculations, an uncertainty of 20% is recommended.
Thermal Conductivity of U-Zr-Pu Alloys (Irradiated) [8-9]

\[ f_p = \frac{k}{k_0} = \frac{(1 - P)}{(1 + \beta P)} \]  

(8-29)

where \( P \) = porosity fraction referenced to initial fuel volume and \( \beta = 1.7 \)

The minimum value of \( f_p \) is taken as 0.5 \( \pm \) 0.1 and the long-time value is 0.7 \( \pm \) 0.1 to reflect the influence of sodium logging and fuel hot pressing. For design purposes an uncertainty of \( \pm 32\% \) is recommended after porosity interlinkage.

Specific Heat of U-Zr-Pu Alloys [8-10]

\[ C_p = \left[ 1.359 + 0.05812T + 1.086 \times 10^6 T^{-2} \right] \left( 238 \times 10^{-3} \right) \]  

(8-30)

where

\[ C_p = \text{specific heat capacity for U-10 wt \% Zr, J/kg K} \]

\[ T = \text{temperature, K} \]

Linear Thermal Expansion Coefficient of U-Zr-Pu Alloys [8-11]

\[ \alpha_t = \frac{1}{\Delta L} \left( \frac{L - L_0}{L_0 (T - T_0)} \right) = \left( \frac{\Delta L}{L_0} \right) \left( \frac{1}{T - T_0} \right) = \left( \frac{\Delta L}{L_0} \right) \frac{1}{T - 293} \]  

(8-31)

where

\[ \alpha_t = \text{linear thermal expansion coefficient of U-10 wt \% Zr, m/m K} \]

\[ \frac{\Delta L}{L_0} = 0.01 \times \left[ -0.424 + (1.658 \times 10^{-3} T) - (1.052 \times 10^{-6} T^2) + (1.115 \times 10^{-9} T^3) \right] \]  

(8-32)

for \( 293 \leq T \leq 900K \) .
Density of U-Zr-Pu Alloys:

\[ \rho = (16.02 \times 10^3) \times \left[ 1.0122 - (4.629 \times 10^{-3} T) + (2.438 \times 10^{-4} T^2) - (2.805 \times 10^{-11} T^3) \right] \]  

for \( 293 \leq T \leq 900 \)K

where \( \rho \) = density of U-10 wt % Zr, kg/m\(^3\)

**Thermal Conductivity of HT9 [8-12]**

\[ k = 29.65 - 6.668 \times 10^{-2} T + 2.184 \times 10^{-4} T^2 - 2.527 \times 10^{-7} T^3 + 9.621 \times 10^{-11} T^4 \]  

where \( k \) = thermal conductivity, W/m K

\( T \) = temperature, K.

**Thermal Expansion of HT9 [8-13]**

\[ \alpha_i = \frac{1}{L_0} \left( \frac{L - L_0}{T - T_0} \right) = \left( \frac{\Delta L}{L_0} \right) \left( \frac{1}{T - T_0} \right) = \left( \frac{\Delta L}{L_0} \right) \frac{1}{T - 293} \]  

where

\( \alpha_i \) = linear thermal expansion coefficient of HT9, m/m K

\[ \frac{\Delta L}{L_0} = 0.01 \times \left[ -0.16256 + (1.62307 \times 10^{-4} T) + (1.42357 \times 10^{-6} T^2) - (5.50344 \times 10^{-10} T^3) \right] \]  

for \( 293 \leq T \leq 1050 \)K

**Density of HT9 [8-14]**

\[ \rho = \left[ 7.778 - 3.07 \times 10^{-4} (T - 273) \right] \times 10^3 \]  

for \( 273 \leq T \leq 1073 \)K
8.1.2.2 Limitations and Future Work

- For the heat transfer coefficient of fuel-clad gap, the contact resistance $h_g$ of input Vessel 20 is used in subroutines gama5s and gama5t whether the metal fuel contacts cladding inner surface or not. This is a reasonable assumption since the metal fuel swells rapidly by irradiation and contacts the clad inner surface at about 2 a/o burnup. There is a need to check the radial fuel expansion.

- Material properties of control rod are necessary for the calculation of the reactivity feedback effects in subroutine crdl5t which needs to be updated.

- A set of material properties data is built into the code. The data required to alter the default values of the material properties provided within SSC-K, or to create new material properties, are input to the code through input records MATDAT 10-19 for sodium, 40-49 for blanket, 50-59 for fuel, 60-69 for cladding, and 70-79 for structural materials. (cf. SSC-L manual Sections 5.1 and 7.7) Temporarily, equations for thermal conductivity, specific heat, linear thermal expansion coefficient, and density of U-Zr-Pu and HT9 are implemented in the subroutines, and hence related coefficients in MATDAT records are dummies.

- With the update of SSC-K input file using the most up-to-date KALIMER design data, a code-to-code comparison with a core T-H design code for the in-core heat transfer would provide confidence in the SSC-K predictions.

- Friction factor and heat transfer correlations for rod bundles also need to be reviewed in comparison with the core T-H design for consistency in in-core heat transfer analysis.

8.1.3 Control Rod Material

For the control rod material (born carbide), the thermal conductivity (W/mK), the specific heat (J/kgK), the average linear thermal coefficient of expansion (m/mK), and the density (kg/m$^3$) are represented by polynomial fits [8-15]. These equations are:

\[
\text{where } \rho = \text{density, kg/m}^3 \\
T = \text{temperature, K}
\]
\[ k(T) = \frac{k_0 (1 - P)}{1 + k_4 P} \frac{1}{k_1 + k_2 T} \]  
(8-38)

\[ c_p(T) = c_o \left(1 + c_1 T + c_6 / T^2 \right) \]  
(8-39)

\[ \overline{\alpha}(T) = \alpha_o + \alpha_1 T \]  
(8-40)

and

\[ \rho(T) = \frac{\rho_o (1 - P)}{\left[1 + \overline{\alpha}(T)(T - T_o)\right]^3} \]  
(8-41)

These equations are similar in form to Equations (8-1), (8-2), (8-7) and (8-12), respectively. Values for the various parameters are noted in Table 8-4, and \( P \) is the porosity, which is an input quantity read in with the control rod geometric data. These correlations are valid in the temperature range from 500 K to 1250 K.

8.1.4 Sodium

All of the required thermo-physical properties for liquid sodium and sodium vapor are taken from Golden and Tokar [8-16]. These are noted as follows:

**Thermal Conductivity (W/mK)**

The thermal conductivity of liquid sodium is given by the following equation:

\[ k(T) = k_o + k_1 T + k_2 T^2 \]  
(8-42)

where

\[ k_o = 109.7 \]  

\[ k_1 = -6.4499 \times 10^{-2} \]  

\[ k_2 = 1.1728 \times 10^{-5} \]  

8-13
Specific Heat Capacity (J/gK)

The specific heat capacity at constant pressure for liquid sodium is given by

\[ c_p(T) = c_0 + c_1 T + c_2 T^2 \]  

(8-43)

where

\[ c_0 = 1630.22, \]
\[ c_1 = -0.83354, \]
\[ c_2 = 4.62838 \times 10^{-4}. \]

Table 8-4
Parameters for Control Rod Material Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_0</td>
<td>334.13</td>
</tr>
<tr>
<td>K_1</td>
<td>21.6178</td>
</tr>
<tr>
<td>K_2</td>
<td>0.05381</td>
</tr>
<tr>
<td>K_3</td>
<td>0.0</td>
</tr>
<tr>
<td>K_4</td>
<td>2.2</td>
</tr>
<tr>
<td>K_5</td>
<td>0.0</td>
</tr>
<tr>
<td>C_0</td>
<td>1741.79</td>
</tr>
<tr>
<td>C_1</td>
<td>2.34856 \times 10^{-4}</td>
</tr>
<tr>
<td>C_2</td>
<td>0.0</td>
</tr>
<tr>
<td>C_3</td>
<td>0.0</td>
</tr>
<tr>
<td>C_4</td>
<td>0.0</td>
</tr>
<tr>
<td>C_5</td>
<td>0.0</td>
</tr>
<tr>
<td>C_6</td>
<td>-46,634.7</td>
</tr>
<tr>
<td>a_0</td>
<td>-1.4886 \times 10^{-3}</td>
</tr>
<tr>
<td>a_1</td>
<td>4.124 \times 10^{-6}</td>
</tr>
<tr>
<td>P_0</td>
<td>2381.0</td>
</tr>
<tr>
<td>T_0</td>
<td>295.4</td>
</tr>
</tbody>
</table>

Enthalpy (J/kg)

The enthalpy of saturated liquid sodium is given by

\[ h_s(T) = h_0 + h_1 T + h_2 T^2 + h_3 T^3 \]  

(8-44)
where
\[
\begin{align*}
h_0 &= -6.7511 \times 10^4 \\
h_1 &= 1630.22, \\
h_2 &= -0.41674, \\
h_3 &= 1.54279 \times 10^{-4}.
\end{align*}
\]

For unsaturated liquid sodium, the enthalpy is written as
\[
h = h_s - \frac{P_s}{\rho_s} + \frac{P}{\rho},
\]
(8-45)

where the saturation vapor pressure \(P_s\) and the liquid sodium density \(\rho_s\) are given in the following equations. For incompressible sodium,
\[
\rho(T, P_s) = \rho(T) = \rho_s(T); \\
\]
hence, Equation (8-45) becomes
\[
h = h_s - \frac{P_s - P}{\rho}
\]
(8-46)

For most purposes, the liquid sodium enthalpy may be approximated by the saturation value.

In SSC-K we also need to compute liquid sodium temperature from its enthalpy value. Although it is computed iteratively in the code by inverting Eq. (8-44), an approximate correlation is given by the following:
\[
T = c_0 + c_1 h + c_2 h^2 + c_3 h^3 + c_4 h^4
\]
(8-47)

where
\[
\begin{align*}
c_0 &= 55.5057, \\
c_1 &= 5.56961 \times 10^{-4}, \\
c_2 &= 2.17341 \times 10^{-10}, \\
c_3 &= -7.27069 \times 10^{-17},
\end{align*}
\]

and
Saturation Vapor Pressure (Pa or N/m²)

The saturation vapor pressure of sodium is expressed by the following two equations:

\[ \log_{10} p_s = p_1 + p_2/T + p_3 \log_{10} T \quad \text{for } T \leq T_1 \quad (8-48) \]

and

\[ \log_{10} p_s = p_4 + p_5/T + p_6 \log_{10} T \quad \text{for } T > T_1 \quad (8-49) \]

where

\[ p_1 = 11.35977 \]
\[ p_2 = -5567.0 \]
\[ p_3 = -0.5 \]
\[ p_4 = 11.68672 \]
\[ p_5 = -5544.97 \]
\[ p_6 = -0.61344 \]

and

\[ T_1 = 1144.2 \]

The saturation temperature of liquid sodium as a function of pressure is given by the following equation [8-17]:

\[ T_s = -\frac{C_0}{\ln(9.869 \times 10^{-6} p) - c_1} \quad (8-50) \]

where

\[ C_0 = 1213.0 \]
\[ C_1 = 10.51 \]

and \( P \) is the pressure in N/m².

Density (kg/m³)

The density of saturated liquid sodium is given by the following relation:

\[ p_s(T) = \rho_0 + \rho_1 T + \rho_2 T^2 + \rho_3 T^3 \quad \text{for } T_1 \leq T \leq T_2 \quad (8-51) \]

where,
\[
\rho_s = 1011.597, \\
\rho_1 = -0.22051, \\
\rho_2 = -1.92243 \times 10^{-5}, \\
\rho_3 = 5.63769 \times 10^{-2}, \\
T_1 = 370.9, \\
\]

\[
T_2 = 1644.2.
\]

The density of unsaturated liquid sodium is related to that of saturated liquid through a compressibility factor (\( \beta_T \)), as follows:

\[
\rho(T, P) = \rho_s(T) \exp[\beta_T(p - p_s)] (8-52)
\]

where \( \rho_s(T) \) is given by Equation (8-51) and \( P_s \) is given by Equations (8-48) or (8-49). If incompressibility is assumed, \( \beta_T = 0 \). Hence,

\[
\rho(t, p) = \rho(T) = \rho_s(T) (8-53)
\]

**Dynamic Viscosity (Pl, i.e., N s/m²)**

The dynamic viscosity of liquid sodium is represented as

\[
\log_{10} \eta = c_1 + \frac{c_2}{T} + c_3 \log_{10} T (8-54)
\]

where

\[
c_1 = -2.4892, \\
c_2 = 220.65, \\
c_3 = -0.4925.
\]

**Heat of Vaporization (J/kg)**

The heat of vaporization, fitted over the range 1150 to 1500 K is given by the following equation [8-17]:

8-17
\[ \lambda(T) = \lambda_0 + \lambda_1 T + \lambda_2 T^2 \quad (8-55) \]

where

\[ \lambda_0 = 4.40241 \times 10^6, \]
\[ \lambda_1 = -17.5055, \]
\[ \lambda_2 = -0.380184. \]

**Specific Heat Capacity (J/kg K)**

The specific heat capacity at constant pressure for sodium vapor was fitted over the range 1150 to 1500 K, and is given by the equation [8-17]:

\[ c_p(T) = c_0 + c_1 T + c_2 T^2 \quad (8-56) \]

where

\[ c_0 = 4.4015 \times 10^3, \]
\[ c_1 = -2.2987, \]
\[ c_2 = 6.347 \times 10^{-4}. \]

**Density (kg/m^3)**

The density of sodium vapor is given by the following equation:

\[ \rho_v = \frac{p A(T)}{T} \quad (8-57) \]

in which the factor A(T) was fitted over the range 1150 to 1600 K and is given by the equation [8-17]:

\[ A(T) = a_0 + a_1 T + a_2 T^2 \quad (8-58) \]

where
\[ a_0 = 3.27317 \times 10^{-3}, \]
\[ a_1 = -8.72393 \times 10^{-7}, \]
\[ a_2 = 6.07353 \times 10^{-10}. \]

**Enthalpy (J/kg)**

At a given reference pressure \( p \), the sodium saturation temperature \( T_s \) is first calculated. The liquid saturation enthalpy \( h_l(T_s) \) and heat of vaporization \( \lambda(T_s) \) are then calculated. The vapor enthalpy is then given by the equation

\[
h_v(T) = h_l(T_s) + \lambda(T_s) + h_{v1}(T-T_s) + h_{v2}(T-T_s)^2 + h_{v3}(T-T_s)^3
\]  
(8-59)

where

\[
h_{v1} = 4.4015 \times 10^3, \]
\[ h_{v2} = -1.14935, \]
\[ h_{v3} = 2.11567 \times 10^{-4}, \]

\( \lambda(T_s) \) is given by Eq.(8-55), and \( h_l(T_s) \) is given by Eq.(8-44).

**8.1.5 Water and Steam**

The constitutive relations for water are currently given by correlations where the properties are evaluated as a function of enthalpy (H) and pressure (P) [8-18].

**Enthalpy of Saturated Liquid (J/kg)**

The enthalpy of saturated water is given by

\[
H_l(p) = a_0 + a_1 p + a_2 p^2 + a_3 p^3 + a_4 p^4 + a_5 p^5
\]  
(8-60)

where
\[ a_0 = 5.7474 \times 10^5, \]
\[ a_1 = 2.09206 \times 10^{-1}, \]
\[ a_2 = -2.8051 \times 10^{-8}, \]
\[ a_3 = 2.38098 \times 10^{-15}, \]
\[ a_4 = -1.0042 \times 10^{-22}, \]
\[ a_5 = 1.6587 \times 10^{-30}, \]

and \( P \) is pressure in N/m\(^2\).

**Enthalpy of Saturated Vapor**

The enthalpy of saturated steam is given by

\[ H(p) = b_0 + b_1 p + b_2 p^2 + b_3 p^3 + b_4 p^4 \quad (8-61) \]

where

\[ b_0 = 2.7396 \times 10^6, \]
\[ b_1 = 3.7588 \times 10^{-2}, \]
\[ b_2 = -7.1640 \times 10^9, \]
\[ b_3 = 4.2002 \times 10^{-16}, \]
\[ b_4 = -9.8507 \times 10^{-24}. \]

**Temperature of Compressed Liquid (K)**

The temperature of compressed liquid is given by

\[ T(H, p) = c_0(p) + c_1(p)H + c_2(p)H^2 + c_3(p)H^3 \quad (8-62) \]

where

\[ c_0(p) = c_{00} + c_{01}p, \]
\[ c_1(p) = c_{10} + c_{11}p, \]
\[ c_2(p) = c_{20} + c_{21}p, \]
\[ c_3(p) = c_{30} + c_{31}p, \]

and the coefficients \( c_{ij} \) are given in Table 8-5.
Temperature of Superheated Vapor (K)

The temperature of superheated steam is given by

\[ T(H, p) = d_0(p) + d_1(p)H + d_2(p)H^2 \]  \hspace{1cm} (8-63)

where

\[ d_0(p) = d_{00} + d_{01}p + d_{02}p^2, \]
\[ d_1(p) = d_{10} + d_{11}p + d_{12}p^2, \]
\[ d_2(p) = d_{20} + d_{21}p + d_{22}p^2, \]

and the coefficients \(d_i\) are given in Table 8-6.

Density of Compressed Liquid (kg/m\(^3\))

The density of compressed water is given by

\[ D(H, p) = f_1 + f_2H + f_3H^2 + f_4H^3 + f_5H^4, \quad \text{for } H \leq 6.513 \times 10^5 \text{ J/kg} \]  \hspace{1cm} (8-64)

\[ D(H, p) = f_4 + \frac{f_5}{H - f_6}, \quad \text{for } H > 6.513 \times 10^5 \text{ J/kg} \]  \hspace{1cm} (8-65)

The coefficients \(f_i\) are given in Table 8-7.
### Table 8-5
Values of Coefficients for Temperature of Compressed Liquid Water

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{00}$</td>
<td>$2.7291 \times 10^2$</td>
</tr>
<tr>
<td>$C_{01}$</td>
<td>$-1.5954 \times 10^7$</td>
</tr>
<tr>
<td>$C_{10}$</td>
<td>$2.3949 \times 10^4$</td>
</tr>
<tr>
<td>$C_{11}$</td>
<td>$-5.1963 \times 10^{-13}$</td>
</tr>
<tr>
<td>$C_{20}$</td>
<td>$5.9660 \times 10^{-12}$</td>
</tr>
<tr>
<td>$C_{21}$</td>
<td>$1.2064 \times 10^{-18}$</td>
</tr>
<tr>
<td>$C_{30}$</td>
<td>$-1.3147 \times 10^{-17}$</td>
</tr>
<tr>
<td>$C_{31}$</td>
<td>$-5.6026 \times 10^{-25}$</td>
</tr>
</tbody>
</table>

### Table 8-6
Values of Coefficients for Temperature of Compressed Water Vapor

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{00}$</td>
<td>$6.5659 \times 10^{-2}$</td>
</tr>
<tr>
<td>$d_{10}$</td>
<td>$-5.2569 \times 10^{-4}$</td>
</tr>
<tr>
<td>$d_{20}$</td>
<td>$1.6221 \times 10^{-10}$</td>
</tr>
<tr>
<td>$d_{01}$</td>
<td>$9.9066 \times 10^{-5}$</td>
</tr>
<tr>
<td>$d_{11}$</td>
<td>$-3.4406 \times 10^{-11}$</td>
</tr>
<tr>
<td>$d_{21}$</td>
<td>$1.8674 \times 10^{-18}$</td>
</tr>
<tr>
<td>$d_{02}$</td>
<td>$-2.1879 \times 10^{-12}$</td>
</tr>
<tr>
<td>$d_{22}$</td>
<td>$7.0081 \times 10^{-19}$</td>
</tr>
<tr>
<td>$d_{22}$</td>
<td>$-1.4567 \times 10^{-26}$</td>
</tr>
</tbody>
</table>

### Table 8-7
Values of Coefficients for Density of Compressed Liquid Water

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1$</td>
<td>$999.65 + 4.9737 \times 10^{-7} p$</td>
</tr>
<tr>
<td>$f_2$</td>
<td>$-2.5847 \times 10^{-10} + 6.1767 \times 10^{-19} p$</td>
</tr>
<tr>
<td>$f_3$</td>
<td>$1.2696 \times 10^{-22} - 4.9223 \times 10^{-31} p$</td>
</tr>
<tr>
<td>$f_4$</td>
<td>$1488.64 + 1.3389 \times 10^{-6} p$</td>
</tr>
<tr>
<td>$f_5$</td>
<td>$1.4695 \times 10^2 + 8.85736 p$</td>
</tr>
<tr>
<td>$f_6$</td>
<td>$3.20372 \times 10^6 + 1.20483 \times 10^{-2} p$</td>
</tr>
</tbody>
</table>
Density of Superheated Vapor (kg/m³)

The density of superheated steam is given by

\[ D(H, p) = \frac{1}{g_0(p) + g_1(p)H} \]  \hspace{1cm} (8-66)

where

\[ g_0(p) = g_{00} + g_{01}p + \frac{g_{02}}{p}, \]
\[ g_1(p) = g_{10} + g_{11}p + \frac{g_{12}}{p}; \]

and

\[ g_{00} = -5.1026 \times 10^{-5}, \]
\[ g_{01} = 1.1208 \times 10^{-10}, \]
\[ g_{02} = -4.4506 \times 10^{-5}, \]
\[ g_{10} = -1.6893 \times 10^{-10}, \]
\[ g_{11} = -3.3980 \times 10^{-17}, \]
\[ g_{12} = 2.3058 \times 10^{-1}. \]

Specific Heat of Compressed Liquid (J/m³K)

The specific heat of compressed water is given by

\[ c_p(H, p) = \frac{1}{a_0(p) + a_1(p)H + a_2(p)H^2} \]  \hspace{1cm} (8-67)

where

\[ a_0(p) = a_{00} + a_{01}p, \]
\[ a_1(p) = a_{10} + a_{11}p, \]
\[ a_2(p) = a_{20} + a_{21}p; \]

and

\[ a_{00} = 2.3949 \times 10^{-4}, \]
\[ a_{01} = -5.1963 \times 10^{-13}, \]
\[ a_{10} = 1.1932 \times 10^{-11}, \]
\[ a_{11} = 2.4127 \times 10^{-18}, \]
\[ a_{20} = -3.9441 \times 10^{-17}, \]
\[ a_{21} = -1.6808 \times 10^{-24}. \]
Specific Heat of Superheated Vapor (J/m³K)

The specific heat of superheated steam is given by

\[ c_p(H, p) = \frac{1}{b_0(p) + b_1(p)H} \]  

where

\[ b_0(p) = b_{00} + b_{01}p + b_{02}p^2, \]
\[ b_1(p) = b_{10} + b_{11}p + b_{12}p^2; \]

and

\[ b_{00} = -5.2569 \times 10^{-4}, \]
\[ b_{01} = -3.4406 \times 10^{-11}, \]
\[ b_{02} = 7.0081 \times 10^{-19}, \]
\[ b_{10} = 3.2441 \times 10^{-10}, \]
\[ b_{11} = 3.7348 \times 10^{-18}, \]
\[ b_{12} = -2.9134 \times 10^{-26}. \]

Viscosity of Compressed Liquid (Ns/m²)

The viscosity of compressed water is given by

\[ n(H, p) = c_0 + c_1x + c_2x^2 + c_3x^3 + c_4x^4 - (d_0 + d_1E + d_2E^2 + d_3E^3)(p - p_1) \quad H \leq H_1 \]  

\[ n(H, p) = e_0(H) + e_1(H)(p - p_1) \quad H_1 < H < H_2 \]  

\[ n(H, p) = f_0 + f_1x + f_2x^2 + f_3x^3 + f_4x^4 \quad H \geq H_2 \]

where

\[ X = g_0(H - g_1), \]
\[ E = g_2(H - g_1), \]
\[ Z = g_4(H - g_1), \]
\[ e_0(H) = e_{00} + e_{01}H + e_{02}H^2 + e_{03}H^3, \]
\[ e_1(H) = e_{10} + e_{11}H + e_{12}H^2 + e_{13}H^3, \]
and the coefficients are given in Table 8-8.

Table 8-8
Values of Coefficients for Viscosity of Compressed Liquid Water

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_0$</td>
<td>1.2995*10^7</td>
</tr>
<tr>
<td>$C_1$</td>
<td>-9.2640*10^-4</td>
</tr>
<tr>
<td>$C_2$</td>
<td>3.8105*10^-4</td>
</tr>
<tr>
<td>$C_3$</td>
<td>-8.2164*10^-5</td>
</tr>
<tr>
<td>$C_4$</td>
<td>7.0224*10^6</td>
</tr>
<tr>
<td>$d_0$</td>
<td>-6.5959*10^-12</td>
</tr>
<tr>
<td>$d_1$</td>
<td>6.763*10^-12</td>
</tr>
<tr>
<td>$d_2$</td>
<td>-2.8883*10^-12</td>
</tr>
<tr>
<td>$d_3$</td>
<td>4.4525*10^-13</td>
</tr>
<tr>
<td>$e_{00}$</td>
<td>1.4526*10^-3</td>
</tr>
<tr>
<td>$e_{01}$</td>
<td>-6.9881*10^-9</td>
</tr>
<tr>
<td>$e_{02}$</td>
<td>1.5210*10^-14</td>
</tr>
<tr>
<td>$e_{03}$</td>
<td>-1.2303*10^-20</td>
</tr>
<tr>
<td>$e_{10}$</td>
<td>-3.8064*10^-11</td>
</tr>
<tr>
<td>$e_{11}$</td>
<td>3.9285*10^-16</td>
</tr>
<tr>
<td>$e_{12}$</td>
<td>-1.2586*10^-21</td>
</tr>
<tr>
<td>$f_{13}$</td>
<td>1.2860*10^-27</td>
</tr>
<tr>
<td>$f_0$</td>
<td>3.0260*10^-4</td>
</tr>
<tr>
<td>$f_1$</td>
<td>-1.8366*10^-4</td>
</tr>
<tr>
<td>$f_2$</td>
<td>7.5671*10^-5</td>
</tr>
<tr>
<td>$f_3$</td>
<td>-1.6479*10^-5</td>
</tr>
<tr>
<td>$f_4$</td>
<td>1.4165*10^-6</td>
</tr>
<tr>
<td>$H_1$</td>
<td>2.76*10^5</td>
</tr>
<tr>
<td>$H_2$</td>
<td>3.94*10^5</td>
</tr>
<tr>
<td>$P_1$</td>
<td>6.8946*10^5</td>
</tr>
<tr>
<td>$g_0$</td>
<td>8.5813*10^-6</td>
</tr>
<tr>
<td>$g_1$</td>
<td>4.2659*10^4</td>
</tr>
<tr>
<td>$g_2$</td>
<td>6.4845*10^-6</td>
</tr>
<tr>
<td>$g_3$</td>
<td>5.5359*10^4</td>
</tr>
<tr>
<td>$g_4$</td>
<td>3.8921*10^-6</td>
</tr>
<tr>
<td>$g_5$</td>
<td>4.0147*10^5</td>
</tr>
</tbody>
</table>
**Viscosity of Superheated Vapor (Ns/m²)**

The viscosity of superheated steam is given by

\[ n(H, p) = (a_0 + a_1 T) - D(b_0 + b_1 T) \quad \text{for} \quad T \leq 300K \quad (8-72) \]

\[ n(H, p) = (a_0 + a_1 T) + (c_0 + c_1 T^2 + c_2 T^3) D + D D (d_0 + d_1 T + d_2 T^2 + d_3 T^3) (e_0 + e_1 D + e_2 D^2) \quad \text{for} \quad 300 < T < 375K \quad (8-73) \]

\[ n(H, p) = (a_0 + a_1 T) - D(e_0 + e_1 D + e_2 D^2) \quad \text{for} \quad T \geq 375K \quad (8-74) \]

where

\[ T = T_v (H, p) - 273.15, \]
\[ D = D_v (H, p), \]

and the coefficients are given in Table 8-9.

### Table 8-9

**Values of Coefficients for Viscosity of Superheated Water Vapor**

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a₀</td>
<td>4.07*10⁻⁸</td>
</tr>
<tr>
<td>a₁</td>
<td>8.04*10⁻⁶</td>
</tr>
<tr>
<td>b₀</td>
<td>1.858*10⁻¹</td>
</tr>
<tr>
<td>b₁</td>
<td>5.9*10⁻¹⁰</td>
</tr>
<tr>
<td>c₀</td>
<td>-2.885*10⁻⁵</td>
</tr>
<tr>
<td>c₁</td>
<td>2.427*10⁻⁸</td>
</tr>
<tr>
<td>c₂</td>
<td>-6.7893*10⁻¹¹</td>
</tr>
<tr>
<td>c₃</td>
<td>6.3170*10⁻¹⁴</td>
</tr>
<tr>
<td>d₀</td>
<td>1.76*10²</td>
</tr>
<tr>
<td>d₁</td>
<td>-1.6</td>
</tr>
<tr>
<td>d₂</td>
<td>4.8*10⁻³</td>
</tr>
<tr>
<td>d₃</td>
<td>-4.7407*10⁻⁶</td>
</tr>
<tr>
<td>e₀</td>
<td>3.53*10⁻⁸</td>
</tr>
<tr>
<td>e₁</td>
<td>6.765*10⁻¹¹</td>
</tr>
<tr>
<td>e₂</td>
<td>1.021*10⁻¹⁴</td>
</tr>
</tbody>
</table>
Conductivity of Compressed Liquid (W/mK)

The thermal conductivity of compressed water is given by

\[ k(H, p) = a_0 + a_1X + a_2X^2 + a_3X^3 \]  \hspace{1cm} (8-75)

where

\[ X = \frac{H}{5.815 \times 10^5} \]

and

\[ a_0 = 5.7374 \times 10^{-1}, \]
\[ a_1 = 2.5361 \times 10^{-1}, \]
\[ a_2 = -1.4547 \times 10^{-1}, \]
\[ a_3 = 1.3875 \times 10^{-2}. \]

Conductivity of Superheated Vapor (W/mK)

The thermal conductivity of superheated steam is given by

\[ k(H, p) = X + D(Z + \frac{cD}{T^4Z^2}), \]  \hspace{1cm} (8-76)

where

\[ T = T(H, p) - 273.15, \]
\[ D = D(H, p), \]
\[ X = z_0 + a_1T + a_2T^2 + a_3T^3, \]
\[ Z = b_0 + b_1T + b_2T^2, \]

and

\[ c = 2.1482E5, \]
\[ a_0 = 1.76 \times 10^{-2}, \]
\[ a_1 = 5.87 \times 10^{-5}, \]
\[ a_2 = 1.04 \times 10^{-7}, \]
\[ a_3 = -4.51 \times 10^{-11}. \]
\[ b_0 = 1.0351 \times 10^{-4}, \]
\[ b_1 = 4.198 \times 10^{-7}, \]
\[ b_2 = -2.771 \times 10^{-11}. \]

In addition to the properties listed above, various partial derivatives of many of the functions were required. These are obtained by analytically differentiating the appropriate correlations.

8.2 Correlations

The required pressure drop and heat transfer correlations for the range of interest are included in this section. Representative valves for various curve-fitted parameters are noted in SI units.

8.2.1 Friction Factor Correlations

8.2.1.1 Pressure Drop in Pipe

In the SSC-K code, the Darcy-Weisbach friction factor, \( f \), is computed from correlations for laminar and turbulent flows with interpolation in the transition regime. There are two turbulent flow friction factor models. The first model computes the turbulent friction factor using an engineering approximation to the well-known Colebrook-White correlation, while the second model uses an exponential friction with user's input coefficients. The frictional pressure drop in the different subchannels of core is calculated by specifying different friction factors. However the default friction law which applies globally throughout the system is specified in the function of FRIC in the SSC-K code.

The friction pressure drop across a pipe of length \( L \), when the developing flow region can be ignored, is given by

\[
\Delta P_{friction} = \int_{z_1}^{z_2} \left( \frac{dp}{dz} \right) = P_{in} - P_{out} = f \frac{L \rho U^2}{D_h} \frac{1}{2}
\]

(8-77)

where \( D_h \) is the hydraulic or equivalent diameter in the case on non-circular channels, defined as
\[ D_h = \frac{4 \text{ (flow area)}}{\text{wetted parameter}} \] (8-78)

and \( U \) is the velocity. The friction factor \( f \), depends on the Reynolds number \((Re)\) of the flow, and the surface roughness \((e)\) of the pipe or channel. Curves of \( f \) vs. \( Re \) for various values of surface roughness are provided in the Moody chart. The surface roughness typically runs from \( 10^{-3} \) for a small commercial grade tube \( 1.5 \times 10^{-6} \) for a very large drawn tube or pipe. For commercial steel, \( e = 0.000046 \) m. It is most likely that the reactor pipes will be even smoother than this (see Table 8-10).

The curves for turbulent flow in the Moody chart [8-19] are generated by the Colebrook-White equation [8-20].

\[
\frac{1}{\sqrt{f}} = -2.0 \log_{10} \left( \frac{e/D_h}{3.7} + \frac{2.51}{Re \sqrt{f}} \right)
\] (8-79)

In the SSC-L code, a simplified form of friction factor [8-20] rather than the above-mentioned transcendental equation is desired, and the following explicit relation for \( f \), which is accurate to within 5\%, was coded.

\[
f = 0.0055 \left\{ 1 + \left[ \frac{20000 e}{D_h Re} + \frac{10^6}{Re} \right]^{1/2} \right\}
\] (8-80)

<table>
<thead>
<tr>
<th>Material</th>
<th>( e ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawn tubing</td>
<td>( 1.5 \times 10^{-6} )</td>
</tr>
<tr>
<td>Commercial steel</td>
<td>( 4.6 \times 10^{-5} )</td>
</tr>
<tr>
<td>Wrought iron</td>
<td>( 4.6 \times 10^{-5} )</td>
</tr>
<tr>
<td>Asphalted cast iron</td>
<td>( 1.2 \times 10^{-4} )</td>
</tr>
<tr>
<td>Galvanized iron</td>
<td>( 1.5 \times 10^{-4} )</td>
</tr>
<tr>
<td>Cast iron</td>
<td>( 2.6 \times 10^{-4} )</td>
</tr>
<tr>
<td>Concrete</td>
<td>( 3 \times 10^{-4} ) to ( 3 \times 10^{-3} )</td>
</tr>
<tr>
<td>Riveted steel</td>
<td>( 10^{-3} ) to ( 10^{-2} )</td>
</tr>
</tbody>
</table>
For smooth pipes, the above equation is reduced to

$$f = 0.0055 + 0.55(Re)^{\frac{1}{3}}$$  \hspace{1cm} (8-81)

According to comparison for computing efficiency in calculating $f$ from either two equations, the Levy's approximate representation [8-21], Eq. (8-80), was found to be 25% more efficient. Since the friction factor needs to be evaluated for each node section of each pipe run, this can result in substantial savings in computing time every time step.

In the SSC-K code, the friction factors for each flow regime are calculated using the following correlations. The friction factor model is simply an interpolation scheme linking the laminar, laminar-turbulent transition, and turbulent flow regimes. The laminar friction factor is calculated as

$$f_L = \frac{64}{Re}, \quad 0 \leq Re \leq 2000$$  \hspace{1cm} (8-82)

where $Re$ is the Reynolds number. The friction factor in the transition region between laminar and turbulent flows is computed by linear interpolation as

$$f_{L,T} = \left(\frac{Re - 2000}{3000 - 2000}\right) [f_{T,3000} - f_{L,2000}], \quad 2000 < Re < 3000$$  \hspace{1cm} (8-83)

where $f_{L,2000}$ is the laminar friction factor at a Reynolds number of 2000, $f_{T,3000}$ is the turbulent friction factor at a Reynolds number of 3000, and the interpolation factor is defined to lie between zero and one.

The turbulent friction factor is given by the Zigrang-Sylvester [8-22] approximation to the Colebrook-White correlation as,

$$\frac{1}{\sqrt{f_T}} = -2\log_{10}\left\{\frac{e / D_h}{3.7} + \frac{2.51}{Re} \left[1.14 - 2\log_{10}\left(\frac{e}{D_h} - \frac{21.25}{Re^{0.8}}\right)\right]\right\}, \quad Re \geq 3000$$  \hspace{1cm} (8-84)

or by

8-30
where $e$ is the surface roughness, $A$, $B$, and $C$ are user input constants, and the other variables have been defined previously. The Zigrang-Sylvester equation has the advantage that it is an explicit relation for the friction factor, while the Colebrook-White correlation is a transcendental function requiring iteration for the determination of the friction factor. The Zigrang-Sylvester approximation to the Colebrook-White correlation for turbulent flow, has a mean square error of 0.1% and a maximum deviation of 0.5% when compared to the Colebrook-White correlation over the ranges $0.5 > e/D_h > 10^{-5}$ and $10^7 > Re > 2500$.

It should be noted that the Moody charts are generated based on isothermal fluid flow. In the presence of heat transfer at the wall, either the fluid properties, such as viscosity and density should be evaluated at a film temperature. The film temperature is assumed to be average of wall temperature ($T_w$) and bulk temperature of coolant ($T_b$). The computed value for $f$ should be modified as follows.

\[
f_{\text{modified}} = f \left( \frac{\mu_w}{\mu_b} \right)^n
\]  

(8-86)

where $n$ is constant. Generally, for steady-state flow in a pipe, $f_{\text{modified}} = f$. These two values are different under transient condition, however, the difference is considered small enough to be neglected.

Pressure losses due to fittings, valves, bends, contractions, and expansions are computed from

\[
\Delta P_e = K \frac{\rho U^2}{2}
\]  

(8-87)

where $U$ is the average velocity in the smaller cross section if there is a change in cross section in the fitting involved. These objects cause the flowing fluid to lose energy owing to a sudden change of cross section or change of direction. Such a loss in energy proportional to square of velocity, and unlike wall friction, has little if any dependence upon Reynolds number and relative roughness. In general, the effects of fittings and valves are evaluated by the velocity-head-loss coefficient $K$. These data can be obtained from typical pipe fittings and other changes.
as shown in Table 8-11 [8-23].

### Table 8-11
Form Loss Coefficient for Various Flow Restrictions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>K</th>
<th>Reference velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe entrance from a plenum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well rounded entrance to pipe</td>
<td>0.04</td>
<td>In pipe</td>
</tr>
<tr>
<td>Slightly rounded entrance to pipe</td>
<td>0.23</td>
<td>In pipe</td>
</tr>
<tr>
<td>Sharp-edged entrance</td>
<td>0.50</td>
<td>In pipe</td>
</tr>
<tr>
<td>Projecting pipe entrance</td>
<td>0.78</td>
<td>In pipe</td>
</tr>
<tr>
<td>Pipe exit to plenum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any pipe exit</td>
<td>1.0</td>
<td>In pipe</td>
</tr>
<tr>
<td>Sudden changes in cross-sectional area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sudden contraction</td>
<td>0.5(1- β²)</td>
<td>Downstream</td>
</tr>
<tr>
<td>Sudden expansion</td>
<td>1- β²</td>
<td>Upstream</td>
</tr>
<tr>
<td>where β = small cross-sectional area / large cross-sectional area</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fittings</th>
<th>(L/D)_{equiv}</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>90° Standard elbow</td>
<td>30</td>
<td>0.35-0.9</td>
</tr>
<tr>
<td>90° Large-radius elbow</td>
<td>20</td>
<td>0.2-0.6</td>
</tr>
<tr>
<td>45° Standard elbow</td>
<td>16</td>
<td>0.17-0.45</td>
</tr>
<tr>
<td>Standard tree (flow through run)</td>
<td>20</td>
<td>0.2-0.6</td>
</tr>
<tr>
<td>Standard tree (flow through branch)</td>
<td>60</td>
<td>0.65-1.7</td>
</tr>
</tbody>
</table>

| Valves (various types)                          |               |                |
| Fully open                                      |               | 0.15-15.0      |
| Half-closed                                     |               |                |
8.2.1.2 Pressure Drop in Wire-Wrapped Rod Bundles

Methods of calculating pressure drop in core assemblies in LMFBR are similar to conventional approaches. The pressure drop across a core assembly consists of (i) entrance and exit pressure losses between the vessel plena and the core internals, (ii) the friction pressure drop along the fuel rods, and (iii) the form losses due to the presence of spacers. The entrance and exit losses are those due to a sudden change in flow area, loss through assembly inlet nozzle, rod bundle, assembly outlet, etc. Generally, empirically determined pressure-loss correlations have been used for wire-wrapped rod bundle applications. Attention here is focused on the friction along the wire-wrapped rod bundles.

(1) Engel, Markley, and Bishop

Based on limited experimental data, Engel, Markley, and Bishop [8-24] have recommended the following generalized correlation for hexagonal fuel assembly applicable in the range $P/D < 1.23$ and $H < 30$ cm.

$$f = \frac{A}{Re} (1 - \chi)^{1/2} + \frac{0.48}{Re^{0.25}} \chi^{1/2}$$ (8-88)

where

$$\chi = 0.0, \quad \text{for } Re \leq 400,$$

$$\chi = \frac{Re-400}{4600}, \quad \text{for } 400 < Re < 5000$$

$$\chi = 1.0, \quad \text{for } Re \geq 5000$$

and the coefficient $A$ is a function of wire-wrap lead $H$ and pitch to rod diameter ratio.

$$A = \frac{320}{\sqrt{H}} (P/D)^{1.5}$$ (8-89)

Note that the wire-wrap lead $H$ in above equation is in centimeters.

(2) Chan and Todreas

8-33
Chan and Todreas [8-25] developed the following generalized correlations applicable to a wide range of wire-wrapped hexagonal fuel assemblies.

\[ f = \frac{C_{19}}{Re} \quad \text{for} \quad Re \leq 400 \quad (8-90) \]

\[ f = \frac{C_{19}}{Re} \left(1 + C_{16} Re^{1.222}\right)^{0.671} \quad \text{for} \quad Re > 400 \quad (8-91) \]

Here, \( Re \) is the bundle Reynolds number and the coefficient \( C_{18} \) and \( C_{19} \) are functions of the number of rods in a bundle \( N \), pitch to rod (pin) diameter ratio \( P/D \), and lead length to rod (pin) diameter ratio \( H/D \).

\[ C_{18} = A(N)^{B}(P/D)^{C}(H/D)^{E} \quad (8-92) \]

\[ C_{19} = 251(N)^{0.097}(P/D)^{0.997}(H/D)^{-0.354} \quad (8-93) \]

The values of the constant \( A, B, C, \) and \( E \) are given in Table 8-12.

<table>
<thead>
<tr>
<th>D ≥ 0.35 inch</th>
<th>D &lt; 0.35 inch</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>A = 0.00221</td>
<td>A = 0.000584</td>
<td>1. 4 H/D</td>
</tr>
<tr>
<td>B = 0.166</td>
<td>B = 0.185</td>
<td>for 2. P/D 1.2 &amp; 8 H/D</td>
</tr>
<tr>
<td>C = 8.297</td>
<td>C = 8.247</td>
<td>3. P/D 1.343 &amp; 12 H/D</td>
</tr>
<tr>
<td>E = -1.457</td>
<td>D = -1.818</td>
<td></td>
</tr>
<tr>
<td>A = 0.0000395</td>
<td>A = 0.000278</td>
<td></td>
</tr>
<tr>
<td>B = 0.063</td>
<td>B = -0.084</td>
<td>for others</td>
</tr>
<tr>
<td>C = 0.174</td>
<td>C = 0.289</td>
<td></td>
</tr>
<tr>
<td>E = 0.178</td>
<td>D = -0.268</td>
<td></td>
</tr>
</tbody>
</table>

For hexagonal assembly, the flow area and hydraulic diameter \( D_h \), can be calculated using the relationships:

8-34
Here, \( d_{ff} \) is the distance between the flat surfaces of hexagonal assembly, \( D \) is the pin diameter, \( D_w \) is wire-wrap diameter, and \( n \) is the number of pins in a bundle.

(3) Experiments for fuel assemblies of CRBR and FFTF

In the Clinch River Breeder Reactor (CRBR) plant, there are several different types of hexagonal rod bundles. The important geometrical characteristics of these bundles are presented in Table 8-13. Based on the experimental measurements [8-26-29], several different correlations for friction factor are recommended for CRBR and Fast Flux Test facility (FFTF) fuel assemblies. The same correlations are applicable to both FFTF and CRBR fuel assemblies. Three sets of correlations for friction factors of in-core assemblies are available in the SSC-K code.

### Table 8-13

<table>
<thead>
<tr>
<th>Assembly</th>
<th>No. of pins</th>
<th>P/D</th>
<th>H/D</th>
<th>D(mm)</th>
<th>D(_w)(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>217</td>
<td>1.24</td>
<td>51.74</td>
<td>5.842</td>
<td>3.254</td>
</tr>
<tr>
<td>Blanket</td>
<td>61</td>
<td>1.072</td>
<td>7.905</td>
<td>12.852</td>
<td>3.399</td>
</tr>
<tr>
<td>Primary control</td>
<td>37</td>
<td>1.05</td>
<td>21.18</td>
<td>15.291</td>
<td>6.862</td>
</tr>
<tr>
<td>Secondary control</td>
<td>31</td>
<td>1.05</td>
<td>10.87</td>
<td>14.036</td>
<td>15.981</td>
</tr>
<tr>
<td>Reactor shield</td>
<td>19</td>
<td>1.0</td>
<td>-</td>
<td>25.197</td>
<td>1.357</td>
</tr>
</tbody>
</table>

**Fuel Assemblies** (L6ATYP ≠ 2 or 3)

\[
f = \min\left\{ \frac{84}{\text{Re}} , 0.5 \right\} \quad \text{for } \text{Re} \leq 800
\]

\[
f = \frac{0.316}{\text{Re}^{0.25}} \left( 1.029 + \frac{2837}{\text{Re}^{1.24}} \right) \quad \text{for } \text{Re} > 800
\]

(8-94) \quad (8-96) \quad (8-95) \quad (8-97)
Blanket Assemblies  

\[ f = \text{Min}\left\{ \frac{110}{\text{Re}}, 0.5 \right\} \]  
for \( \text{Re} < 400 \)  

\[ f = \frac{110}{\text{Re}} \sqrt{1 - \frac{\text{Re} - 400}{4600} + \frac{0.48}{\text{Re}^{0.25}} \sqrt{\frac{\text{Re} - 400}{4600}}} \]  
for \( 400 \leq \text{Re} < 5000 \)  

\[ f = \frac{0.48}{\text{Re}^{0.25}} \]  
for \( \text{Re} > 5000 \)  

Control Assemblies  

\[ f = \text{Min}\left\{ \frac{84}{\text{Re}}, 0.5 \right\} \]  
for \( \text{Re} < 800 \)  

\[ f = \frac{84}{\text{Re}} + (0.316\text{Re}^{-0.25} - 84\text{Re})\frac{(\text{Re} - 800)}{1200} \]  
for \( 800 \leq \text{Re} < 2000 \)  

\[ f = 0.316\text{Re}^{-0.25}\left( \frac{1034}{(P/D)_{24}^{0.94}} + 29.7(P/D)^{0.66} \left(\frac{\text{Re}^{0.66}}{(P/D)_{w}^{2.299}} \right)^{0.885} \right) \]  
for \( \text{Re} \geq 2000 \)  

Here, \( P/D \) is assembly pitch to diameter ratio and \( (P/D)_{w} \) is wire wrap pitch to diameter ratio. Constants \( A \) and \( B \) are supplied by user as input.

For the inlet orifice region and bypass region, SSC-K uses the following corrections.

\[ f = \text{Min}\left\{ \frac{96}{\text{Re}}, 0.5 \right\} \]  
for \( \text{Re} < 2000 \)  

\[ f = 0.316\text{Re}^{-0.25} \]  
for \( \text{Re} \geq 2000 \)
8.2.2 Heat Transfer Correlations

Heat transfer correlations for liquid metal turbulent flow in channels or rod bundles are in the form of:

\[ \text{Nu} = A + B(Pe)^C \]  \hfill (8-106)

where the Peclet number \( Pe \), is the product of the Reynolds and Prandtl numbers. \( A, B, \) and \( C \) are constants that depend on the geometry and the boundary conditions. The constant \( C \) is a number close to 0.8. The constant \( A \) reflects the fact that significant transfer in liquid metals occurs even as \( Re \) goes to zero.

(1) Circular tube

The following relations hold for the boundary conditions cited and fully developed flow conditions.

Lyon's correlation for constant heat flux along and around the tube [8-30]

\[ \text{Nu} = 7 + 0.025Pe^{0.8} \]  \hfill (8-107)

Seban and Shimazaki's correlation for uniform axial wall temperature and uniform radial heat flux [8-31]

\[ \text{Nu} = 5.0 + 0.025Pe^{0.8} \]  \hfill (8-108)

Aoki's correlation [8-32]

\[ \text{Nu} = 6.0 + 0.025(\phi Pe)^{0.8} \]  \hfill (8-109)

where

\[
\phi = \frac{0.014[1-\exp(-71.8\chi)]}{\chi}
\]  \hfill (8-110)
\( \chi = \frac{1}{Re^{0.43} Pr^{0.2}} \)  

(8-111)

In the laminar region,

\[ Nu = 4.36 \quad \text{for} \quad Re \leq 3000 \]  

(8-112)

(2) Parallel plates

For fully developed flow [8-33],

For constant heat flux through one wall only (the other is adiabatic)

\[ Nu = 5.8 + 0.02 Pe^{0.8} \]  

(8-113)

For constant heat flux through both walls, a graphic correction factor for the heat transfer coefficient was supplied by Seban [8-33].

(3) Concentric annuli

For fully developed flow and boundary condition of uniform heat flux in the wall when \( D_2/D_1 > 1.4 \).

\[ Nu = 5.25 + 0.0188 Pe^{0.8} \left( \frac{D_2}{D_1} \right)^{0.3} \]  

(8-114)

If \( D_2/D_1 \) is close to unity, the use of Eq. (8-113) for parallel plate was recommended by Seban [8-33].

(4) Rod bundles

The non-uniformity of the subchannel shape creates substantial azimuthal variation of \( Nu \). Also in finite rod bundles the turbulent effects in a given subchannel affect adjacent subchannels differently depending on the location of the subchannels with respect to the duct boundaries. Therefore the value of \( Nu \) is a function of position within the bundle. However, overall heat transfer correlations are provided in this section.
The liquid metal heat transfer correlations for forced convection in a rod bundle have been developed by many researchers. These experimental have been compared with the experimental data by Kazimi [8-34].

**Westinghouse [8-35]**

For \(1.4 \geq P/D \geq 1.1\) and \(5000 \geq Pe \geq 10\)

\[
Nu = 4.0 + 0.33(P/D)^{38}(Pe/100)^{0.86} + 0.16(P/D)^{5.0}
\]

(8-115)

**Modified Schad [8-35]**

For \(1.5 \geq P/D \geq 1.1\) and \(1000 \geq Pe \geq 150\): Turbulent flow regime

\[
Nu = [-16.15 + 24.96(P/D) - 8.55(P/D)^2]Pe^{0.3}
\]

(8-116)

For \(150 \geq Pe\) : Lamina flow regime

\[
Nu = 4.496[-16.15 + 24.96(P/D) - 8.55(P/D)^2]
\]

(8-117)

**Garber and Rieger [8-36]**

For the shell side in the IHX, the following correlations are used in SSC-K;

For \(1.95 \geq P/D \geq 1.25\) and \(3000 \geq Pe \geq 150\)

\[
Nu = [0.25 + 6.2(P/D)] + [0.32(P/D) - 0.007]Pe^{0.8-0.024(P/D)}
\]

(8-118)

For \(Pe < 110\)

\[
Nu = [0.25 + 6.2(P/D) + 0.32(P/D) - 0.007](110)^{0.8-0.034(P/D)}
\]

(8-119)
For $1.5 \geq P/D \geq 1.1$ and $2000 \geq Pe \geq 200$

$$Nu = 24.15 \log \left[ -8.12 + 12.76(P/D) - 3.65(P/D)^2 \right] + 0.0174 \left[ 1 - \exp \left( 6 \left( 1 - \frac{P}{D} \right) \right) \right] \left\{ Pe - 200 \right\}^{0.99}$$  \hspace{1cm} (8-120)

For $1.5 > P/D > 1.1$ and $200 > Pe$

$$Nu = 24.15 \log \left[ -8.12 + 12.76(P/D) - 3.65(P/D)^2 \right]$$  \hspace{1cm} (8-121)

Currently in the SSC-K code, Aoki's correlation is used for liquid metal flow in a pipe, Graber-Rieger correlation for the shell side in the intermediate heat exchanger (IHX), and Modified-Schad correlation for Rod bundles. Table 8-14 summarizes the correlations used for both SSC-L and SSC-K.

### Table 8-14
Comparison of correlations used for SSC-L and SSC-K

<table>
<thead>
<tr>
<th>Friction Factor</th>
<th>SSC-L</th>
<th>SSC-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>For pipe</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Moody Chart, Levy model</td>
<td>-</td>
<td>Zigrang-Sylvester approximation</td>
</tr>
<tr>
<td>For in-core assembly</td>
<td>-</td>
<td>For in-core assembly</td>
</tr>
<tr>
<td>CRBR specific experiments for Fuel, Blanket and Control assemblies</td>
<td>-</td>
<td>Engel, Markley, and Bishop</td>
</tr>
<tr>
<td>For circular tube</td>
<td>-</td>
<td>Aoki for turbulent flow</td>
</tr>
<tr>
<td>Theoretical Nu for laminar flow</td>
<td>-</td>
<td>Lyon for const. heat flux</td>
</tr>
<tr>
<td>Aoki for turbulent flow</td>
<td>-</td>
<td>Seban and Shimazaki for const. temperature</td>
</tr>
<tr>
<td>For IHX shell-side</td>
<td>-</td>
<td>For IHX shell-side</td>
</tr>
<tr>
<td>Graber and Rieger</td>
<td>-</td>
<td>Graber and Rieger</td>
</tr>
<tr>
<td>For rod bundle</td>
<td>-</td>
<td>For rod bundle</td>
</tr>
<tr>
<td>Modified Schad for both laminar and turbulent flows</td>
<td>-</td>
<td>Westinghouse</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kazimi and Carelli</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Borishanskii</td>
</tr>
</tbody>
</table>

8-40
The heat transfer correlations for water/steam are given for four different modes of heat transfer. The first mode of heat transfer is forced convection. The Nusselt number for nucleate boiling is given as [8-38]:

\[
Nu = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4}
\]  

(8-122)

The heat transfer for nucleate boiling is given as [8-39]:

\[
h = S \cdot h_{NB} + F \cdot h_{c}
\]

(8-123)

where the nucleate boiling coefficient \( h_{NB} \) is given as:

\[
h_{NB} = 0.00122 \left( \frac{K_b^{0.79} C_i^{0.145} \rho_i^{0.49}}{\Omega^{0.5} \mu_i^{0.29} \lambda_{fg}^{0.24} \rho^{0.24}} \right) \Delta P^{0.75}
\]

(8-124)

where

- \( C_i \) = specific heat of liquid
- \( K_i \) = thermal conductivity of liquid
- \( \Omega \) = surface tension
- \( \lambda_{fg} \) = latent heat of vaporization, and
- \( \Delta P \) = difference in saturation pressure corresponding to the wall superheat.

The Reynolds number correction factor \( F \), and the nucleate boiling suppression factor \( S \) are represented as:

\[
F = \begin{cases} 
2.84 \frac{1}{X_u}^{0.45}, & \frac{1}{X_u} < 2. \\
2.57 + 0.7643 \frac{1}{X_u}, & \frac{1}{X_u} \geq 2.
\end{cases}
\]

(8-125)

\[
S = \begin{cases} 
1.05 - 1.3 \times 10^{-5} \text{Re}, & \text{Re} \leq 2.5 \times 10^4 \\
0.83 - 4.3 \times 10^{-6} \text{Re}, & 2.5 \times 10^4 < \text{Re} \leq 10^5 \\
0.32 \exp(-1.92 \times 10^{-6} \text{Re}), & 10^5 < \text{Re} \leq 6 \times 10^5 \\
0.09 & \text{Re} > 6 \times 10^5
\end{cases}
\]

(8-126)
and

$$Re = Re_1 F^{1.25}$$

Where $X_n$ is the Lockhart/Martinelli [8-40] parameter:

$$\frac{1}{X_n} = \left( \frac{X}{1-X} \right)^{0.9} \left( \frac{\rho_l}{\rho_v} \right)^{0.5} \left( \frac{\mu_v}{\mu_l} \right)^{0.10}$$  \hspace{1cm} (8-127)

The convection coefficient $h_c$ is calculated from the Dittus Boelter equation based on liquid thermodynamic properties [8-38].

The heat transfer for film boiling regime is given as [8-41]:

$$Nu = 0.0193 Re_l^{0.8} Pr_l^{1.23} \left( \frac{\rho_B}{\rho_g} \right)^{0.64} \left( \frac{\rho_l}{\rho_v} \right)^{0.63}$$ \hspace{1cm} (8-128)

where subscripts l and g denote, respectively, liquid and vapor phase at saturation and subscript $B$ indicates a bulk property of the steam/water mixture.

For superheat steam, the following heat transfer correlation for forced convection is used [8-42]:

$$Nu = 0.0133 Re^{0.84} Pr^{0.333}$$ \hspace{1cm} (8-129)

The steam/water quality at the DNB point is given by [8-43]:

$$X_{DNB} = \frac{4.38 \times 10^4 \rho_l}{H_{lg} \rho_g \sqrt{G/1350.0}}$$ \hspace{1cm} for $q > 6.3 \times 10^5$,  \hspace{1cm} (8-130)

or

$$X_{DNB} = \frac{4.38 \times 10^4 \nu_t \left(5.3 \times 10^5 / q\right)^{1.5}}{H_{lg} \rho_g \sqrt{G/1350.0}}$$ \hspace{1cm} for $q < 6.3 \times 10^5$ \hspace{1cm} (8-131)

where $H_{lg}$ is the latent heat of vaporization (J/kg), $G$ is the mass flow rate per unit area (kg/s m$^2$), and $q$ is in W/m$^2$. 

8-42
9. TWO-DIMENSIONAL HOT POOL MODEL

9.1 Introduction

During a normal reactor scram, the heat generation is reduced almost instantaneously while the coolant flow rate follows the pump coastdown. This mismatch between power and flow results in a situation where the core flow entering the hot pool is at a lower temperature than the temperature of the bulk pool sodium. This temperature difference leads to thermal stratification. Thermal stratification can occur in the hot pool region if the entering coolant is colder than the existing hot pool coolant and the flow momentum is not large enough to overcome the negative buoyancy force. Since the fluid of hot pool enters IHXs, the temperature distribution of hot pool can alter the overall system response. Hence, it is necessary to predict the pool coolant temperature distribution with sufficient accuracy to determine the inlet temperature conditions for the IHXs and its contribution to the net buoyancy head. Therefore, in this section two-dimensional hot pool model is developed instead of existing one-dimensional model to predict the hot pool coolant temperature and velocity distribution more accurately and is applied to the SSC-K code.

9.2 Theory

9.2.1 Governing Equations

The governing equations for conservation of mass, momentum, energy, turbulent kinetic energy and rate of turbulent kinetic energy dissipation for \( k-\varepsilon \) turbulence model in a generalized coordinate system \( x' \) can be written as follows;

\[
\frac{\partial}{\partial x^1} (rU_1) + \frac{\partial}{\partial x^2} (rU_2) = 0 \tag{9-1}
\]

\[
\frac{\partial}{\partial t} (rJ\rho u_1) + \frac{\partial}{\partial x^1} \left[ rU_1 u_1 - \frac{r}{J} (\mu + \mu_t) \left\{ \frac{\partial u_1}{\partial x^1} B_1^1 + \frac{\partial u_1}{\partial x^2} B_2^1 + b_1^1 w_1^1 + b_2^1 w_2^1 \right\} + rb_1^1 p \right] \\
+ \frac{\partial}{\partial x^2} \left[ rU_2 u_1 - \frac{r}{J} (\mu + \mu_t) \left\{ \frac{\partial u_1}{\partial x^1} B_1^2 + \frac{\partial u_1}{\partial x^2} B_2^2 + b_1^2 w_1^2 + b_2^2 w_2^2 \right\} + rb_2^1 p \right] = 0. \tag{9-2}
\]
\[ \frac{\partial}{\partial t} (r \rho u_1) + \frac{\partial}{\partial x_1} \left[ r U_1 u_1 - r \left( \frac{\mu + \mu_1}{J} \right) \left( \frac{\partial u_{11}}{\partial x_1} B_{11} + \frac{\partial u_{12}}{\partial x_2} B_{12} + b_{11} w_{11} + b_{12} w_{12} \right) + r b_{11} p \right] = 0 \] (9.3)

\[ \frac{\partial}{\partial t} (r \rho T) + \frac{\partial}{\partial x_1} \left[ r U_1 T - r \left( \frac{\mu + \mu_t}{J} \right) \left( \frac{\partial T}{\partial x_1} B_{11} + \frac{\partial T}{\partial x_2} B_{12} \right) \right] 
+ \frac{\partial}{\partial x_2} \left[ r U_2 T - r \left( \frac{\mu + \mu_t}{J} \right) \left( \frac{\partial T}{\partial x_1} B_{21} + \frac{\partial T}{\partial x_2} B_{22} \right) \right] = 0. \] (9.4)

\[ \frac{\partial}{\partial t} (r \rho k) + \frac{\partial}{\partial x_1} \left[ r U_1 k - r \left( \frac{\mu + \mu_k}{\sigma_k} \right) \left( \frac{\partial k}{\partial x_1} B_{11} + \frac{\partial k}{\partial x_2} B_{12} \right) \right] 
+ \frac{\partial}{\partial x_2} \left[ r U_2 k - r \left( \frac{\mu + \mu_k}{\sigma_k} \right) \left( \frac{\partial k}{\partial x_1} B_{21} + \frac{\partial k}{\partial x_2} B_{22} \right) \right] = rJ(G - \rho \varepsilon) \] (9.5)

\[ \frac{\partial}{\partial t} (r \rho \varepsilon) + \frac{\partial}{\partial x_1} \left[ r U_1 \varepsilon - r \left( \frac{\mu + \mu_\varepsilon}{\sigma_\varepsilon} \right) \left( \frac{\partial \varepsilon}{\partial x_1} B_{11} + \frac{\partial \varepsilon}{\partial x_2} B_{12} \right) \right] 
+ \frac{\partial}{\partial x_2} \left[ r U_2 \varepsilon - r \left( \frac{\mu + \mu_\varepsilon}{\sigma_\varepsilon} \right) \left( \frac{\partial \varepsilon}{\partial x_1} B_{21} + \frac{\partial \varepsilon}{\partial x_2} B_{22} \right) \right] = rJ \left( \frac{C_{\varepsilon_1}}{k} G - \frac{C_{\varepsilon_2}}{k} \varepsilon^2 \right) \] (9.6)

where

\[ U_i = \rho u_i b_i' \], \quad B_{n}^i = b_{i}^n b_{n}^i \], \quad w_{j}^i = \frac{\partial u_{j}}{\partial x_i} b_{j}^i \]

(9.7)

and

\[ \mu_i = \frac{C_{\mu} \rho k^2}{\varepsilon} \] (9.8)

\[ G = \frac{\mu_1}{J^2} \left[ 2 \left( \frac{\partial u_{11}}{\partial x_1} b_{11} + \frac{\partial u_{12}}{\partial x_2} b_{12} \right)^2 + 2 \left( \frac{\partial u_{21}}{\partial x_1} b_{21} + \frac{\partial u_{22}}{\partial x_2} b_{22} \right)^2 \right] \]
\[
\left[ \frac{\partial u_1}{\partial x^1} b_2^1 + \frac{\partial u_1}{\partial x^2} b_2^2 + \frac{\partial u_2}{\partial x^1} b_1^1 + \frac{\partial u_2}{\partial x^2} b_1^2 \right]^2 + 2\frac{u_2^2}{r^2} \right] \quad (9-9)
\]

\[C_{e1} = 1.44, \quad C_{e2} = 1.92, \quad P_t = 0.9, \quad C_\mu = 0.09, \quad \sigma_k = 1.0, \quad \sigma_\varepsilon = 1.3 \quad (9-10)\]

In above equations \( u_1, T, k, \varepsilon \) denote two cylindrical velocity components, temperature, turbulent kinetic energy and rate of turbulent kinetic energy dissipation respectively. The geometric coefficients \( b_j^i \) represent the cofactors of \( \partial y^j / \partial x^i \) in the Jacobian matrix of the coordinate transformation, \( J \) stands for the determinant of the Jacobian matrix, \( y^j \) is the cylindrical coordinate system and \( \rho, \mu, p, P \) denote density, viscosity, pressure and Prandtl number respectively.

9.2.2 Discretization of Governing Equation

The solution domain is divided into a finite number of quadrilateral control volumes and the discretization of the governing equation is performed following the finite volume approach. The convection terms are approximated by a higher-order bounded scheme HLPA developed by Zhu [9-1] and the unsteady terms are treated by the backward differencing scheme.

9.2.3 Momentum Interpolation Method

In the present study, the Rhie and Chow’s scheme [9-2] is modified to obtain a converged solution for unsteady flows which is independent of the size of time step and relaxation factors. The momentum equations are solved implicitly at the cell-centered locations in the Rhie and Chow’s scheme. The discretized form of momentum equations for the cell-centered velocity components can be written as follows with the under-relaxation factors expressed explicitly;

\[ u_{1,p} = (H_{u_1})_p + (D^1_{u_1})_p (P_u - P_s) + (D^2_{u_1})_p (P_z - P_s) + (E_{u_1})_p u_{i,p}^{-1} + (1-\alpha) u_{i,p}^{-1} \quad (9-11) \]
\[ u_{2,p} = (H_{u_1})_p + (D^1_{u_1})_p (P_w - P_e)_p + (D^2_{u_1})_p (P_z - P_e)_p + (E_{u_1})_p u_{2,p}^{n-1} + (1 - \alpha_{u_1}) u_{2,p}^{l-1} \quad (9-12) \]

where

\[ H_{u_1} = \alpha_{u_1} \left( \sum A_{nb}^n u_{1,ab} + (S^n \Delta V) \right) / A_p^n \quad (9-13) \]

\[ D^1_{u_1} = \alpha_{u_1} r b_i^j / A_p^n \quad (9-14) \]

\[ E_{u_1} = \frac{\alpha_{u_1} \rho \Delta V}{\Delta t} / A_p^n \quad (9-15) \]

\[ A_p^n = \sum A_{nb}^n - S_p^n \Delta V + \frac{\rho \Delta V}{\Delta t} \quad (9-16) \]

and \( \alpha_{u_1} \) are the under-relaxation factors for \( u_i \) velocity components and the superscripts \( n-1, l-1 \) denote the previous time step and iteration level, respectively. The discretized form of momentum equations for the cell-face velocity component, for example \( u_1 \) at the east face, can be written as follows;

\[ u_{1,e} = (H_{u_1})_e + (D^1_{u_1})_e (P_e - P_p)_e + (D^2_{u_1})_e (P_{ze} - P_{pe}) + (E_{u_1})_e u_{1,e}^{n-1} + (1 - \alpha_{u_1}) u_{1,e}^{l-1} \quad (9-17) \]

In the present modified Rhie and Chow's scheme, this cell-face (the east face) velocity component is obtained explicitly through the interpolation of momentum equations for the neighboring cell-centered cylindrical velocity components. Following assumptions are introduced to evaluate this cell-face velocity component.

\[ (H_{u_1})_e \approx f_e^* (H_{u_1})_E + (1 - f_e^*) (H_{u_1})_p \quad (9-18) \]

\[ (D^2_{u_1})_e (P_{ze} - P_{pe}) \approx f_e^* (D^2_{u_1})_E (P_{ze} - P_{pe})_E + (1 - f_e^*) (D^2_{u_1})_p (P_{ze} - P_{pe})_p \quad (9-19) \]
where \( f_e^+ \) is the geometric interpolation factor defined in terms of distances between nodal points. Similar assumptions can be introduced for evaluating the velocity components at the north face. Using above assumptions, the velocity component \( u_{i,e} \) can be obtained as follows;

\[
\frac{1}{(A_p^u)_{e}} f_e^+ \left[ \frac{f_e^+}{(A_p^u)_{e}} + (1 - f_e^+) \right] = \frac{\alpha_t}{\Delta t} \left[ \frac{(\Delta V)^u_{e}}{(A_p^u)_{e}} u_{i,e}^{n+1} - f_e^+ (\Delta V)^E_{e} u_{i,E}^{n+1} - (1 - f_e^+) (\Delta V)^p_{e} u_{i,p}^{n+1} \right]
\]

(9-21)

9.2.4 Solution Algorithm

The SIMPLEC algorithm by Van Doormal and Raithby [9-5] is used for pressure-velocity coupling in the present study. In this algorithm the momentum equations are implicitly solved at cell-centered locations using Eqs. (9-1) and (9-2). Then the cell-face velocities are evaluated by Eq. (9-11). Since these starred velocities do not satisfy the continuity equation unless the pressure field is correct, they should be corrected to satisfy the continuity equation during the iteration process. The following velocity correction equations are assumed in the SIMPLEC algorithm.
Inserting above equations into the continuity equation leads to a pressure correction equation. After solving the pressure correction equation, the cell-face velocities are corrected by above equations and the cell-centered velocities are corrected by following equations.

\[ u_1^{*} = u_{1, c}^{*} - u_{1, e} = (D_{v_1})_c (P_{p}^{'} - P_{E}^{'}) / \left[ 1 - \alpha_n (\sum A_{nb}^{n} / A_P^{n})_c \right] \]  \hspace{1cm} (9-22)

\[ u_2^{*} = u_{2, c}^{*} - u_{2, e} = (D_{v_2})_c (P_{p}^{'} - P_{E}^{'}) / \left[ 1 - \alpha_n (\sum A_{nb}^{n} / A_P^{n})_c \right] \]  \hspace{1cm} (9-23)

The pressure correction equations as well as other algebraic equations of momentum equations, energy equation and turbulent transport equations are solved by the strongly implicit procedure by Stone [9-6] in the present study.

9.2.5 Treatment of Boundary Conditions

At the inlet both the velocity components and turbulent quantities are prescribed. At the outlet the zero gradient conditions are imposed while the velocity components are adjusted to satisfy the overall mass conservation. At the symmetry line the symmetry conditions are imposed. At the wall node both the velocity components are set to zero. For the near-wall control volumes, the wall shear-stress vector is expressed as a function of the nodal velocity component parallel to the wall. The wall shear stress is again decomposed in two components along \( u_1 \) and \( u_2 \), respectively, to be used as source terms in the corresponding momentum equations. The wall function method is used for the near-wall nodes.
9.3 Modeling

As shown in Fig. 9.1, in the case of one-dimensional model the steady-state hot pool coolant temperature is calculated in MAIN9S using the input values from MAIN9R and the transient hot pool temperature is calculated in MAIN9T. In UPLS6T the hot pool energy variation is calculated and is corrected by prediction-correction method in INTG1T. And then correct hot pool temperature is fixed in UQIV1T. Therefore, two-dimensional hot pool coolant temperature is calculated by coupling the developed two-dimensional hot pool model with UPLS6T.

As shown in Fig. 9.2, the developed two-dimensional hot pool model consists of three subprograms, i.e, BFC, FLOW2D and UFLOW2D. In BFC the grid is generated automatically. In FLOW2D steady-state hot pool coolant temperature and velocity distributions are calculated and are used as input values of UFLOW2D. In the UFLOW2D coupled with UPLS6T, the transient hot pool coolant temperature and velocity distributions are calculated. In Figs. 9.3 and 9.4, the flowcharts of each subprogram are illustrated.

The main functions of the subprograms are as follows:

<table>
<thead>
<tr>
<th>Subprogram</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF</td>
<td>grid generation module</td>
</tr>
<tr>
<td>BINDEX</td>
<td>calculate location address for the near boundary nodes</td>
</tr>
<tr>
<td>BKIND</td>
<td>define various boundary conditions</td>
</tr>
<tr>
<td>BOUNDPP</td>
<td>extrapolate pressure at boundary nodes</td>
</tr>
<tr>
<td>BOUNDS</td>
<td>call appropriate boundary conditions</td>
</tr>
<tr>
<td>CDFLUX</td>
<td>calculate cross-derivative fluxes</td>
</tr>
<tr>
<td>COEFF</td>
<td>calculation of algebraic coefficients of transport equations HLPA scheme on non-uniform grid</td>
</tr>
<tr>
<td>COFCON</td>
<td>calculate coefficients for pressure correction equation and face convective fluxes using momentum interpolation (SIMPLEC)</td>
</tr>
<tr>
<td>CWCS</td>
<td>initializing mass fluxes</td>
</tr>
<tr>
<td>FLOSOL</td>
<td>solving all the conservation equations transient</td>
</tr>
<tr>
<td>GEOMET</td>
<td>calculate geometric coefficients and center-points of control volume</td>
</tr>
<tr>
<td>INFORM</td>
<td>printing important informations</td>
</tr>
<tr>
<td>INP</td>
<td>read input variables</td>
</tr>
<tr>
<td>INPUT</td>
<td>read input variables</td>
</tr>
</tbody>
</table>
numerical solution of incompressible flows on a nonorthogonal grid using momentum interpolation method - steady
numerical solution of incompressible flows on a nonorthogonal grid using momentum interpolation method - transient
print output variables
calculate pressure difference
print major output
calculate fluid properties
correct velocity, flux and pressure
solving all the conservation equations - steady
numerical scheme: Stone's strongly implicit method - transient
calculation of sources for the conservation equations
numerical scheme: Stone's strongly implicit method - steady
initialize some variables - steady
initialize some variables - transient
user define module - steady
plotting module
user define module - transient

9.4 Sample Run

9.4.1 Constant Inlet Temperature Increase

The KALIMER design is a pool-type system, with the entirety of the primary heat transport system contained within the reactor vessel. During normal operation, the sodium core inlet and outlet temperatures are 386°C and 530°C, and the other initial conditions used and important system parameters are listed in Table 9-1. In the case of two-dimensional model, the hot pool is modeled as shown in Fig. 9.5. The input parameters of the two-dimensional hot pool model named HP2D are core outlet temperature and flowrate. In the model, the temperature and velocity distributions in the hot pool are calculated.

Firstly, in the case of constant inlet temperature increase, we compare the prediction accuracy between one- and two-dimensional hot pool model. During normal operation, the sodium bulk temperature of the hot pool is 530°C and flowrate is 2143.1kg/sec. Also the sodium
velocity distribution in the hot pool is shown in Fig. 9.6. In the case that the hot pool sodium inlet temperature increases from 530°C to 647°C suddenly, the hot pool sodium temperature increases until it reaches to the inlet temperature. As shown in Fig. 9.7, the temperature behaviors of the both models are quite different. In the one-dimensional model, the outlet temperature increases slowly and immediately, and is reached to 645°C after 420 seconds. However, in the two-dimensional model, the outlet temperature is not changed until 20 seconds and then increases steeply. The outlet temperature is reached to 645°C after 250 seconds.

In two-dimensional model, the outlet sodium temperature is affected by the inlet sodium temperature change after several tens of seconds during normal operation and is more actual qualitative prediction than one-dimensional model. The time delay can alter the overall reactor system response, so that it is necessary to predict the hot pool sodium temperature distribution with sufficient accuracy.

9.4.2 Unprotected Transient Overpower Events

An unprotected transient overpower (UTOP) event results when positive reactivity is inadvertently inserted into the core and there is a failure to scram. The limiting case assumption is that all the control rods are accidently removed. The event is initiated from full power. The control rods are assumed to begin withdrawing with a speed of 0.67 cents per second. The control rod stops are set to limit the withdrawal worth to 10 cents. The UTOP transient results for hot pool temperatures, power and flow in both cases of one- and two-dimensional models are shown in Figs. 9-8 through 9-10. As shown in Fig. 9.6, the power reaches a peak of 1.130 and 1.124 times the rated power at 34 and 27 seconds into the transient, and begins to level off at 1.019 and 1.021 times the rated power in the case of one- and two-dimensional model cases, respectively.

In the case of one-dimensional model, the hot pool inlet temperature increases from a normal value of 530°C to a peak of 551°C and outlet temperature increases from 530°C to a peak of 543°C and then the inlet and outlet temperatures are reestablished at around 542°C, which is 12°C above the initial temperature, as shown in Fig. 9.9. On the other hand, in the case of two-dimensional model, the hot pool inlet temperature increases from 530°C to 550°C and outlet temperature increases from 530°C to 546°C, and then the inlet and outlet temperatures are
reestablished at around 543°C, which is 13°C above the initial temperature. The outlet temperature is not affected by the inlet coolant until 25 seconds.

As a result of this comparison, it is considered that the time delay effect of the hot pool affects the core inlet sodium temperature. And then core inlet sodium temperature change affects the reactivity feedback and reactor power also. Therefore, it seems that the two-dimensional modeling of the hot pool can predict the overall reactor system response more realistic than one-dimensional model.
Table 9-1
Initial and Key Operating Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (MWth)</td>
<td>392.2</td>
</tr>
<tr>
<td>Number of IHTS loops</td>
<td>2</td>
</tr>
<tr>
<td>Cover gas pressure (MPa)</td>
<td>0.1013</td>
</tr>
<tr>
<td>Primary sodium flowrate (kg/s)</td>
<td>2143.1</td>
</tr>
<tr>
<td>Primary sodium core outlet temperature (°C)</td>
<td>530.0</td>
</tr>
<tr>
<td>Primary sodium core inlet temperature (°C)</td>
<td>386.2</td>
</tr>
<tr>
<td>Number of Primary pumps</td>
<td>4</td>
</tr>
<tr>
<td>Intermediate sodium flowrate (kg/s)</td>
<td>1803.6</td>
</tr>
<tr>
<td>IHX-IHTS inlet temperature (°C)</td>
<td>339.7</td>
</tr>
<tr>
<td>IHX-IHTS outlet temperature (°C)</td>
<td>511.0</td>
</tr>
<tr>
<td>Number of IHXs</td>
<td>4</td>
</tr>
<tr>
<td>Number of SGs</td>
<td>2</td>
</tr>
<tr>
<td>Steam flowrate (kg/s)</td>
<td>155.5</td>
</tr>
<tr>
<td>Steam temperature (°C)</td>
<td>483.2</td>
</tr>
<tr>
<td>Steam pressure (MPa)</td>
<td>15.5</td>
</tr>
</tbody>
</table>
1-Dim. Hot Pool Model

START

MAIN9R

MAIN9S

PBAL9S: \( T_{\text{bom}}, T_{\text{ini}}, W_{\text{com}} \) - know 2 of 3 from input
Calculated the unknown variable using known 2 variables

COOL6S

OPTN6S: Calculates \( E_{\text{out}} \)
\[ E_{\text{out}} = E(T_{\text{out}}) \]

UPLN6S: Calculates \( E_{\text{in}} \)
\[ E_{\text{in}} = E(T_{\text{in}}) \]

INIT9T

INIT6T: Calculates initial values of \( T_{\text{ini}}, T_{\text{ini}}, E_{\text{ini}}, E_{\text{ini}} \)

DRIV9T

DRIV1T

INTG1T: Prediction of the \( Y_{1}(KK), Y_{1}(KK+1) \) from old \( Y_{1DYDT} \)

EOIV1T(2): Reset integrated variables \( T_{\text{ini}}, T_{\text{ini}} \)
\[ T_{\text{ini}} = Y_{1}(KK), T_{\text{ini}} = Y_{1}(KK+1) \]

FLOW1T

UPLN6T

UPLS6T: Updates \( Y_{1DYDT} \) and calculates \( T_{\text{ini}} \)
\[ Y_{1DYDT}(KK) = \Delta \varepsilon, \]
\[ Y_{1DYDT}(KK+1) = \Delta \varepsilon, \]
\[ T_{\text{ini}} = F_{w} T_{\text{ini}} + F_{x} T_{\text{ini}} \]

INTG1T: Correction of the \( Y_{1}(KK), Y_{1}(KK+1) \) from new \( Y_{1DYDT} \)

EOIV1T(2): Reset integrated variables \( T_{\text{ini}}, T_{\text{ini}} \)
\[ T_{\text{ini}} = Y_{1}(KK), T_{\text{ini}} = Y_{1}(KK+1) \]

STOP

Fig. 9.1 Flowchart of One-dimensional Hot Pool Model
Fig. 9.2 Flowchart of Two-dimensional Hot Pool Model
Fig. 9.3 Flowchart of HP2D; Steady-State
Fig. 9.4 Flowchart of HP2D; Transient
Axi-symmetry

Fig. 9.5  Two-Dimensional Hot Pool Model
Fig. 9.6  Sodium Velocity Distribution in Hot Pool during Normal Operation
Constant Inlet Temp. ($T_{INLET}=647°$C)

Fig. 9.7 Hot Pool Sodium Outlet Temperatures

10 cents/15 sec UTOP without PSDRS

Fig. 9.8 Power and Flow during 10 Cent UTOP
Fig. 9.9 Hot Pool Temp. during 10 Cent UTOP
Fig. 9.10   Hot Pool Temperature Distribution during 10 Cent UTOP
REFERENCES


6-1 Lee W. Johnson et al, "Numerical Analysis", Addison-Wesley Publishing Company


8-9 – 8-14 blank


8-26 HEDL-TI-76049, "Covered pressure drop flow test / Crossflow mixing test" (1976).


Appendix A  SSC-K INPUT DESCRIPTION

The basic component of the SSC-K input is the input record. These records are grouped on a modular basis to form subdivisions of the input, which in turn are referred to as data files. Each data file has been assigned a file name to delimit as well as to identify the file partitioning. The entire sequence of input records constitutes the input file.

File name:

- VESSEL
- NALOOP
- MINETD
- OPDATA
- MATDAT
- OLDATA
- TRNDAT
- PSDRS

Core and in-vessel components
Primary and secondary heat transport system
Steam generator and balance-of-plant
Overall plant operating conditions
material properties
User initiated program control
Conditions to initiate transient scenario
Passive decay heat removal system

In-Vessel Data (VESSEL)

Geometric and hydraulic data required to specify the core and in-vessel components

<table>
<thead>
<tr>
<th>Rec.</th>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L6RTYP</td>
<td>Reactor type</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 = loop type, 1 = pool type</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N6CHAN</td>
<td>Number of channels being simulated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N5RTYP</td>
<td>Number of rod types</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N5ASEC(L)</td>
<td>Number of axial sections (slices) of each rod type</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(L=1,N5RTYP)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N5NFR(K)</td>
<td>Number of radial fuel nodes in an axial slice of each channel (K=1,N6CHAN)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>L6ATYP(K)</td>
<td>Rod type assigned to each channel. Also used for friction factor correlation. See Eqs. 5.71-5.73 for acceptable type</td>
<td></td>
</tr>
</tbody>
</table>
selections \((K=1,N6\text{CHAN})\):

2 for blanket assemblies, 3 for control assemblies

<table>
<thead>
<tr>
<th>Selection</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 F6TPOW(K)</td>
<td>Fraction of total power in each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>4 F6FLOW(K)</td>
<td>Fraction of total vessel flow in each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>5 N5ASSY(K)</td>
<td>Number of assemblies represented by each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>6 A6ROD(K)</td>
<td>Sodium flow area per rod in each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>8 Y6HYDR(K)</td>
<td>Hydraulic diameter of each coolant channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>11 X5FIR(K)</td>
<td>Fuel inner radius of each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>12 X5FOR(K)</td>
<td>Fuel outer radius of each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>13 X5CLIR(K)</td>
<td>Cladding inner radius of each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>14 X5CLOR(K)</td>
<td>Cladding outer radius of each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>15 X5LBIR(K)</td>
<td>Lower blanket inner radius of each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>16 X5LBOR(K)</td>
<td>Lower blanket outer radius of each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>17 X5UBIR(K)</td>
<td>Upper blanket inner radius for each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>18 X5UBOR(K)</td>
<td>Upper blanket outer radius for each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>19 F5ASTR(K)</td>
<td>Fractional heat transfer area of structure used per channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>20 H5NOGP(K)</td>
<td>Heat transfer coeff. for fuel-clad contact for each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>21 P5FGAS(K)</td>
<td>Fission gas pressure for each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>23 L6WOPT</td>
<td>Flow fraction option indicator</td>
</tr>
<tr>
<td></td>
<td>0 - fractions known, 1 - fractions unknown</td>
</tr>
<tr>
<td>23 F6LSA4(K)</td>
<td>Total K-loss coeff. at top of each channel ((K=1,N6\text{CHAN}))</td>
</tr>
<tr>
<td>23 F6LSBP</td>
<td>Bypass flow K-loss coeff.</td>
</tr>
<tr>
<td>23 P6DSGN</td>
<td>When L6WOPI=0, Actual nozzle to nozzle pressure</td>
</tr>
</tbody>
</table>
When \( L6WOPI=1 \), Core design delta-P (used in P6INLT guess) \[ \text{[N/m}^2\text{]} \]

**Design core flow rate** \[ \text{[kg/s]} \]

**Maximum iteration for pressure calculation**

**Maximum iterations for flow calculation**

**Convergence criterion (relative)**

**Maximum flow fraction change allowed per iteration**

**Maximum pressure change allowed per iteration** \[ \text{[N/m}^2\text{]} \]

Note: Non-zero value(s) need be assigned only when \( L6WOPT=1. \)

### Volume of lower plenum \[ \text{[m}^3\text{]} \]

### Mass heat capacity of metal in lower plenum \[ \text{[J/K]} \]

### Overall heat transfer coefficient in lower plenum \[ \text{[W/K]} \]

### Cross-sectional flow area of lower plenum \[ \text{[m}^2\text{]} \]

If >0, total K-loss coeff. from inlet nozzle elevation to core bottom.

If <0, total K-loss press. drop from inlet nozzle elevation to core bottom.

### Fuel radial mesh indicator:
0 - equal radius, 1 - equal area

### Temperature at which the rod dimensions are referenced \[ \text{[K]} \]

set as 0

### Reference elevation of reactor vessel \[ \text{[m]} \]

Refer to Fig. 1.1 for the below variables

### Elevation of vessel inlet nozzle above Z6REF \[ \text{[m]} \]

### Elevation of bottom of core above Z6REF \[ \text{[m]} \]

### Elevation of top of core above Z6REF \[ \text{[m]} \]

### Elevation of initial upper plenum sodium level above Z6REF \[ \text{[m]} \]

### Elevation of vessel outlet nozzle above Z6REF (loop) or elevation of IHX inlet nozzle above Z6REF (pool) \[ \text{[m]} \]

### Elevation of top of thermal liner above Z6REF \[ \text{[m]} \]

### Elevation of top of vessel above Z6REF \[ \text{[m]} \]

### Area between gas and liquid in vessel upper plenum (same as flow cross-sectional area) \[ \text{[m}^2\text{]} \]

A-3
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A6GM1</td>
<td>Area between gas and metal 1 in vessel upper plenum</td>
<td>m²</td>
</tr>
<tr>
<td>A6GM2</td>
<td>Area between gas and metal 2 in vessel upper plenum</td>
<td>m²</td>
</tr>
<tr>
<td>A6GM3</td>
<td>Area between gas and metal 3 in vessel upper plenum</td>
<td>m²</td>
</tr>
<tr>
<td>A6LM1</td>
<td>Area between liquid and metal 1 in vessel upper plenum</td>
<td>m²</td>
</tr>
<tr>
<td>A6LM2</td>
<td>Area between liquid and metal 2 in vessel upper plenum</td>
<td>m²</td>
</tr>
<tr>
<td>A6JET</td>
<td>Area of core jet flow</td>
<td>m²</td>
</tr>
<tr>
<td>H6GAS</td>
<td>Heat transfer coeff. for cover gas in upper plenum</td>
<td>W/Km²</td>
</tr>
<tr>
<td>H6LNA</td>
<td>Heat transfer coeff. at interface of two sodium zones in upper plenum</td>
<td>W/Km²</td>
</tr>
<tr>
<td>H6INF</td>
<td>Heat transfer coeff. at interface of two sodium zones in upper plenum</td>
<td>W/Km²</td>
</tr>
<tr>
<td>Z6CHIM</td>
<td>Length of chimney above core outlet</td>
<td>m</td>
</tr>
<tr>
<td>F6PKUP</td>
<td>If &gt;0, total K-loss coeff. from core top to outlet nozzle elevation. If &lt;0, total K-loss P-drop from core top to outlet nozzle elevation.</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>F6LEAK</td>
<td>Fraction of bypass flow leaking directly into upper plenum from lower bypass region</td>
<td></td>
</tr>
<tr>
<td>B6UMC1</td>
<td>Mass heat capacity of metal 1 in upper plenum</td>
<td>J/K</td>
</tr>
<tr>
<td>B6UMC2</td>
<td>Mass heat capacity of metal 2 in upper plenum</td>
<td>J/K</td>
</tr>
<tr>
<td>B6UMC3</td>
<td>Mass heat capacity of metal 3 in upper plenum</td>
<td>J/K</td>
</tr>
<tr>
<td></td>
<td>* See 3.1.3 Upper Plenum of SSC-K Manual for descriptions of Metals 1, 2 and 3.</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>A6LFBP</td>
<td>Flow area of lower region of bypass channel</td>
</tr>
<tr>
<td>30</td>
<td>A6UFBP</td>
<td>Flow area of upper region of bypass channel</td>
</tr>
<tr>
<td></td>
<td>Y6LRBP</td>
<td>Hydraulic diameter of lower bypass region channel</td>
</tr>
<tr>
<td></td>
<td>Y6URBP</td>
<td>Hydraulic diameter of upper bypass region channel</td>
</tr>
<tr>
<td></td>
<td>F6INBP</td>
<td>If &gt;0, total K-loss coeff. at bypass inlet. If &lt;0, total K-loss P-drop at bypass inlet.</td>
</tr>
<tr>
<td></td>
<td>H6ABP</td>
<td>Overall heat transfer coeff. between upper bypass region sodium and liner</td>
</tr>
<tr>
<td></td>
<td>F6FRC1</td>
<td>Coeff. used in friction factor correlation for rod bundles (Eq. 8-71)</td>
</tr>
<tr>
<td></td>
<td>F6FRC2</td>
<td>Coeff. used in friction factor correlation for rod bundles (Eq. 8-71)</td>
</tr>
<tr>
<td></td>
<td>F6NUC1</td>
<td>Coeff. used in Nu number correlation (Forced</td>
</tr>
</tbody>
</table>
convection - Rod Bundle) (Eq. 8-75)

**F6NUC2** Coeff. used in Nu number correlation (Forced convection - Rod Bundle) (Eq. 8-75)

**F6NUC3** Coeff. used in Nu number correlation (Forced convection - Rod Bundle) (Eq. 8-75)

**F6NUC4** Exp. used in Nu number correlation (Forced Convection - Rod Bundle) (Eq. 8-75)

31 **Y6HYOZ(K)** Hydraulic diameter of inlet orifice zone of each channel (K=1,N6CHAN) [m]

Note: Of the three parameters Y6HYOZ, P6FINZ, and F6ZINZ, two must be non-zero. The other is zero for each channel.

32 **F6LSA(1,K)** K-loss pressure at inlet orifice zone for each channel (K=1,N6CHAN)

**F6LSA(2,K)** K-loss pressure at assembly outlet for each channel (K=1,N6CHAN)

Note: If value positive, the actual K-loss factor. If value negative, the K-loss pressure drop. [N/m²]

Note: Data for this consists of a series of paired points. The index K is incremented over the set of all data required.

That is, F6LSA(1,1), F6LSA(2,1), F6LSA(1,2), etc.

33 **P6FINZ(K)** Pressure drop due to friction across the inlet orifice zone for each channel (K=1,N6CHAN) [N/m²]

Note: Of the three parameters Y6HYOZ, P6FINZ, and F6ZINZ, two must be non-zero. The other is zero for each channel.

34 **F6ZINZ(K)** Fraction of assembly inlet orifice zone length (Z6INZ) assigned to each channel (K=1,N6CHAN)

Note: Of the three parameters Y6HYOZ, P6FINZ, and F6ZINZ, two must be non-zero. The other is zero for each channel.

39 set to 0.

41 set to (N6CHAN), 0

101 - 199 (Implied rod type dependency, L = Number - 100)

**Z6LFGP** Axial length of lower fission gas plenum region of L-th rod type [m]
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z6LBLK</td>
<td>Axial length of lower blanket region of L-th rod type</td>
<td>[m]</td>
</tr>
<tr>
<td>Z6AFUL</td>
<td>Axial length of active fuel region of L-th rod type</td>
<td>[m]</td>
</tr>
<tr>
<td>Z6UBLK</td>
<td>Axial length of upper blanket region of L-th rod type</td>
<td>[m]</td>
</tr>
<tr>
<td>Z6UFGP</td>
<td>Axial length of upper fission gas plenum region of L-th rod type</td>
<td>[m]</td>
</tr>
<tr>
<td>N6LFGP</td>
<td>Number of axial coolant nodes in lower fission gas plenum region of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>N6LBLK</td>
<td>Number of axial coolant nodes in lower blanket region of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>N6AFUL</td>
<td>Number of axial coolant nodes in active fuel region of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>N6UBLK</td>
<td>Number of axial coolant nodes in upper blanket region of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>N6UFGP</td>
<td>Number of axial coolant nodes in upper fission gas plenum region of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>F6PD</td>
<td>Pitch to diameter ratio of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>F6PWD</td>
<td>Pitch to diameter ratio for wire wrap of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>L5CLMT</td>
<td>Index of cladding material of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>L5STMT</td>
<td>Index of structural material of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>L5LBMT</td>
<td>Index of lower blanket material of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>F5DLBU</td>
<td>Fractional unrestructured grain density of lower blanket of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>F5DLBE</td>
<td>Fractional equiaxed grain density of lower blanket of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>F5DLBC</td>
<td>Fractional columnar grain density of lower blanket of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>L5AFMT</td>
<td>Index of active fuel material of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>F5DAFU</td>
<td>Fractional unrestructured grain density of active fuel of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>F5DAFE</td>
<td>Fractional equiaxed grain density of active fuel for L-th rod type</td>
<td></td>
</tr>
<tr>
<td>F5DAFC</td>
<td>Fractional columnar grain density of active fuel for L-th rod type</td>
<td></td>
</tr>
<tr>
<td>L5UBMT</td>
<td>Index of upper blanket material of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>F5DUBU</td>
<td>Fractional unrestructured grain density of upper blanket of L-th rod type</td>
<td></td>
</tr>
<tr>
<td>F5DUBE</td>
<td>Fractional equiaxed grain density of upper blanket of L-th rod type</td>
<td></td>
</tr>
</tbody>
</table>
L-th rod type

**F5DUBC** Fractional columnar grain density of upper blanket of L-th rod type

**N5AROD** Number of rods per assembly of L-th rod type

**Y5WIRE** Wire wrap diameter of L-th rod type [m]

**Y5FLAT** Hex-Can flat-to-flat inner diameter of L-th rod type

**X5HXCN** Total Hex-Can wall thickness of L-th rod type [m]

**Z6INZ** Length of the inlet hydraulic orifice zone of L-th rod type [m]

201 - 299 (Implied channel dependency, K = Number - 200)

**F5PAX(J)** Axial power fraction for each node in the K-th channel (J=N5ASEC(L5ATYP(K)))

301 - 399 (Implied channel dependency, K = Number - 300)

**F5PRAD(I)** Fuel power fraction in each radial fuel node in the K-th Channel (I=N5NFR(K))

Note: No axial dependence

401 - 499 (Implied channel dependency, K = Number - 400)

**F5PWR5** Fraction of power generated in the K-th channel deposited directly into the fuel

**F5PWR6** Fraction of power generated in the K-th channel deposited directly into the clad

**F5PWR1** Fraction of power generated in the K-th channel deposited directly into the coolant

501 - 599 (Implied channel dependency, K = Number - 500)

**L5GAS(I)** Index of each fission gas type in the K-th channel

**F5GAS(I)** Mole fraction of each fission gas in the K-th channel

Note: Data for this consists of a maximum of 3 paired points. The index I is incremented over the set of all data required for the That is, L5GAS(1), F5GAS(1), L5GAS(2), F5GAS(2), etc.
**Sodium Loop Data (NALOOP)**

Geometric and hydraulic data required to specify the primary and secondary loop piping, pumps and IHX.

<table>
<thead>
<tr>
<th>Rec.</th>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N1LOOP</td>
<td>Must be the first in file NALOOP</td>
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</tr>
<tr>
<td></td>
<td>N1PIPE</td>
<td>Number of primary loops simulated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N1NODE(J)</td>
<td>Number of nodes in each pipe of primary loop (J=1,N1PIPE)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N2PIPE</td>
<td>Number of pipes in intermediate loop</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N2NODE(J)</td>
<td>Number of nodes in each pipe of intermediate loop (J=1,N2PIPE)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Note:</td>
<td>There exists an implied maximum number of data elements for any record.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>At present this limit is 99. This may restart the heat transport system</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>nodalization.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>F1LUMP(K)</td>
<td>Number of actual loops in each simulated loop (K=1,N1LOOP)</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>N1TUBE</td>
<td>Number of tubes in IHX</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y1TUB1</td>
<td>Inner diameter of IHX tubes</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>Y1TUB2</td>
<td>Outer diameter of IHX tubes</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>A1IHX</td>
<td>Flow area on primary side of IHX</td>
<td>[m²]</td>
</tr>
<tr>
<td></td>
<td>V1BYP</td>
<td>Volume of sodium in IHX primary bypass</td>
<td>[m³]</td>
</tr>
<tr>
<td></td>
<td>V1IHX</td>
<td>Volume of sodium in IHX primary heat exchange region</td>
<td>[m³]</td>
</tr>
<tr>
<td></td>
<td>B1SHEL</td>
<td>Mass of IHX shell</td>
<td>[kg]</td>
</tr>
<tr>
<td></td>
<td>A1SHEL</td>
<td>Heat transfer area of IHX shell</td>
<td>[m²]</td>
</tr>
<tr>
<td></td>
<td>F1POD</td>
<td>Pitch-to-diameter ratio for IHX tube bundle</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H1FLP</td>
<td>Fouling resistance on outer (primary) surface of tubes</td>
<td>[m² K/W]</td>
</tr>
<tr>
<td></td>
<td>H1FLS</td>
<td>Fouling resistance on inner (secondary) surface of tubes</td>
<td>[m² K/W]</td>
</tr>
<tr>
<td></td>
<td>L1STRC</td>
<td>Primary loop structural material ID</td>
<td></td>
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<tr>
<td>101</td>
<td>L1FDIR</td>
<td>IHX flow indicator: 1 = parallel flow in IHX,</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>-1 = counter flow</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L1KP</td>
<td>Input option indicator: 0 = P1PDHX specified,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 = F1LOSS(JIHX) specified</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F1IN</td>
<td>Primary inlet loss coefficient for IHX</td>
<td></td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit(s)</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------------------------------------------------------------------------------</td>
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<tr>
<td>F1OUT</td>
<td>Primary outlet loss coefficient for IHX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1KS</td>
<td>Input option indicator: 0 = P2PDHX specified, 1 = F2LOSX specified</td>
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</tr>
<tr>
<td>F2INHX</td>
<td>Inlet loss coefficient to IHX secondary side</td>
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</tr>
<tr>
<td>F2EXPN</td>
<td>Loss coefficient for expansion from tubes to outlet region in IHX</td>
<td></td>
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<tr>
<td>F2CONT</td>
<td>Loss coefficient for contraction from inlet plenum to tubes in IHX</td>
<td></td>
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<tr>
<td>F2OUHX</td>
<td>Outlet loss coefficient from IHX secondary side</td>
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<td></td>
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<tr>
<td>X1PLEN(1)</td>
<td>Length of IHX primary inlet plenum</td>
<td>m</td>
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<tr>
<td>X1PLEN(2)</td>
<td>Length of IHX primary outlet plenum</td>
<td>m</td>
<td></td>
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<tr>
<td>X2PLEN(1)</td>
<td>Length of IHX intermediate inlet plenum</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>X2PLEN(2)</td>
<td>Length of IHX intermediate outlet plenum</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>V1PLEN(1)</td>
<td>Sodium volume of IHX primary inlet plenum</td>
<td>m³</td>
<td></td>
</tr>
<tr>
<td>V1PLEN(2)</td>
<td>Sodium volume of IHX primary outlet plenum</td>
<td>m³</td>
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<tr>
<td>V2PLEN(1)</td>
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<td>m³</td>
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<td>V2PLEN(2)</td>
<td>Sodium volume of IHX intermediate outlet plenum</td>
<td>m³</td>
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<tr>
<td>R1PLEN(1)</td>
<td>The angle of flow in IHX primary inlet plenum</td>
<td>deg</td>
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<td>R1PLEN(2)</td>
<td>The angle of flow in IHX primary outlet plenum</td>
<td>deg</td>
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<tr>
<td>R2PLEN(1)</td>
<td>The angle of flow in IHX secondary inlet plenum</td>
<td>deg</td>
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</tr>
<tr>
<td>R2PLEN(2)</td>
<td>The angle of flow in IHX secondary outlet plenum</td>
<td>deg</td>
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</tr>
<tr>
<td>X2DOWN</td>
<td>Length of IHX central downcomer region</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Y2DOWN</td>
<td>Inner diameter of IHX central downcomer</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>R2DOWN</td>
<td>The angle of flow in the IHX central downcomer</td>
<td>deg</td>
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<tr>
<td>T1CONV</td>
<td>Convergence criterion for temperatures in IHX</td>
<td>K</td>
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<tr>
<td>F1EPS</td>
<td>Roughness of primary loop piping</td>
<td>m</td>
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<tr>
<td>F2EPS</td>
<td>Roughness of intermediate loop piping</td>
<td>m</td>
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<tr>
<td>I1FAIL</td>
<td>Mode of primary check valve: 0 - working, 1 - failed</td>
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<tr>
<td>I1TYPE</td>
<td>Type of primary check valve</td>
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<tr>
<td>P1PCV</td>
<td>Backpressure for check valve to close</td>
<td>N/m²</td>
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</tr>
<tr>
<td>F1CVAL(1)</td>
<td>Check valve charact. coeff. for positive flow w/ open valve (Eq. 3.2-71)</td>
<td>m⁴</td>
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<tr>
<td>F1CVAL(2)</td>
<td>Check valve charact. coeff. for positive flow w/ open valve (Eq. 3.2-71)</td>
<td>m⁴</td>
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<tr>
<td>F1CVAL(3)</td>
<td>Check valve charact. coeff. for positive flow w/ open valve (Eq. 3.2-71)</td>
<td>m⁴</td>
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<tr>
<td>Code</td>
<td>Description</td>
<td>Unit</td>
<td></td>
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<td>-------</td>
<td>------------------------------------------------------------------------------</td>
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<tr>
<td>Z1HEDR</td>
<td>Rated head of primary pump</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>U1OMGR</td>
<td>Rated speed of primary pump</td>
<td>[rpm]</td>
<td></td>
</tr>
<tr>
<td>Q1FLOR</td>
<td>Rated volumetric flow rate of primary pump</td>
<td>[m³/s]</td>
<td></td>
</tr>
<tr>
<td>T1ORKR</td>
<td>Rated torque of primary pump</td>
<td>[N-m]</td>
<td></td>
</tr>
<tr>
<td>Z1RTOT</td>
<td>Height of primary pump tank if L6RTYP ≠1</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>N1RES</td>
<td>Cross-sectional area of primary pump tank</td>
<td>[m²]</td>
<td></td>
</tr>
<tr>
<td>Q1PYTQ</td>
<td>Pump torque under pony motor operation</td>
<td>[N-m]</td>
<td></td>
</tr>
<tr>
<td>V6BPMP</td>
<td>Cold pool volume below pump inlet</td>
<td>[m³]</td>
<td></td>
</tr>
<tr>
<td>N6IHXP</td>
<td>Height from pump inlet to IHX exit if L6RTYP=1</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>A6IHXP</td>
<td>Cross-sectional area of cold pool region between pump inlet and IHX exit if L6RTYP=1</td>
<td>[m²]</td>
<td></td>
</tr>
<tr>
<td>A6OVRF</td>
<td>Cross-sectional area of cold pool region above IHX exit if L6RTYP=1</td>
<td>[m²]</td>
<td></td>
</tr>
</tbody>
</table>

* Refer to Fig.1.1 for Z1RTOT, A1RES, V6BPMP, Z6IHXP, A6IHXP, and A6OVRF

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z2HEDR</td>
<td>Rated head of intermediate pump</td>
<td>[m]</td>
</tr>
<tr>
<td>U2OMGR</td>
<td>Rated speed of intermediate pump</td>
<td>[rpm]</td>
</tr>
<tr>
<td>Q2FLOR</td>
<td>Rated volumetric flow rate of intermediate pump</td>
<td>[m³/s]</td>
</tr>
<tr>
<td>T2ORKR</td>
<td>Rated torque of intermediate pump</td>
<td>[N-m]</td>
</tr>
<tr>
<td>Z2RTOT</td>
<td>Height of intermediate pump tank</td>
<td>[m]</td>
</tr>
<tr>
<td>A2RES</td>
<td>Cross-sectional area of intermediate pump tank</td>
<td>[m²]</td>
</tr>
<tr>
<td>Z2TANK</td>
<td>Height of surge tank</td>
<td>[m]</td>
</tr>
<tr>
<td>A2TANK</td>
<td>Cross-sectional area of surge tank</td>
<td>[m²]</td>
</tr>
<tr>
<td>Q2PYTQ</td>
<td>Pump torque under pony motor operation</td>
<td>[N-m]</td>
</tr>
</tbody>
</table>

<p>| Code  | Description                                                                 ||
|-------|------------------------------------------------------------------------------|
| L1PUMP | Pipe number preceding pump in primary loop                                  |
| L1CV   | Pipe number preceding check valve in primary loop                            |
| L1IHX  | Pipe number of IHX in primary loop                                           |
| L2PUMP | Pipe number preceding pump in intermediate loop                              |
| L2TANK | Pipe number preceding expansion tank in intermediate loop                   |</p>
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>L2SG</td>
<td>Pipe number preceding evaporator in intermediate loop</td>
<td></td>
</tr>
<tr>
<td>1002</td>
<td><strong>F1BETA</strong> Primary bypass fraction through IHX</td>
<td></td>
</tr>
<tr>
<td>N1ACTV</td>
<td>Number of active (unplugged) tubes in IHX of loop</td>
<td></td>
</tr>
<tr>
<td>P1PDHX</td>
<td>Pressure drop over IHX primary side</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>10003</td>
<td><strong>P2PDHX</strong> Pressure drop over secondary side of IHX</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>F2LOSX</td>
<td>Loss coefficient for secondary side of IHX</td>
<td></td>
</tr>
<tr>
<td>1101-1199</td>
<td>(Implied (Primary loop) pipe dependency, J = Number - 1100)</td>
<td></td>
</tr>
<tr>
<td>F1LOSS</td>
<td>Loss coefficient for J-th pipe in primary loop</td>
<td></td>
</tr>
<tr>
<td>X1PIPE</td>
<td>Length of J-th pipe in primary loop</td>
<td>[m]</td>
</tr>
<tr>
<td>Y1PIPE</td>
<td>Inner diameter of J-th pipe in primary loop</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>Note: For IHX, enter primary side hydraulic diameter.</td>
<td></td>
</tr>
<tr>
<td>Y1THIK</td>
<td>Thickness of J-th pipe wall in primary loop</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>Note: This value is ignored for IHX primary pipe.</td>
<td></td>
</tr>
<tr>
<td>R1SIN(I)</td>
<td>Angle of primary flow at each node in J-th pipe of loop (I = 1, N1NODE(N1PIPE(J)))</td>
<td>[deg]</td>
</tr>
<tr>
<td>1201-1299</td>
<td>(Implied (Intermed. loop) pipe dependency, J = Number - 1200)</td>
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</tr>
<tr>
<td>F2LOSS</td>
<td>Loss coefficient for J-th pipe in intermediate loop</td>
<td></td>
</tr>
<tr>
<td>X2PIPE</td>
<td>Length of J-th pipe in intermediate loop</td>
<td>[m]</td>
</tr>
<tr>
<td>Y2PIPE</td>
<td>Inner diameter of J-th pipe in intermediate loop</td>
<td>[m]</td>
</tr>
<tr>
<td>Y2THIK</td>
<td>Thickness of J-th pipe wall in intermediate loop</td>
<td>[m]</td>
</tr>
<tr>
<td>R2SIN(I)</td>
<td>Angle of intermediate flow at each node of J-th pipe of loop (I = 1, N2NODE(N2PIPE(J)))</td>
<td>[deg]</td>
</tr>
</tbody>
</table>
MINET DATA (MINETD)

Steam Generator and Balance of Plant Data. All data required to specify the steam generator system (including balance of plant) and its associated sodium-side interfaces.

<table>
<thead>
<tr>
<th>Rec.</th>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MODID</td>
<td>Module ID assigned to pipe</td>
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</tr>
<tr>
<td></td>
<td>INLETID</td>
<td>Port identifier assigned to inlet port</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OUTLETID</td>
<td>Port identifier assigned to outlet port</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X3MOD</td>
<td>Length of module</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>Y3ID</td>
<td>Diameter of module</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>E3PSI</td>
<td>Surface roughness factor, roughness/surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N3NODE</td>
<td>Number of nodes to be used for module</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N3PATH</td>
<td>Number of parallel units being represented</td>
<td></td>
</tr>
<tr>
<td>101</td>
<td>MODID</td>
<td>Module ID assigned to valve</td>
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<tr>
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<td>INLETID</td>
<td>Port identifier assigned to inlet port</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OUTLETID</td>
<td>Port identifier assigned to outlet port</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X3MOD</td>
<td>Length of module (Pipe-like portion)</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>Y3ID</td>
<td>Diameter of module (Pipe-like portion)</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>E3PSI</td>
<td>Surface roughness factor, roughness/surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N3NODE</td>
<td>For valve, must use 1 node</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N3PATH</td>
<td>Number of parallel units being represented</td>
<td></td>
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<tr>
<td></td>
<td>A3VMAX</td>
<td>Maximum flow area thru valve when open</td>
<td>[m²]</td>
</tr>
<tr>
<td></td>
<td>S3VMIN</td>
<td>Minimum valve position, relative, must be GT 0.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F3STOA</td>
<td>Factor, position to area, AREA=POSITN**F3STOA</td>
<td></td>
</tr>
<tr>
<td>201</td>
<td>MODID</td>
<td>Module ID assigned to pump</td>
<td></td>
</tr>
<tr>
<td></td>
<td>INLETID</td>
<td>Port identifier assigned to inlet port</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OUTLETID</td>
<td>Port identifier assigned to outlet port</td>
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</tr>
<tr>
<td></td>
<td>X3MOD</td>
<td>Length of module (Pipe-like portion)</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>Y3ID</td>
<td>Diameter of module (Pipe-like portion)</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>E3PSI</td>
<td>Surface roughness factor, roughness/surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N3NODE</td>
<td>Number of nodes, for pump use 1 node</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N3PATH</td>
<td>Number of parallel units being represented</td>
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<tr>
<td>301</td>
<td>MODID</td>
<td>Module ID assigned to pump</td>
<td></td>
</tr>
<tr>
<td></td>
<td>INLETID</td>
<td>Port identifier assigned to inlet port</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OUTLETID</td>
<td>Port identifier assigned to outlet port</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X3MOD</td>
<td>Length of module (Pipe-like portion)</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>Y3ID</td>
<td>Diameter of module (Pipe-like portion)</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>E3PSI</td>
<td>Surface roughness factor, roughness/surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N3NODE</td>
<td>Number of nodes, for pump use 1 node</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N3PATH</td>
<td>Number of parallel units being represented</td>
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</tr>
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</table>

A-12
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODID</td>
<td>Module ID assigned to heat exchanger</td>
</tr>
<tr>
<td>INLETID</td>
<td>Port ID assigned to inlet port, inside tube</td>
</tr>
<tr>
<td>OUTLETID</td>
<td>Port ID assigned to outlet port, inside tube</td>
</tr>
<tr>
<td>X3MOD</td>
<td>Length of module (Active heat transfer length) [m]</td>
</tr>
<tr>
<td>Y3ID</td>
<td>Inner diameter of heat transfer tubes [m]</td>
</tr>
<tr>
<td>E3PSI</td>
<td>Surface roughness factor inside tubes</td>
</tr>
<tr>
<td>N3NODE</td>
<td>Number of axial nodes to be used</td>
</tr>
<tr>
<td>N3PATH</td>
<td>Number of parallel units being represented</td>
</tr>
<tr>
<td>INLETID</td>
<td>Port ID assigned to inlet port, outside tube</td>
</tr>
<tr>
<td>OUTLETID</td>
<td>Port ID assigned to outlet port, outside tube</td>
</tr>
<tr>
<td>Y3OD</td>
<td>Outer diameter of heat transfer tube [m]</td>
</tr>
<tr>
<td>F3TBPD</td>
<td>Pitch to diameter ratio (Tube spacing / Diameter)</td>
</tr>
<tr>
<td>N3TUBE</td>
<td>Number of tubes per heat exchanger</td>
</tr>
<tr>
<td>M3TYPE</td>
<td>Material type in tubing</td>
</tr>
<tr>
<td>I3GRID</td>
<td>Number of tubes equal-distant from center tube, 1, 4, 6</td>
</tr>
<tr>
<td>D3COIL</td>
<td>Helical coil diameter, 0 for straight tubes [m]</td>
</tr>
<tr>
<td>F3ITOO</td>
<td>Ratio of flow length inside tube to outside</td>
</tr>
<tr>
<td>Y3CORO</td>
<td>Diameter of core tube (Zero of none)</td>
</tr>
<tr>
<td>M3CORT</td>
<td>Material type of core tube</td>
</tr>
<tr>
<td>M3STRC</td>
<td>Material type of heat exchanger shell and structure</td>
</tr>
<tr>
<td>A3STRC</td>
<td>Surface area between structure - fluid, sum - path [m²]</td>
</tr>
<tr>
<td>B3STRC</td>
<td>Mass of structure, summed over parallel paths [kg]</td>
</tr>
</tbody>
</table>

M3TYPE, M3CORT, M3STRC Options:
1 - St Steel, 2- 2.25 Ch-Mly, 3- Admrty, 4- 90-10 Cu-Ni 8- 80-20 Cu-Ni, 6- 70-30 Cu-Ni, 7- Monel, 8-Inconnel 9- Carbon Steel, 10- Aluminum

401 Inlet boundary module geometric

MODID Module ID assigned to inlet boundary
OUTLETID Port ID assigned to BND outlet (System Inlet)

402 Outlet boundary module geometric
MODID Module ID assigned to outlet boundary
INLETID Port ID assigned to BND inlet (System Outlet)

501 Volume geometric
MODID Module ID assigned to volume
L3VSHP Component shape,
1=vertical cylinder or box, 2=horizontal cylinder
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>V3VOL</td>
<td>Volume within module (Portion of component)</td>
<td>[m$^3$]</td>
</tr>
<tr>
<td>Y3VOL</td>
<td>Total height of component</td>
<td>[m]</td>
</tr>
<tr>
<td>F3VMIN</td>
<td>Relative height of module low point with respect to component</td>
<td></td>
</tr>
<tr>
<td>F3VMAX</td>
<td>Relative height of module high point with respect to component</td>
<td></td>
</tr>
<tr>
<td>Z3VOL</td>
<td>Elevation of component vertical midpoint</td>
<td>[m]</td>
</tr>
<tr>
<td>N3PATH</td>
<td>Number of parallel units being represented</td>
<td></td>
</tr>
<tr>
<td>L3PSEP</td>
<td>1=homogeneous, 2=separated phases, 3=1SS-2TRN</td>
<td></td>
</tr>
<tr>
<td>511</td>
<td>Volume inlet port geometric</td>
<td></td>
</tr>
<tr>
<td>MODID</td>
<td>Module ID assigned to volume</td>
<td></td>
</tr>
<tr>
<td>INLETID</td>
<td>Port ID assigned to incoming volume port</td>
<td></td>
</tr>
<tr>
<td>512</td>
<td>Volume outlet port geometric</td>
<td></td>
</tr>
<tr>
<td>MODID</td>
<td>Module ID assigned to volume</td>
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</tr>
<tr>
<td>OUTLETID</td>
<td>Port ID assigned to outgoing volume port</td>
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<tr>
<td>601</td>
<td>Turbine stage geometric</td>
<td></td>
</tr>
<tr>
<td>MODID</td>
<td>Module ID assigned to turbine stage</td>
<td></td>
</tr>
<tr>
<td>INLETID</td>
<td>Port ID assigned to inlet port</td>
<td></td>
</tr>
<tr>
<td>OUTLETID</td>
<td>Port ID assigned to outlet port</td>
<td></td>
</tr>
<tr>
<td>ALPHA</td>
<td>Absolute angle of approach steam with respect to blade, eg-15</td>
<td>[deg]</td>
</tr>
<tr>
<td>801</td>
<td>Network geometric</td>
<td></td>
</tr>
<tr>
<td>MODID</td>
<td>Module ID of any boundary or accumulator in network</td>
<td></td>
</tr>
<tr>
<td>IFTYPN</td>
<td>Fluid type, 1-H2O, 2-Sodium, 3-Air, 4-NaK</td>
<td></td>
</tr>
<tr>
<td>901</td>
<td>Junction</td>
<td></td>
</tr>
<tr>
<td>Z3J</td>
<td>CTN Elevation of interface between module ports</td>
<td>[m]</td>
</tr>
<tr>
<td>MODID1</td>
<td>Module ID of first module</td>
<td></td>
</tr>
<tr>
<td>PORTID1</td>
<td>Port ID of first module</td>
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<tr>
<td>MODID2</td>
<td>Module ID of second module</td>
<td></td>
</tr>
<tr>
<td>PORTID2</td>
<td>Port ID of second module</td>
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<tr>
<td>1001</td>
<td>Pipe performance</td>
<td></td>
</tr>
<tr>
<td>MODID</td>
<td>Module ID of pipe</td>
<td></td>
</tr>
<tr>
<td>F3KMI</td>
<td>Loss coefficient (K) for module</td>
<td></td>
</tr>
<tr>
<td>1101</td>
<td>Valve performance (If choked, must isolate)</td>
<td></td>
</tr>
<tr>
<td>MODID</td>
<td>Module ID of valve</td>
<td></td>
</tr>
<tr>
<td>F3KMI</td>
<td>Module loss coefficient - pipe-like section</td>
<td></td>
</tr>
<tr>
<td>F3VALV</td>
<td>Loss coefficient across valve opening</td>
<td></td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td></td>
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<tr>
<td><strong>I3CHOK</strong></td>
<td>Choke flow option, 0-none, 1-choking expected</td>
<td></td>
</tr>
<tr>
<td><strong>J3VPRS</strong></td>
<td>Volume where pressure taken, not used= -999</td>
<td></td>
</tr>
<tr>
<td><strong>P3VOPN</strong></td>
<td>Pressure at which valve trips open [Pa]</td>
<td></td>
</tr>
<tr>
<td><strong>S3VOPN</strong></td>
<td>Valve opening time constant [s]</td>
<td></td>
</tr>
<tr>
<td><strong>P3VCLO</strong></td>
<td>Pressure at which valve trips shut [Pa]</td>
<td></td>
</tr>
<tr>
<td><strong>S3VCLO</strong></td>
<td>Valve closing time constant [s]</td>
<td></td>
</tr>
</tbody>
</table>

**Alternate use of last parameters** For check valve
- J3VPRS=0 for check valve
- P3VOPN=flow/path [kg/s] to open
- P3VCLO=flow/path [kg/s] to close

**1201 Pump performance**
- **MODID**: Module ID of pump
- **F3KMI**: Module loss coefficient
- **W3REFF**: Reference flow rate (per unit) [kg/s]
- **H3REF**: Reference pump head [m]
- **F3REF**: Reference pump speed [rpm]
- **A3PUMP**:
  1. \(\text{HEAD}(\text{SPEED}, \text{FLOW}) = H3REF \times (\text{SPEED}/F3REF)^2\)
  2. \((A3PUMP(1) + A3PUMP(2) \times \text{WRATIO})\)
  3. \((A3PUMP(3) \times \text{WRATIO}^2 + A3PUMP(4) \times \text{WRATIO}^3 + A3PUMP(5) \times \text{WRATIO}^4)\)

  \(\text{where WRATIO} = \frac{W}{(W3REFF \times (\text{SPEED}/F3REF))}\)
- **S3PTAU**: Pump coastdown time constant, SPD=SPD0*E-T/TAU [s]
- **S3PSEZ**: Pump seizure time after trip [s]

**1301 Heat exchanger performance**
- **MODID**: Module ID of heat exchanger
- **F3KMI**: Module loss coefficient, inside tubes
- **F3KMO**: Module loss coefficient, outside tubes
- **I3LVTI**: DNB/DRYOUT option,
  1-DNB, 2-DRYOUT, 3-X=0.75
- **I3LVTO**: Same as I3LVTI, but applied outside tubes
- **F3CCFL**: Flow direction, 1=parallel, 0=cross, -1=counter

**1601 Turbine performance**
- **MODID**: Module ID for turbine
- **I3TTYP**: Turbine stage type, 1=impulse, 2=impuls-react
- **E3FGEN**: Efficiency to electrical grid
- **W3TREF**: Reference flow rate [kg/s]
- **P3ITRF**: Reference inlet pressure [Pa]
<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3OTRF</td>
<td>Reference outlet pressure</td>
<td>[Pa]</td>
</tr>
<tr>
<td>T3ITRF</td>
<td>Reference inlet temperature</td>
<td>[K]</td>
</tr>
<tr>
<td>R3TSRF</td>
<td>Reference speed</td>
<td>[rpm]</td>
</tr>
<tr>
<td>S3TTAU</td>
<td>Coastdown time constant, SPD=SPD0*EXP(-T/TAU)</td>
<td>[s]</td>
</tr>
<tr>
<td>S3TSEZ</td>
<td>Seizure time (After Trip)</td>
<td>[s]</td>
</tr>
<tr>
<td>MODID</td>
<td>Module ID of pipe</td>
<td></td>
</tr>
<tr>
<td>Q3MOD</td>
<td>Heat put into module, sum over parallel units</td>
<td>[J/s]</td>
</tr>
<tr>
<td>MODID</td>
<td>Module ID of valve</td>
<td></td>
</tr>
<tr>
<td>Q3MOD</td>
<td>Heat put into module, sum over parallel units</td>
<td>[J/s]</td>
</tr>
<tr>
<td>S3VPOS</td>
<td>Initial stem position, relative, 0=closed, 1=open</td>
<td></td>
</tr>
<tr>
<td>MODID</td>
<td>Module ID of pump</td>
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</tr>
<tr>
<td>Q3MOD</td>
<td>Heat put into module, sum over parallel units</td>
<td>[J/s]</td>
</tr>
<tr>
<td>F3PUMP</td>
<td>Initial pump speed</td>
<td>[rpm]</td>
</tr>
<tr>
<td>MODID</td>
<td>Module ID of heat exchanger</td>
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</tr>
<tr>
<td>Q3MOD</td>
<td>Total heat transfer, out to in, sum over parallel units</td>
<td>[J/s]</td>
</tr>
<tr>
<td>MODID</td>
<td>Module ID of boundary</td>
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</tr>
<tr>
<td>K3EBST</td>
<td>Boundary status, 0=inlet, 1=floating, 2=fixed</td>
<td></td>
</tr>
<tr>
<td>K3EBC</td>
<td>E3BC flag, 1=enthalpy, 2=temperature, 3=quality</td>
<td></td>
</tr>
<tr>
<td>E3BC</td>
<td>Enthalpy, temperature, or quality (If H2O)</td>
<td>J/KG</td>
</tr>
<tr>
<td>W3BC</td>
<td>Mass flow (total) used for inlets only</td>
<td>[kg/s]</td>
</tr>
<tr>
<td>P3BC</td>
<td>Pressure used for outlets only</td>
<td>[Pa]</td>
</tr>
<tr>
<td>MODID</td>
<td>Module ID of volume</td>
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</tr>
<tr>
<td>Q3MOD</td>
<td>Heat put into module, sum over parallel units</td>
<td>[J/s]</td>
</tr>
<tr>
<td>F3LQLV</td>
<td>Relative liquid level vs component height</td>
<td></td>
</tr>
<tr>
<td>P3VOL</td>
<td>Estimated volume pressure at steady state</td>
<td>[Pa]</td>
</tr>
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<td>MODID</td>
<td>Module ID of volume</td>
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</tr>
<tr>
<td>OUTLETID</td>
<td>Outlet port ID of volume</td>
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</tr>
<tr>
<td>W3VOUT</td>
<td>Estimate of flow exiting, sum over parallel path</td>
<td>[kg/s]</td>
</tr>
</tbody>
</table>

Pipe initial condition (All QMOD's subject to adjust.)

Valve initial condition

Pump initial condition

Heat exchanger initial condition

Boundary module initial condition

Mass flow (total) used for inlets only

Pressure used for outlets only

Volume initial condition

Volume outlet port initial condition

Turbine stage initialization
MODID    Module ID of turbine stage
R3TS     Initial turbine speed [rpm]
Q3MOD    Work done on turbine stage [J/s]

3011  Pipe heat input table (Repeat 2 and 3 entries)
MODID    Module ID of pipe
S3QT     Time of table entry [s]
Q3MDT    Heat input for corresponding time [J/s]

3111  Valve heat input table (Repeat 2 and 3 entries)
MODID    Module ID of valve
S3QT     Time of table entry [s]
Q3MDT    Heat input for corresponding time [J/s]

3121  Valve position table - optional (Repeat entries 2 and 3)
MODID    Module ID of valve
S3VTIM   Time of valve position table entry [s]
S3VPSN   Relative valve stem position

3201  Pump transient (Can be over-ruled by 3221D)
MODID    Module ID of pump
S3PTRP   Time at which pump is tripped [s]

3211  Pump heat input table (Repeat entries 2 and 3)
MODID    Module ID of pump
S3QT     Time of table entry [s]
Q3MDT    Heat input at corresponding time [J/s]

3221  Pump speed table - optional (Repeat entries 2 and 3)
MODID    Module ID of pump
S3PTIM   Time of table entry [s]
R3PMPT   Pump speed at corresponding time [rpm]

3411  Boundary condition table (Repeat entries 4, 5, and 6)
MODID    Module ID of boundary
I3BCTP   Key, 1=flow specified, 2=pressure specified
K3ETAB   Key for ETAB, 1=enthalpy, 2=temperature, 3=quality
S3TAB    Time of table entry [s]
E3TAB    Enthalpy, temperature, or quality entry [J/kg] or [K]
P3WTAB   Flow or pressure table entry [kg/s] or [Pa]

3511  Volume heat input table (Repeat 2, 3 entries)
MODID    Module ID of volume
<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3QT</td>
<td>Time of table entry</td>
<td>[s]</td>
</tr>
<tr>
<td>Q3MDT</td>
<td>Heat input at corresponding time</td>
<td>[J/s]</td>
</tr>
<tr>
<td>3601</td>
<td>Turbine trip (Can be overruled by 3611D)</td>
<td></td>
</tr>
<tr>
<td>MODID</td>
<td>Module ID of turbine stage</td>
<td></td>
</tr>
<tr>
<td>S3TSTP</td>
<td>Turbine trip time</td>
<td>[s]</td>
</tr>
<tr>
<td>3611</td>
<td>Turbine speed table - optional (Repeat entries 2 and 3)</td>
<td></td>
</tr>
<tr>
<td>MODID</td>
<td>Module ID of turbine stage</td>
<td></td>
</tr>
<tr>
<td>S3TSTB</td>
<td>Time of turbine speed table entry</td>
<td>[s]</td>
</tr>
<tr>
<td>R3TSTB</td>
<td>Turbine speed at corresponding time</td>
<td>[rpm]</td>
</tr>
<tr>
<td>4000</td>
<td>Run control card</td>
<td></td>
</tr>
<tr>
<td>S3END</td>
<td>End of transient simulation</td>
<td>[s]</td>
</tr>
<tr>
<td>4100</td>
<td>Print control (Repeat entries 3 and 4)</td>
<td></td>
</tr>
<tr>
<td>L3PRON</td>
<td>Step number to start frequent prints, -1 for SS</td>
<td></td>
</tr>
<tr>
<td>L3PRNT</td>
<td>Keys print detail, 1=brief, 2=middle, 3=detailed</td>
<td></td>
</tr>
<tr>
<td>S3PRIN</td>
<td>Print interval</td>
<td>[s]</td>
</tr>
<tr>
<td>S3PLIM</td>
<td>Time limit for corresponding print interval value</td>
<td>[s]</td>
</tr>
<tr>
<td>4200</td>
<td>Context save control</td>
<td></td>
</tr>
<tr>
<td>L3REST</td>
<td>Context restore control, 0=no restore, 1=restore context</td>
<td></td>
</tr>
<tr>
<td>N3SINT</td>
<td>Context save control, defines print count between saves</td>
<td></td>
</tr>
</tbody>
</table>
Initial overall plant operating conditions and specification of plant balance initialization logic.

<table>
<thead>
<tr>
<th>Rec.</th>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P9OP</td>
<td>Reactor power</td>
<td>[W]</td>
</tr>
<tr>
<td></td>
<td>N9LOOP</td>
<td>Number of operating loops present in plant</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>T6OUTL</td>
<td>Vessel sodium outlet temperature</td>
<td>[K]</td>
</tr>
<tr>
<td></td>
<td>T6INLT</td>
<td>Vessel sodium inlet temperature</td>
<td>[K]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cf. TRNDAT 8015, T81REF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W1LOOP</td>
<td>Sodium flow rate in primary loop</td>
<td>[kg/s]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cf. TRNDAT 8015, W81REF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Note: Of the three parameters in this, two must be specified as known (denoted by entering values greater than zero) while the other one is assumed unknown (denoted by entering a value less than zero) and will be calculated by SSC. The unknown value to be entered need not be too precise; it can be an approximate initial guess.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>T2IHXI</td>
<td>IHX intermediate sodium inlet temperature</td>
<td>[K]</td>
</tr>
<tr>
<td></td>
<td>T2IHXO</td>
<td>IHX intermediate sodium outlet temperature</td>
<td>[K]</td>
</tr>
<tr>
<td></td>
<td>W2LOOP</td>
<td>Sodium flow rate in intermediate loop</td>
<td>[kg/s]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cf. TRNDAT 8015, W82REF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Note: Of the three parameters in this one must be specified as known (denoted by entering values greater than zero) while the others are assumed unknown (denoted by entering a value less than zero) and will be calculated by SSC. The accuracy of the initial guesses for this are more important.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>P1GASI</td>
<td>Initial cover gas pressure in each primary pump tank</td>
<td>[N/m²]</td>
</tr>
<tr>
<td></td>
<td>P2GASI</td>
<td>Initial cover gas pressure in each intermediate loop</td>
<td>[N/m²]</td>
</tr>
<tr>
<td></td>
<td>Z2TANK</td>
<td>Height of coolant in surge (expansion) tank</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>T1PUMP</td>
<td>Temperature rise across primary pump</td>
<td>[K]</td>
</tr>
<tr>
<td></td>
<td>T2PUMP</td>
<td>Temperature rise across intermediate pump</td>
<td>[K]</td>
</tr>
<tr>
<td>5</td>
<td>L1EPRT</td>
<td>Primary and intermediate loop detailed print option; 1= report, 0= no report</td>
<td></td>
</tr>
<tr>
<td>Code</td>
<td>Description</td>
<td>Value</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>--------------------------------------------------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>L3PRNT</td>
<td>SG detailed print option;</td>
<td>1-4,0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 - 4 = low to high detail report,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 = no report</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L5PRNT</td>
<td>Detailed in vessel temp. distribution print option;</td>
<td>1,0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 = report, 0 = no report</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L6PRNT</td>
<td>In-vessel fluid dynamics detailed print option;</td>
<td>1,0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 = report, 0 = no report</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
MATDAT

A set of material properties data is built into the code. The data required to alter the default values of the material properties, or to create new material properties, are input to the code through data file MATDAT.

<table>
<thead>
<tr>
<th>Rec.</th>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td></td>
<td>Material properties for sodium</td>
<td></td>
</tr>
<tr>
<td>40 - 49</td>
<td></td>
<td>Material properties for blanket</td>
<td></td>
</tr>
<tr>
<td>50 - 59</td>
<td></td>
<td>Material properties for fuel</td>
<td></td>
</tr>
<tr>
<td>60 - 69</td>
<td></td>
<td>Material properties for cladding</td>
<td></td>
</tr>
<tr>
<td>70 - 79</td>
<td></td>
<td>Material properties for structural material</td>
<td></td>
</tr>
<tr>
<td>80 - 89</td>
<td></td>
<td>Material properties for cover gas</td>
<td></td>
</tr>
</tbody>
</table>

TRNDAT

Transient scenario data

<table>
<thead>
<tr>
<th>Rec.</th>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1001</td>
<td>L1PONY(K)</td>
<td>Primary loop pony motor status; 1 = motor is on, 0 = motor is off ( K = 1, N1LOOP )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F1PONY</td>
<td>Primary pony motor speed fraction of rated speed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Q1NRTA</td>
<td>Primary pump inertia [KG*M2]</td>
<td></td>
</tr>
<tr>
<td>1002</td>
<td>L2PONY(K)</td>
<td>Secondary loop pony motor status; 1 = motor is on, 0 = motor is off ( K = 1, N1LOOP )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F2PONY</td>
<td>Secondary pony motor speed fraction of rated speed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Q2NRTA</td>
<td>Secondary pump inertia</td>
<td>[kg,m^2]</td>
</tr>
<tr>
<td>1003</td>
<td>L1GV(K)</td>
<td>Guard vessel option; 0 = no guard vessel, 1 = reactor vessel outlet, 2 = RV inlet, 3 = pump inlet, 4 = pump outlet, 5 = IHX inlet, 6 = IHX outlet ( K = 1, N1LOOP )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V1MINR</td>
<td>R.V. guard vessel volume at level with break</td>
<td>[m^3]</td>
</tr>
<tr>
<td></td>
<td>Z1MAXR</td>
<td>R.V. guard vessel maximum level that can be reached by coolant</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>F1GVR(1)</td>
<td>R.V. guard vessel volume to level coeff.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F1GVR(2)</td>
<td>R.V. guard vessel volume to level coeff.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F1GVR(3)</td>
<td>R.V. guard vessel volume to level coeff.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V1MINP</td>
<td>Pump guard vessel volume at level with pipe break</td>
<td>[m^3]</td>
</tr>
</tbody>
</table>
Z1MAXP  Pump guard vessel maximum level that can be reached by coolant [m]
F1GVP(1)  Pump guard vessel volume to level coeff.
F1GVP(2)  Pump guard vessel volume to level coeff.
F1GVP(3)  Pump guard vessel volume to level coeff.
V1MINX  IHX guard vessel volume at level with pipe break [m^3]
Z1MAXX  IHX guard vessel maximum level that can be reached by coolant [m]
F1GVX(1)  IHX guard vessel volume to level coeff.
F1GVX(2)  IHX guard vessel volume to level coeff.
F1GVX(3)  IHX guard vessel volume to level coeff.
V1MAX  Maximum volume that can be filled in guard vessel in any location [m^3]

1004  I1FAIL(K)  Primary check valve status;
0 = working,  1 = failed  (K = 1, N1LOOP)

1101 - 1199  (Implied primary loop dependency, J = number - 1100)
J1BREK  Primary loop pipe number containing break
N1NBRK  Number of nodes in broken primary pipe upstream of break
X1BREK  Length of primary pipe upstream of break [m]
F1LSBK  Loss coefficient at primary break
A1BREK  Break area in primary pipe [m^2]
A1GAP  X-sectional area between broken primary pipe and guard vessel [m^2]
S1BREK  Time of primary pipe break [s]
Note: This series is specified only for loop(s) containing break(s).

1201 - 1299  (Implied secondary loop dependency, J = number - 1200)
J2BREK  Secondary loop pipe number containing break
N2NBRK  Number of nodes in broken secondary pipe upstream of break
X2BREK  Length of primary pipe upstream of break [m]
F2LSBK  Loss coefficient at secondary break
A2BREK  Break area in secondary pipe [m^2]
A2GAP  X-sectional area between broken secondary pipe and guard pipe [m^2]
S2BREK  Time of secondary pipe break [s]
<table>
<thead>
<tr>
<th>3101 MODID</th>
<th>Module ID of boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>N3TAB</td>
<td>Number of table entries on corresponding 3111</td>
</tr>
<tr>
<td>I3BCTP</td>
<td>Boundary condition type; 1 = flow, 2 = pressure</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3111 MODID</th>
<th>Module ID of boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3TAB(I)</td>
<td>Time for table entry [s]</td>
</tr>
<tr>
<td>E3TAB(I)</td>
<td>Enthalpy [J/KG] or temperature [K] for table entry</td>
</tr>
<tr>
<td>P3WTAB(I)</td>
<td>Pressure [Pa] of flow [kg/s] for table entry</td>
</tr>
</tbody>
</table>

Note: Data is entered as a user defined series of paired points.

<table>
<thead>
<tr>
<th>3201 MODID</th>
<th>Module ID of volume (Accumulator)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N3VOLT</td>
<td>Number of table entries on corresponding 3211</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3211 MODID</th>
<th>Module ID of volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3VOLT(I)</td>
<td>Time for table entry [s]</td>
</tr>
<tr>
<td>Q3VOLT(I)</td>
<td>Heat input to all parallel volumes [J/s]</td>
</tr>
</tbody>
</table>

Note: Data is entered as a user defined series of paired points.

<table>
<thead>
<tr>
<th>3301 MODID</th>
<th>Module ID of valve</th>
</tr>
</thead>
<tbody>
<tr>
<td>N3VALT(I)</td>
<td>Number of table entries on corresponding 3311</td>
</tr>
<tr>
<td>N3VCAS</td>
<td>PPS/PCS option; 0 = Ignore PPS/PCS, 1 = Accept PPS/PCS signal</td>
</tr>
</tbody>
</table>

Note: At present, N3VCAS must be set equal to zero.

<table>
<thead>
<tr>
<th>3311 MODID</th>
<th>Module ID of valve</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3VALT(I)</td>
<td>Time for table entry [s]</td>
</tr>
<tr>
<td>S3VPST(I)</td>
<td>Valve stem position; 0 = Full closed, 1 = Full open</td>
</tr>
</tbody>
</table>

Note: Data is entered as a user defined series of paired points.

<table>
<thead>
<tr>
<th>3401 MODID</th>
<th>Module ID of pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>N3PUMT(I)</td>
<td>Number of table entries on corresponding 3411</td>
</tr>
<tr>
<td>S3PTRP</td>
<td>Pump trip time [s]</td>
</tr>
<tr>
<td>N3PCAS</td>
<td>PPS/PCS option; 0 = Ignore PPS/PCS, 1 = Accept PPS/PCS signal</td>
</tr>
</tbody>
</table>

Note: At present, N3PCAS must be set equal to zero.

<table>
<thead>
<tr>
<th>3411 MODID</th>
<th>Module ID of pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3PUMT(I)</td>
<td>Time for table entry [s]</td>
</tr>
<tr>
<td>R3PUMT(I)</td>
<td>Relative pump speed; 0 = Full stop, 1 = Full speed</td>
</tr>
</tbody>
</table>
Note: Data is entered as a user defined series of paired points.

5001  **L5POPT**  Transient power flag;
0 = Prompt jump approximation,  1 = exact

**NSDNGP**  Number of delayed neutron groups (Maximum of 6)

**CSLN**  Prompt neutron generation time  [s]

5002  **F5PFIS(K)**  Fractional power in each channel and bypass due to fission heating ( K = 1,N6CHAN+1 )

5003  **F5BETA(N)**  Fraction of N-th effective delayed neutron group (0<N<7)

5004  **C5LMDA(N)**  Decay constant of N-th delayed neutron group (0<N<7)

5005  **F5PBPD(I)**  Fractional transient decay power in bypass
**SSPBPD(I)**  Transient postscram time for decay power in bypass  [s]

Note: Data is assigned as a user defined series of paired points of up to 25 pairs

5101 - 5199  (Implied channel dependency, K= Number - 5100)
**F5PD(I)**  Fractional transient decay power in K-th channel
**S5PD(I)**  Transient postscram time for decay power in K-th channel  [s]

Note: Data is assigned as a user defined series of paired points of up to 25 pairs

5201 - 5299  (Implied channel dependency, K= Number - 5200)
**F5BDOP(J)**  Mesh weighted Doppler reactivity coefficient with sodium present for K-th channel (J=1,N5SLIC(K))  [p]

5301 - 5399  (Implied channel dependency, K= Number - 5300)
**F5GDOP(J)**  Mesh weighted Doppler reactivity coefficient w/o sodium present for K-th channel (J=1,N5SLIC(K))  [p]

5401 - 5499  (Implied channel dependency, K= Number - 5400)
**F5VWG(T(J)**  Mesh weighted sodium void reactivity coefficient for K-th channel (J=1,N5SLIC(K))  [p/kg]

5501 - 5599  (Implied channel dependency, K= Number - 5500)
**F5AWG(T(J)**  Mesh weighted fuel axial expansion reactivity coefficient for K-th channel (J=1,N5SLIC(K))  [p/kg]

6001  **L6MIX**  Upper Plenum Mixing type option;
1= one zone mixing,  2= two zone mixing

A-24
L6FLOW  Flow redistribution option; 0 = No flow redistribution,
1 = Flow redistribution

T6SUPH  Super heat temperature
If set .LT. 0.0, thermal expansion model will be used in
boiling calculations.
If set .GE. 0.0, single mass flow rate will be used in
boiling calculations.

6002  L6CGAS  Cover gas pressure option;
1 = constant mass,  2 = constant pressure
3 = constant feed/bleed rate

Q6CGFB  Cover gas feed/bleed rate
[kg/s]

P6CGFB  Cover gas pressure change required to actuate
feed/bleed valve
[N/m^2]

8001  N8PCSD  Number of feedback cascades in the reactor
power controller

N8CBNK  Number of primary control rod banks

8002  L8PUMP(J)  Manual/Auto pump trip flag;
1 = manual, 0 = auto (J=1,(4*N1LOOP+1))

Note: Parameters are assigned on a subsystem/component
basis. That is, data assignments are made for the pump in
primary loop 1, the pump in primary loop 2 (if needed), and
so on, up to the pump in primary loop "N1LOOP". The data
for all "N1LOOP" primary loop pumps is followed by
corresponding series for the secondary loop(s) and each of
two dummy steam generator pumps. Data for the last pump is
assigned to the turbine. Pump trips for the steam generator
and turbine must be set through RECORD 3401.

8003  S8TDLY(J)  Pump trip time delay after an automatic PPS signal
(J=1,(4*N1LOOP+1))
[s]

Note: Parameters are assigned on a subsystem and
component basis.

That is, data assignments are made for the pump in primary
loop 1, the pump in primary loop 2 (if needed), and so on,
up to the pump in primary loop "N1LOOP". The data for all
"N1LOOP" primary loop pumps is followed by corresponding
series for the secondary loop(s) and each of two dummy steam
generator pumps. Data for the last pump is assigned to the

A-25
turbine. Pump trips for the steam generator and turbine must be set through RECORD 3401.

8004 S8MANP(J) Time at which pumps are to be tripped manually (J=1,(4*NILOOP+1)) and time at which IHX are to be isolated manually

* Note: Parameters are assigned on a subsystem/component basis. That is, data assignments are made for the pump in primary loop 1, the pump in primary loop 2 (if needed), and so on, up to the pump in primary loop "NILOOP". The data for all "NILOOP" primary loop pumps is followed by corresponding series for the secondary loop(s) and each of two dummy steam generator pumps. Data for the last pump is assigned to the turbine. Pump trips for the steam generator and turbine must be set through RECORD 3401.

8005 F8PD1 Fractional power demand at time S8DT1
F8PD2 Fractional power demand at time S8DT2
S8DT1 Time at which the load demand starts changing [s]
S8DT2 Time at which the load demand reaches a constant level [s]

8006 F8RSCR Reactivity worth due the secondary control rods (Eq. 3.4-30) [$]
F8RSDM Cold shutdown margin of reactivity (Constant) (Eq. 3.4-30) [$]
Z8SRMX Maximum insertion limit of the secondary control rods corresponding to F8SRMX (Eq. 3.4-31) [m]
F8SRMX Maximum reactivity worth of the secondary control rods (Eq. 3.4-31) [$]
F8RSTP Reactivity worth of the primary system stuck rod (Eq. 3.4-38A) [$]
F8RSTS Reactivity worth of the secondary system stuck rod (Eq. 3.4-38B) [$]

8007 C8A0 Coefficients for a 6th degree polynomial (Eq. 3.4-37)*
C8A1 Coefficients for a 6th degree polynomial (Eq. 3.4-37)*
C8A2 Coefficients for a 6th degree polynomial (Eq. 3.4-37)*
C8A3 Coefficients for a 6th degree polynomial (Eq. 3.4-37)*
C8A4 Coefficients for a 6th degree polynomial (Eq. 3.4-37)*
C8A5 Coefficients for a 6th degree polynomial (Eq. 3.4-37)*
<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C8A6</td>
<td>Coefficients for a 6th degree polynomial (Eq. 3.4-37)*</td>
</tr>
<tr>
<td>C8B0</td>
<td>Coefficients for a 6th degree polynomial (Eq. 3.4-37)**</td>
</tr>
<tr>
<td>C8B1</td>
<td>Coefficients for a 6th degree polynomial (Eq. 3.4-37)**</td>
</tr>
<tr>
<td>C8B2</td>
<td>Coefficients for a 6th degree polynomial (Eq. 3.4-37)**</td>
</tr>
<tr>
<td>C8B3</td>
<td>Coefficients for a 6th degree polynomial (Eq. 3.4-37)**</td>
</tr>
<tr>
<td>C8B4</td>
<td>Coefficients for a 6th degree polynomial (Eq. 3.4-37)**</td>
</tr>
<tr>
<td>C8B5</td>
<td>Coefficients for a 6th degree polynomial (Eq. 3.4-37)**</td>
</tr>
<tr>
<td>C8B6</td>
<td>Coefficients for a 6th degree polynomial (Eq. 3.4-37)**</td>
</tr>
<tr>
<td>S8DSPT</td>
<td>Maximum time range of validity of polynomials for the primary rods</td>
</tr>
<tr>
<td>F8ZSPT</td>
<td>Fractional portion of the scram rods at which we shift to second polynomial fit</td>
</tr>
<tr>
<td>8008</td>
<td>C8C0  Coefficients for a 6th degree polynomial (Eq. 3.4-37)*</td>
</tr>
<tr>
<td></td>
<td>C8C1  Coefficients for a 6th degree polynomial (Eq. 3.4-37)*</td>
</tr>
<tr>
<td></td>
<td>C8C2  Coefficients for a 6th degree polynomial (Eq. 3.4-37)*</td>
</tr>
<tr>
<td></td>
<td>C8C3  Coefficients for a 6th degree polynomial (Eq. 3.4-37)*</td>
</tr>
<tr>
<td></td>
<td>C8C4  Coefficients for a 6th degree polynomial (Eq. 3.4-37)*</td>
</tr>
<tr>
<td></td>
<td>C8C5  Coefficients for a 6th degree polynomial (Eq. 3.4-37)*</td>
</tr>
<tr>
<td></td>
<td>C8C6  Coefficients for a 6th degree polynomial (Eq. 3.4-37)*</td>
</tr>
<tr>
<td>S8DSST</td>
<td>Maximum time range of validity of polynomials for the secondary rods</td>
</tr>
<tr>
<td>8009</td>
<td>S8RI1 Time at which the reactivity insertion starts [s]</td>
</tr>
<tr>
<td></td>
<td>S8RI2 Time at which the reactivity insertion ends [s]</td>
</tr>
<tr>
<td></td>
<td>F8RI1 Reactivity at the start of the insertion</td>
</tr>
<tr>
<td></td>
<td>(Corresponding to S8RI1)                                                   [$]</td>
</tr>
<tr>
<td></td>
<td>F8RI2 Reactivity at the end of the insertion</td>
</tr>
<tr>
<td></td>
<td>(Corresponding to S8RI2)                                                   [$]</td>
</tr>
<tr>
<td>8010</td>
<td>F8VMAX(I) Maximum fractional valve opening</td>
</tr>
</tbody>
</table>

Note: * This polynomial describes the primary rod position as a function of time after scram with the rods fully out. ** This polynomial describes the primary rod position as a function of time after scram with the rods partially inserted.

Note: This polynomial describes the secondary rod position as a function of time after scram. Since the secondary rods are assumed to be fully out, only one polynomial is used.
F8TRMA(I)  
Maximum valve trim (I=1,(N1LOOP+3)) (Eq. 3.4-57)*
Note: * Data is entered as a series of paired points.
The index "I" is incremented over the set of all required data. The required valve sequencing is:
- Main feed water control valve (one entry per loop)
- Throttle valve, Bypass valve, Motor operated relief valve

8011 F8VMIN(I)  
Minimum fractional valve opening
(I=1,(N1LOOP+3)) (Eq. 3.4-57)*

F8TRMN(I)  
Minimum valve trim (I=1,(N1LOOP+3))
(Eq. 3.4-57)*
Note: * Data is entered as a series of paired points.
The index "I" is incremented over the set of all required data. The required valve sequencing is:
- Main feed water control valve (one entry per loop)
- Throttle valve, Bypass valve, Motor operated relief valve

8012 S8OPEN(I)  
Valve opening time (I=1,(N1LOOP+3)) (Eq. 3.4-57)
Note: The required valve sequencing is:
- Main feed water control valve (one entry per loop)
- Throttle valve, Bypass valve, Motor operated relief valve

8013 S8CLOS(I)  
Valve closing time (I=1,(N1LOOP+3)) (Eq. 3.4-57)
Note: The required valve sequencing is:
- Main feed water control valve (one entry per loop)
- Throttle valve, Bypass valve, Motor operated relief valve

8014 C8TIME(I)  
Time constants used in computing sensor measurement time lags (I=1,3+5*N1LOOP)
Note: These constants correspond to the following sensors:
- Reference pressure
- Sodium level
- IHX outlet temperature (one entry per loop)
- Evaporator inlet temperature (one entry per loop)
- Feed water flow rate (one entry per loop)
- Steam flow rate (one entry per loop)
- Steam drum level (one entry per loop)
- Reactor outlet nozzle temperature

8015 U81REF  
Reference 100 % power, primary loop pump speed [rpm]
U82REF Reference 100 % power, intermediate loop pump speed [rpm]
W81REF Reference 100 % power, primary loop sodium mass flow rate, cf. OPDATA 2, W1LOOP [kg/s]
W82REF Reference 100 % power, intermediate loop sodium mass flow rate, cf. OPDATA 3, W2LOOP [kg/s]
T8RREF Reference 100 % power, core mixed mean outlet temperature [K]
T81REF Reference 100 % power, reactor vessel sodium inlet temperature, cf. OPDATA 2, T6INLT [K]
T8TREF Reference 100 % power, cold shutdown temperature [K]
P86REF Reference 100 % power, reactor inlet plenum pressure [N/m²]
P8TREF Reference 100 % power, turbine inlet pressure [N/m²]
P8DPRF Reference 100 % power, pressure drop across feedwater valve [N/m²]
W8FWRF Reference 100 % power, feedwater flow rate [kg/s]
W8STRF Reference 100 % power, steam flow rate [kg/s]
8016 L8AVLP(I) Protective functions examined by the primary shutdown system, (I=1,J: 0<J<21)
8017 L8AVLS(I) Protective functions examined by the secondary shutdown system, (I=1,J: 0<J<21)
8018 L8FUNP(I) Protective functions operative for primary shutdown system (I=1,J: 0<J<21)
Note: At least one must be operative.
8019 L8FUNS(I) Protective functions operative for secondary shutdown system (I=1,J: 0<J<21)
Note: At least one must be operative.
8020 L8PMAN Manual/auto scram flag for the primary shutdown system, 1 - manual, 0 - auto
S8PDLY Primary shutdown system scram time delay after an automatic PPS signal [s]
S8PMAN Time at which primary shutdown system is to be manually tripped [s]
Note: Selection of manual scram does not prevent an automatic scram. To prevent an automatic scram from the primary shutdown system, S8PDLY should be set to a long time.
8021 L8SMAN Manual/auto scram flag for the secondary shutdown
Secondary shutdown system scram time delay after an automatic PPS signal [s]

Time at which secondary shutdown system is to be manually tripped [s]

Note: Selection of manual scram does not prevent an automatic scram. To prevent an automatic scram from the secondary shutdown system, S8SDLY should be set to a long time.

8101 F86SFX Fractional high neutron flux (PPS setting) (Eq. 3.4-2)
8106 Z86SNA Reactor vessel sodium level PPS setting (Eq. 3.4-10)
8107 C8PET Setpoint constant for steam to feedwater ratio function (PPS function 7) (Eq. 3.4-11)
8108 T82SHX IHX outlet temperature PPS setting (Eq. 3.4-12) [K]
8110 C8PG1 Constant used in determining the setpoint for the primary to intermediate flow ratio (PPS function 10) (Eq. 3.4-14)
8110 C8PG2 Constant used in determining the setpoint for the primary to intermediate flow ratio (PPS function 10) (Eq. 3.4-14)
8110 C8PG3 Constant used in determining the setpoint for the primary to intermediate flow ratio (PPS function 10) (Eq. 3.4-14)
8110 C8PG4 Constant used in determining the setpoint for the primary to intermediate flow ratio (PPS function 10) (Eq. 3.4-14)
8110 C8PG5 Constant used in determining the setpoint for the primary to intermediate flow ratio (PPS function 10) (Eq. 3.4-14)
8110 C8PG6 Constant used in determining the setpoint for the primary to intermediate flow ratio (PPS function 10) (Eq. 3.4-14)
8111 Z83SMX Setpoint steam drum maximum water level PPS setting (Eq. 3.4-15) [m]
8112 T83SEV PPS setting evaporator exit sodium temperature (Eq. 3.4-16) [K]
8113 T86SNZ PPS setting reactor outlet nozzle temperature (Eq. 3.4-17) [K]
8114 F81SFL Primary pump PPS setting (Eq. 3.4-18)
8115 F82SFL Intermediate pump speed PPS setting (Eq. 3.4-18)
8200 F8HFXL High flux limiter (Fraction of 1)
F8CRDZ Control rod dead zone (Fraction of 1)
Constants used in determining the setpoint for flux delayed flux function when RHO is greater than 0 (PPS function 2) (Eq. 3.4-3)

C8PA2

Constants used in determining the setpoint for flux delayed flux function when RHO is greater than 0 (PPS function 2) (Eq. 3.4-3)

C8PA3

Constants used in determining the setpoint for flux delayed flux function when RHO is greater than 0 (PPS function 2) (Eq. 3.4-3)

C8PA4

Constants used in determining the setpoint for flux delayed flux function when RHO is greater than 0 (PPS function 2) (Eq. 3.4-3)

C8PA5

Constants used in determining the setpoint for flux delayed flux function when RHO is greater than 0 (PPS function 2) (Eq. 3.4-3)

C8PB1

Constants used in determining the setpoint for flux delayed flux function when RHO is less than 0 (PPS function 2) (Eq. 3.4-3)

C8PB2

Constants used in determining the setpoint for flux delayed flux function when RHO is less than 0 (PPS function 2) (Eq. 3.4-3)

C8PB3

Constants used in determining the setpoint for flux delayed flux function when RHO is less than 0 (PPS function 2) (Eq. 3.4-3)

C8PB4

Constants used in determining the setpoint for flux delayed flux function when RHO is less than 0 (PPS function 2) (Eq. 3.4-3)

C8PB5

Constants used in determining the setpoint for flux delayed flux function when RHO is less than 0 (PPS function 2) (Eq. 3.4-3)

Constant used in determining the setpoint for flux-sqrt (Pressure) function (PPS function 3) (Eq. 3.4-8)

C8PC1

Constant used in determining the setpoint for flux-sqrt (Pressure) function (PPS function 3) (Eq. 3.4-8)

C8PC2

Constant used in determining the setpoint for flux-sqrt (Pressure) function (PPS function 3) (Eq. 3.4-8)

C8PC3

Constant used to determine the setpoint for primary to
intermediate speed ratio function (PPS function 4) (Eq. 3.4-9)

**C8PD2** Constant used to determine the setpoint for primary to intermediate speed ratio function (PPS function 4) (Eq. 3.4-9)

**C8PD3** Constant used to determine the setpoint for primary to intermediate speed ratio function (PPS function 4) (Eq. 3.4-9)

**C8PD4** Constant used to determine the setpoint for primary to intermediate speed ratio function (PPS function 4) (Eq. 3.4-9)

**C8PD5** Constant used to determine the setpoint for primary to intermediate speed ratio function (PPS function 4) (Eq. 3.4-9)

**C8PD6** Constant used to determine the setpoint for primary to intermediate speed ratio function (PPS function 4) (Eq. 3.4-9)

8201 **MODID** PPS/PCS module identifier*

**Z8CRIN** Initial position of the primary control rods. May vary from 0.0 (Fully inserted) to the value assigned Z8CRMX (Fully withdrawn) (Eq. 3.4-34) [m]

**Z8CRMX** Maximum insertion limit of the primary control rods (Eq. 3.4-34) [m]

**Z8SAT** Primary control rod saturation position [m]

**Z8LOCR** Lower position of the rod bank before the next bank movement begins [m]

**Z8CRUP** Upper position of the rod bank before the next bank movement begins [m]

**U8CRDN** Primary control rod downward velocity (negative value) (Eq. 3.4-36) [m/s]

**U8CRUP** Primary control rod upward velocity (positive value) (Eq. 3.4-36) [m/s]

**F8ROMX** Maximum reactivity of the primary control rod banks (Eq. 3.4-34) [$]\]

Note: A MODID is a three (3) digit code designed to uniquely identify a PCS controller. Since a control rod bank is defined with neither sub-system nor loop
dependencies, digits one (1) and three (3) are by
convention always assigned a value of zero (0). The
remaining digit (2) designates the bank to which the
data is associated. It's value will range from one (1) to
the user defined maximum number of control rod
banks (N8CBNK) which is found on record 8001

8301 MODID PPS/PCS module identifier *
M8MOTR Motor type flag (0/1, squirrel cage/wound rotor)
N8POLE Number of pairs of poles for squirrel cage type motor
(Q8FRER 100% reference frequency of the motor-generator set [Hz]
C8PCS Constants associated with the pump drive system
(Eq. 3.4-40)
C8ACT Actuator constants (Eq. 3.4-44)
F8HSPL Pump high speed limit
R8MAX Maximum resistance of the liquid rheostat actuator
(Eq. 3.4-51)
R8ROT Motor resistance (Eq. 3.4-50)
U8SRPM Synchronous speed of the sodium pumps
(Eq. 3.4-53)

Note: * A MODID is a three (3) digit code designed to
uniquely identify a PCS controller. Since there is only
one driver per pump and one pump per loop, the second
digit of the pump controller MODID is superfluous and is
by convention always assigned a value of zero (0).
The first digit of the MODID code is assigned on a subsystem
basis. A pump driver in a primary heat transport system is
assigned a value of one (1) while the secondary system
counterpart is assigned a value of two (2). The plant loop is
identified by the MODID's last digit. It's range of valid values
is one (1) through the maximum number of loops simulated
(N1LOOP).

8400 N8CSCD(I) Number of flow controller cascades associated with
each subsystem component (I=1,(4*N1LOOP+3))

Note: The following cascade sequencing is assumed:
- Primary heat transport system (one entry for each loop)
- Secondary heat transport system (one entry for each loop)
- Feedwater water pump (one entry for each loop)
- Feedwater valve (one entry for each loop)
- Throttle valve
- Bypass valve
- Relief valve

8401 MODID PPS/PCS module identifier*
M8FLAG Controller mode flag (0/1, automatic/manual)
(Figure 3.4-3)
F8GAIN Controller gain (Eq. 3.4-22)
F8REPT Integral controller repetition rate [1/s]
C8TIME Time constants (Eq. 3.4-22) [s]
F8ROLU Integral limiter (Upper limit)
F8ROLD Integral limiter (Lower limit)
F8DBND Dead band (Fraction of 1)
X8PM Manual adjustable setpoints for controllers
C8TIME Time constants [s]
C8FP Flow controller part load profile coefficients for load dependent set points

Note: A MODID is a three (3) digit code designed to uniquely identify a PCS controller. The first digit denotes the subsystem/component. It may assume values of one (1) through eight (8) in accordance with the following definition:
1 - Primary heat transport system
2 - Secondary heat transport system
3 - Feedwater pump
4 - Feedwater valve
5 - Throttle valve
6 - Bypass valve
7 - Relief valve
8 - Power controller

Digit two (2) identifies a cascade within a subsystem. It is assigned a value of one(1) to a user defined maximum. For subsystems 1 through 7, this maximum is defined by a corresponding entry on the REORD 8400.
The maximum number of power controllers(subsystem 8) is defined on RECORD 8001. The plant loop is
identified by the last digit of the MODID. It's range is zero (0) through the maximum number of loops simulated (N1LOOP). A valve of zero (0) in the third digit indicates no loop dependency. By convention, a zero (0) is always assigned to the third digit of power controller MODID.

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S9LAST</td>
<td>Total problem simulation time</td>
</tr>
<tr>
<td>S9MAXA</td>
<td>Maximum timestep allowed</td>
</tr>
<tr>
<td>S9MINA</td>
<td>Minimum timestep allowed</td>
</tr>
<tr>
<td>S9SINT</td>
<td>Master clock interval at which a restart dump will occur</td>
</tr>
<tr>
<td>S9PINT(J)</td>
<td>Master clock interval at which a system report will be generated.</td>
</tr>
<tr>
<td>S9PINT(J+1)</td>
<td>Master clock time after which the corresponding S9PINT is no longer valid.</td>
</tr>
</tbody>
</table>

Note: The index J is incremented over the set of paired points. There may be as many pairs (intervals) as the users find necessary.

S9PINT(1) is imposed from time 0.0 to S9PINT(2). S9PINT(3) is then used from the master clock time S9PINT(2) to S9PINT(4). Similarly, S9PINT(5) is used from S9PINT(4) to S9PINT(6), and so on.

It should be apparent that S9PINT(4) must be strictly greater than S9PINT(2), and S9PINT(6) must be strictly greater than S9PINT(4), and so on.

There is quite a bit of latitude permitted in the selection of print intervals, but they must be carefully chosen (see section 7.8).

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1EMXA</td>
<td>Relative accuracy acceptance limit for loop thermal calculations</td>
</tr>
<tr>
<td>F1WMXA</td>
<td>Relative accuracy acceptance limit for loop hydraulic calculations</td>
</tr>
<tr>
<td>F5MAXA</td>
<td>Relative accuracy acceptance limit for fuel calculations</td>
</tr>
<tr>
<td>F6MAXA</td>
<td>Relative accuracy acceptance limit for in-vessel coolant calculations</td>
</tr>
<tr>
<td>F1ICDA</td>
<td>Relative interface condition acceptance limit for loop hydraulic calculations</td>
</tr>
<tr>
<td>F6ICDA</td>
<td>Relative interface condition acceptance limit for in-vessel coolant calculations</td>
</tr>
</tbody>
</table>
Loop thermal option;
1 - module is called, 0 - module is not called
Loop hydraulic option;
1 - module is called, 0 - module is not called
Steam generator option;
1 - module is called, 0 - module is not called
Fuel option;
1 - module is called, 0 - module is not called
In-vessel option;
1 - module is called, 0 - module is not called
PCS option;
1 - module is called, 0 - module is not called
Loop thermal report option;
0 - no report, 1 - report is generated
Loop hydraulic report option;
0 - no report, 1 - report is generated
Steam generator report option;
0 - no report, 1-4 - report is generated with correspondingly greater detail
Fuel report option;
0 - no report, 1 - report is generated
In-vessel coolant report option;
0 - no report, 1 - report is generated
PPS/PCS report option;
0 - no report, 1 - report is generated
set to 0
Dump labeled common before initialization;
1 - yes, 0 - no
Dump labeled common after initialization;
1 - yes, 0 - no
Dump labeled common after last time step;
1 - yes, 0 - no
Dump container array table information;
1 - yes, 0 - no
Note: This is currently valid only on CDC installations.
May be used to alter a transient proceeding from a restart at simulation time greater than zero. Corresponds to TRNDAT RECORDs 9001 and 9005.

<table>
<thead>
<tr>
<th>Rec.</th>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>S9LAST</td>
<td>Total problem simulation time [s]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S9MAXA</td>
<td>Maximum time step allowed [s]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S9MINA</td>
<td>Minimum time step allowed [s]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S9SINT</td>
<td>Master clock interval at which a restart dump will occur</td>
<td>[s]</td>
</tr>
<tr>
<td></td>
<td>S9PINT(J)</td>
<td>Master clock interval at which a system report will be generated.</td>
<td>[s]</td>
</tr>
<tr>
<td></td>
<td>S9PINT(J+1)</td>
<td>Master clock time after which the corresponding S9PINT is no longer valid.</td>
<td>[s]</td>
</tr>
</tbody>
</table>

Note: The index J is incremented over the set of paired points. There may be as many pairs (intervals) as the users find necessary.

S9PINT(1) is imposed from time 0.0 to S9PINT(2). S9PINT(3) is then used from the master clock time S9PINT(2) to S9PINT(4). Similarly, S9PINT(5) is used from S9PINT(4) to S9PINT(6), and so on. It should be apparent that S9PINT(4) must be strictly greater than S9PINT(2), and S9PINT(6) must be strictly greater than S9PINT(4), and so on.

There is quite a bit of latitude permitted in the selection of print intervals, but they must be carefully chosen (see section 7.8).

| 105  | L1EPRT     | Loop thermal report option;                                   |      |
|      |            | 0 - no report, 1 - report is generated                        |      |
|      | L1WPRT     | Loop hydraulic report option;                                 |      |
|      |            | 0 - no report, 1 - report is generated                        |      |
|      | L3PRNT     | Steam generator report option;                                |      |
|      |            | 0 - no report, 1-4 - report is generated with correspondingly greater detail |      |
|      | L5PRNT     | Fuel report option;                                          |      |

A-37
0 - no report, 1 - report is generated

**L6PRNT**
In-vessel coolant report option;
0 - no report, 1 - report is generated

**L8PRNT**
PPS/PCS report option;
0 - no report, 1 - report is generated

**OLDATA:**

Exercise of other than default program control for the generation and subsequent use of restart data files.
PSDRS

Passive Decay Heat Removal System (PSDRS)

<table>
<thead>
<tr>
<th>Rec.</th>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Title</td>
<td>The character of the problem title should not exceed 80 characters and there is no need for a card number.</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>ICARD(1)</td>
<td>Card identification number (= 1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NTRAN</td>
<td>Steady Option Flag (0 = Steady cal./Otherwise, Number of steps for transient temperature variation)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ITRIP</td>
<td>PSDRS Trip Flag in ‘driv9.t’ in SSC-K (= 0 : No Trip, Otherwise, Skip PSDRS Transient Calculation)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SEND</td>
<td>Steady calculation end time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NEQUTN</td>
<td>Number of equations to be solved (= 7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>JNODES</td>
<td>Total axial node numbers – same numbers for all components</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>*Two air channels, namely, down-flow and up-flow</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Channels have JNODES each</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DELT</td>
<td>Maximum time-step</td>
<td>s</td>
</tr>
<tr>
<td>2</td>
<td>ICARD(2)</td>
<td>Card identification number (= 2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TEND</td>
<td>Transient end time</td>
<td>s</td>
</tr>
<tr>
<td></td>
<td>TPRINT</td>
<td>Major printing time</td>
<td>s</td>
</tr>
<tr>
<td></td>
<td>JW</td>
<td>Node number where the temp. is to be monitored with time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NITER</td>
<td>Maximum allowable iteration number for air temperature convergence</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CRIT</td>
<td>Convergence criteria for air temperature calculation</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>KTRAN(I)</td>
<td>Number of transient steps for each variable</td>
<td>s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( 3 consecutive numbers), ( I = 1, 3 )</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>ICARD(4)</td>
<td>Card identification number (= 4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TRANS(1,J)</td>
<td>Sodium level initiating time , ( I = 1, KTRAN(1) )</td>
<td>s</td>
</tr>
<tr>
<td></td>
<td>XLSODM(I)</td>
<td>Sodium level inside the reactor vessel at the initiating time (( I = 1, KTRAN(1) ))</td>
<td>m</td>
</tr>
</tbody>
</table>

A-39
1 integer, 2*KTRAN(2) real numbers

**ICARD(5)**  
Card identification number (= 5)

**TRANS(2,I)**  
Sodium temp. initiating time, \( I = 1, \text{KTRAN}(2) \)  
[s]

**TEMPNA(I)**  
Sodium temp. inside the Rx vessel at the initiating time \( I = 1, \text{KTRAN}(2) \)  
[°C]

1 integer, 2*KTRAN(3) real numbers

**ICARD(6)**  
Card identification number (= 6)

**TRANS(1,I)**  
Cover gas initiating time, \( I = 1, \text{KTRAN}(3) \)  
[s]

**TEMPHE(I)**  
Cover gas (HE) temp. inside the Rx vessel at the initiating time, \( I = 1, \text{KTRAN}(3) \)  
[°C]

1 integer, 6 real numbers

**ICARD(7)**  
Card identification number (= 7)

**DXRV**  
Thickness of reactor vessel  
[m]

**DXGV**  
Thickness of guard vessel  
[m]

**DXCON**  
Thickness of concrete wall  
[m]

**DHGVFI**  
Hydraulic diameter between guard vessel and finned shell  
[m]

**HRX**  
Height of active reactor vessel  
[m]

**DHRX**  
Hydraulic Diameter of the inner Rx vessel  
[m]

1 integer, 6 real numbers

**ICARD(8)**  
Card identification number (= 8)

**ZINLET**  
Height of air channel inlet to the ref. position  
[m]

**DELTIN**  
Length of air channel inlet  
[m]

**AREAIN**  
Air channel inlet area  
\[m^2\]

**DHINLT**  
Hydraulic diameter of inlet air channel  
[m]

**AAIR2**  
Down-flowing air channel area  
\[m^2\]

**DHADWN**  
Hydraulic diameter of down-flowing air channel  
[m]

1 integer, 6 real numbers

**ICARD(9)**  
Card identification number (= 9)

**ZSTACK**  
Height of air channel stack to the ref. position  
[m]

**DELZSK**  
Length of air channel stack  
[m]

**AREASK**  
Air flow area of stack  
\[m^2\]

**DHSTCK**  
Hydraulic dia. of stack  
[m]

**AAIR1**  
Up-flowing air channel area  
\[m^2\]

**DHAUP**  
Hydraulic diameter of up-flowing air channel  
[m]

1 integer, 3 real numbers

**ICARD(10)**  
Card identification number (= 10)
AREAFR  Turbulence friction factor
BCONST  Constant to be used for boundary Reynold number between turbulent flow and laminar flow
AREAFL  Laminar friction factor

11
ICARD(11)  Card identification number (= 11)
ANW01  Vessel inner heat transfer area per unit length [W/m]
AW012  Circumference between reactor vessel and guard vessel [W/m]
AW023  Circumference between guard vessel and inner finned shell [W/m]
AW034  Circumference between inner finned shell and outer finned shell [W/m]
AW045  Circumference between outer finned shell and Concrete [W/m]
AW056  Circumference of concrete wall between the positions of TEMPW5(J) and TEMPW6 [W/m]

12
ICARD(12)  Card identification number (= 12)
AW02A  Outer circumference of guard vessel [W/m]
AW03A  Inner circumference of finned shell [W/m]
AW04A  Outer circumference of finned shell [W/m]
AW05A  Inner circumference of concrete [W/m]

13
ICARD(13)  Card identification number (= 13)
FKORI1  Form Loss Coefficients for Orifices in the up-flowing channel
FKORI2  Form Loss Coefficients for Orifices in the down-flowing channel

14
ICARD(14)  Card identification number (= 14)
HCONHE  Vessel inner heat transfer coef. between Helium and vessel wall [W/m²·°C]

15
ICARD(15)  Card identification number (= 15)
HCV12(J)  Heat transfer coef. between reactor vessel and guard vessel, J=1, JNODES [W/m²·°C]
16

**ICARD(16)** Card identification number (= 16)
**HW034** Heat transfer coef. between inner node and outer node of divider [W/m$^2$-°C]
**HW056** Heat transfer coef. between concrete and constant heat sink [W/m$^2$-°C]

17

**ICARD(17)** Card identification number (= 17)
**WLMASS(I)** Mass per unit length for each wall [Kg/m]

18

**ICARD(18)** Card identification number (= 18)
**WLSPEC(I)** Specific heat for each wall [J/Kg-°C]
**WLCONK(I)** Thermal conductivity for each wall [W/m-°C]

19

**ICARD(19)** Card identification number (= 19)
**EPSRV** Emissivity on reactor vessel wall
**EPSGVI** Emissivity on guard vessel inner wall
**EPSGVO** Emissivity on guard vessel outer wall
**EPSFSI** Emissivity on finned shell inner wall
**EPSFSO** Emissivity on finned shell outer wall
**EPSOW** Emissivity on concrete wall
**CONCK** Thermal conductivity of concrete [W/m-°C]

20

**ICARD(20)** Card identification number (= 20)
**TEMPIN** Inlet air temperature [°C]
**TEMPW6** Constant concrete outer wall temperature [°C]
**WAIR0** Initial user guessing air flow rate [kg/s]

21

**ICARD(21)** Card identification number (= 21)
**XLSODM1** Initial sodium level in the reactor vessel [m]
**TEMPNA1** Initial sodium temp. in the reactor vessel [°C]
**TEMPHE1** Initial cover gas (Helium) temp. in the reactor vessel [°C]

22

**ICARD(22)** Card identification number (= 22)
**TEMP1** Reactor vessel initial temp. [°C]
**TEMP2** Guard vessel initial temp. [°C]
**TEMPA** Upflow air initial temp. [°C]
| TEMP3 | Divider inner node initial temp. | [°C] |
| TEMP4 | Divider shell outer node initial temp. | [°C] |
| TEMP5 | Concrete inner node initial temp. | [°C] |
APPENDIX B  Subroutines in SSC-K

The SSC-K code has a modularized structure. The code is divided into three major sequentially disjointed processes of MAIN9R, MAIN9S, and MAIN9T as shown in Fig. B.1. These routines are the main driver programs and are called in succession by the controller routine. Each performs a unique set of tasks and is executed only once for any given case. It should be noted that the modules necessary to describe the characteristics of the pool design and reactivity models for metallic fuel were changed or added to the SSC-K code. The remainder of the code was obtained from the SSC-L library.

The flow chart of each of the drivers, along with its associated subroutines, is shown in Figs. B.1 through B.5. Note on these figures that subroutines designated by an underline are the changed or added ones for SSC-K. A brief description of all subroutines used in SSC-K, except for the MINET code portion, is presented in Appendix B.
Fig. B.1 Subroutines for Input Processing
main driver for the input initialization module
primary controller for the processing of initialization data. It calls the free-format reader routines
reads a program generated file for the re-initialization of labeled common in the event of a restart
processes the input for the initialization of the primary and secondary loop module
general purpose reader routine
processes input for the initialization of the steam generator module
general purpose reader routine
processes input for the initialization of the in-vessel module
general purpose reader routine
processes input for the initialization of the plant balance routine
general purpose reader routine
processes input for the initialization of the material property parameters
general purpose reader routine
calls for the verification routines
validates the data processed by the corresponding READ routines
lists the data processed by the corresponding READ routines
validates the data processed by the corresponding READ routines
assists in the decoding of steam generator input
lists the data processed by the corresponding READ routines
validates the data processed by the corresponding READ routines
lists the data processed by the corresponding READ routines
validates the data processed by the corresponding READ routines
lists the data processed by the corresponding READ routines
validates the data processed by the corresponding READ routines
lists the data processed by the corresponding READ routines
calls a series of intermediate data management routines
manipulates certain primary and secondary loop input data /
initializes subsequent loop structures
loads the input data into the data arrays
initializes certain steam generator constants
sets slice-type dependent arrays and determines normalized axial and radial power distribution
interprets the coded iterative scheme for establishing the initial plant balance
loads channel-dependent parameters for use in the slice-type-dependent in-vessel modules
generates an ordered file for a re-initialization restart
Fig. B.2 Subroutines for Steady-State Calculation
main driver for the steady-state calculations

performs the global thermal balance for the whole plant
solves the steady-state energy equations for the IHX. IHX1S and HYDR1S are the only interface between the primary and intermediate loop

main driver for the SG calculations
determines the sodium inlet temperature
determines the sodium flow rate per tube
computes the pressure at the exit of a pipe
loads initial guesses for steam pressures, mass flow rates, enthalpies and heat transfer rates. Values for pressure and mass are user-input. Initial enthalpies and heat transfer rates are zeroed, as ENET3S is called soon after INIT3S.
performs the heat exchanger model calculations. It determines the pressure drop in the inlet plenum of the heat exchanger, calls the routines which determines the enthalpy and pressure distributions in the heat transfer tube, and calculates the pressure drop in the outlet plenum of the heat exchanger. It determines the location of the DNB point and adjusts the total heat transfer area to produce specified outlet conditions.
computes the pump outlet pressure at rated pump speed or the pump speed if the pump outlet pressure is specified
calculates the mixed mean enthalpy in a volume based on the liquid level and the pressure specified in the volume
interfaces the in-vessel and primary loop pressures
driver module for in-vessel coolant calculations
computes the steady-state channel flow rate distribution or pressure loss coefficients
core coolant: It calculates axial temp., enthalpy gradients, friction factors, heat transfer coefficients and pressures each node in each channel
determines the nodal pressures in each reactor coolant channel
coolant module: calculates upper plenum temp. exit quality, outlet, and top of core pressures and finds pressure loss factors for each channel
calculates pressure equalization loss coefficient at top of assembly
lower plenum module: initializes values of temperature, enthalpy, and pressure for the first axial nodal interface of each channel. It calculates pressures at the bottom of the core
driver module for fuel heat conduction calculations. It treats a fuel slice as the basic computational element, calls all major fuel computational modules, and controls convergence
performs the initialization for FUEL5S by obtaining data computed by other modules. Among others, it sets the proper rod nodal
temperature to T6COOL(J,K), places the heat transfer coefficient for the slice in a local variable HCOOL, initializes tags for restructuring and calls PREX5S to initialize nodal distances at temperature T5REF

PREX5S initializes nodal distances for either equal radius increments or equal area increments of the rod slice
FRAD5S calculates the average power generation for all radial nodes in any core channel slice
ALFA5S calculates the coefficient of thermal expansion for each node in the fuel slice
XPAN5S adjusts radii due to thermal expansion for each node in the fuel slice
GRO5S sets pointers for restructuring in the slice
TEMP5S calculates the steady-state radial temperature distribution in the rod and cladding for any slice
GAMA5S calculates the thermal conductivity for fuel and clad nodes for the slice and heat transfer coefficients for the interfaces
STEM5S calculates the temperature of the fuel rod structure and fission gas plenum for steady-state
PUT5S moves the calculated steady-state values for the slice into storage locations
TSAV5S determines the average temperature in each rod slice except fission gas plenum slice
PRNT5S prints steady-state results for the fuel calculations

LOOP1S drives the primary loop steady-state calculations. It interprets the logical variables in order to select the proper calling sequence to the various subroutines. This routine also copies the results of the computations for loop-1 into the arrays for the rest of the loop

HYDR1S solves the steady-state hydraulic momentum equations for both primary and secondary sides of the IHX
PIPE1S solves the steady-state energy and momentum equations for pipe J in the primary coolant loop
END1S calculates the temperature boundary conditions for the sub-pipe in the primary loop and accounts for the temperature rise across pump, as well as IHX plena temperatures at the proper locations
PUMP1S determines pump pressure rise by matching it with overall load in the primary circuit. It then sets up the polynomial equation for pump head and calls ROOT1U to calculate pump operating speed
RES1S computes the height of coolant in the primary pump tank, and the mass of cover gas above the coolant level
RITE1S prints the primary loop steady-state solution
CVAL1S computes the steady-state pressure drop over the check valve
PRNT9S prints a plant-wide steady-state summary of results
LOOP2S drives the intermediate loop steady-state computation. The rest of the description is the same as for LOOP1S
<table>
<thead>
<tr>
<th>Command</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>RITE2S</td>
<td>prints the secondary loop steady-state solution</td>
</tr>
<tr>
<td>PIPE2S</td>
<td>solves the steady-state energy and momentum equations for pipe J in the intermediate coolant loop</td>
</tr>
<tr>
<td>SPHT2S</td>
<td>calculates the pressure drop or loss coefficient on the shell side of the superheater</td>
</tr>
<tr>
<td>EVAP2S</td>
<td>calculates the pressure drop or loss coefficient on the shell side of the evaporator</td>
</tr>
<tr>
<td>PUMP2S</td>
<td>determines pump pressure rise by matching it with overall load in the intermediate circuit</td>
</tr>
<tr>
<td>TANK2S</td>
<td>computes the pressure in the loop at the location of the surge tank, and further, calculates the mass of gas in the surge tank</td>
</tr>
<tr>
<td>PRES2S</td>
<td>determines the pressure at pipe end points around the intermediate loop</td>
</tr>
<tr>
<td>RES2S</td>
<td>computes the height of coolant in the intermediate pump tank, and the mass of cover gas above the coolant level</td>
</tr>
<tr>
<td>END2S</td>
<td>sets the inlet temperature and mass flow rate boundary conditions for pipe J+1 in the intermediate coolant loop</td>
</tr>
<tr>
<td>SAV9S</td>
<td>creates an ordered file containing information necessary to re-initialize all common blocks to computed steady-state values</td>
</tr>
</tbody>
</table>
Fig. B.3 Subroutines for Transient Calculation
Fig. B.3  Subroutines for Transient Calculation (Continued)
MAIN9T: overall driver routine for the transient calculations
CRDR9T: intermediate controller for the transient initialization routines
INIT9T: initiates variables used by the in-vessel coolant hydraulics modules
TBLDMP: lists global container allocations
CNTDMP: list all global locations in the container
COMDMP: initiates calls to other modules to obtain the various applied and
INIT6T: sets variables needed for the first call to the primary loop hydraulic integration scheme
DEFN1T: defines pipe flow rates, and input and output pump flow rates for primary loop
XI1T: equivalences the names of primary loop variables and their time intervals in terms of names in the integrating subroutine
EQIV1T: sets variables needed for the first call to the secondary loop hydraulic integrating routine
INTG1T: advances the hydraulic equations using the predictor-corrector method of the Adams type
PRET1T: initializes the primary and secondary loop variables for the thermal calculations
INIT5T: initializes variables used in the fuel and reactivity calculations
INIT8T: initializes values used in the PPS/PCS subroutines
COUR9T: calculates Courant condition for all channels
READ9T: reads free-format card-image input for the initialization of transient parameters
GENRD: general purpose reader routine
VRFY9T: validates the data processed by the READ9T routine against the criteria established in the data dictionary
LIST9T: lists the data processed by READ9T
INIT3T: initializes transient variables used by the steam generator modules
INTF3T: interfaces the required boundary conditions between all intermediate sodium loops and all steam generator heat exchanger
DRIV9T: driver routine for the transient calculations. It also handles the overall time step control
DRIV1T: driver for heat transport system transient hydraulics
REAC5T: calculates Courant condition for all channels

B-10
feedback reactivity contributions

DOPP5T calculates the reactivity feedback due to Doppler effect
VOID5T calculates the reactivity feedback due to sodium voiding
GROW5T calculates the reactivity feedback due to axial expansion
GRWD5T calculates the reactivity feedback due to radial expansion
CRDL5T calculates the reactivity feedback due to CRDL expansion
GEM5T calculates the reactivity feedback due to GEM

COEF6T calculates coefficients for the various pressure loss terms used in FLOW6T

INTG1T advances the hydraulic equations using the predictor-corrector method of the Adams type

EQIV1T equivalences the names of primary loop variables and their time derivatives in terms of names used in the integrating subroutine

EQIV2T equivalences the names of intermediate loop variables and their time derivatives in terms of names used in the integrating subroutine

FLOS1T calls subroutines to integrate implicit hydraulic differential equations

FLOS2T calls subroutines to integrate implicit hydraulic equations in intermediate loop

FLOW1T sets proper calling sequence to primary loop hydraulic computation submodules

DEFN1T defines pipe flow rates, and input and output pump flow rates for primary loop

PDFG1T sets the logic to compute pressure losses across different elements of primary loops

PIPW1T computes pressure losses in pipe sections in primary loops
HYDR1T computes transient hydraulics in IHX
CVAL1T computes the pressure loss across the check valve
RESI1T computes variables and time derivatives for level in primary pump reservoir

PUMP1T computes primary pump variables and time derivative for pump speed
HEAD1T computes head of primary pumps and defines its operational region
PLOS1T computes pressure losses in appropriate sections of primary loop from the losses in individual components
GVSL1T computes coolant level in guard vessel, pressure external to break,
and time derivative for accumulated volume of coolant in the guard vessel

**VESL1T** calculates certain algebraic relationships at the vessel-loop(s) interface(s) and within the vessel which are used in the hydraulic computations

**BREK1T** computes pressures at eventual break in primary loop

**VJ1T** determines velocity of jet out of a pipe break

**PRUP6T** calculates the vessel outlet pressure and core top pressure for the one-dimensional two zone upper plenum model

**UPLN6T** one-dimensional two zone upper plenum model

**PRUP6T** calculates the vessel outlet pressure and core top pressure for the one-dimensional two zone upper plenum model

**UPLS6T** updates the time derivatives for sodium level, sodium temperatures in two mixing zones, cover gas temperature, and temperature of the inner structure, thermal liner and vessel

**FLOW6T** simulates the flow redistribution model. It calculates the mass flow rate in each channel and bypass channel

**PRES1T** sets inlet and outlet pressures of uniform mass flow rate sections in primary loops

**FUNC1T** calculate the time derivatives of differential equations for primary loop hydraulics

**EQIV1T** equivalences the names of primary loop variables and their time derivatives in terms of names used in the integrating subroutine

**FLOW2T** sets proper calling sequence to intermediate loop hydraulic computation submodules

**FUNC2T** calculate the time derivatives of differential equations for intermediate loop hydraulics

**PRES2T** sets inlet and outlet pressures of uniform mass flow rate sections in intermediate loops

**BREK2T** computes pressures at eventual break in intermediate loop

**VJ1T** determines velocity of jet out of a pipe break

**PLOS2T** computes pressure losses in appropriate sections of intermediate loop from the losses in individual components

**PUMP2T** computes intermediate pump variables and time derivatives for pump speed

**TORK2T** computes hydraulic and friction torques for intermediate pumps

**HEAD2T** computes head of intermediate pumps and defines its operational
region

RES2T computes variables and time derivatives for level in intermediate pump reservoir

TANK2T computes pressures and time derivatives for level in surge tank

PDFG2T sets the logic to compute pressure losses across different elements of intermediate loops

EVAP2T computes pressure loss across the shell side of evaporator

SPHT2T computes pressure loss across the shell side of superheater

HYDR1T computes transient hydraulics in IHX

PIPW2T computes pressure losses in pipe sections in intermediate loops

DEFN2T defines pipe flow rates, and input and output pump flow rate for intermediate loop

EQIV2T equivalences the names of intermediate loop variables and their time derivatives in terms of names used in the integrating subroutine

STOR1T stores the intermediate updated values of flow rate

IHX1T solves transient energy equations in the IHX

PIPE2T solves transient energy equations in the intermediate loop piping

POW5T serves as the driver for the rod transient fission power generation calculations

PRMT5T handles the advancement in time of the fission power generation main driver for the steam generator calculation. It calls routines which computes accumulator conditions, backsubstitutes accumulator conditions to advance flow sequence variables, and determines the maximum change in water side variables during this step

UP2D6T 2D upper plenum model

IMPX1T

LOOP1T main driver for transient thermal calculations in primary loop

PIPE1T solves transient energy equations in the primary loop piping

IHX1T solves transient energy equations in the IHX

END1T sets transient thermal boundary conditions from one pipe to the next in primary loop

LOOP2T main driver for transient thermal computations in intermediate loop

IHX1T solves transient energy equations in the IHX

PIPE2T solves transient energy equations in the intermediate loop piping

END2T sets transient thermal boundary conditions from one pipe to the next
intermediate loop

PPCS8T main driver for the PPS/PCS transient calculations

INT8T interfaces the PPS/PCS modules to the rest of SSC by fetching the actual values of the desired process variables for cascade selection for reactor power control and normalizing them against their respective 100% steady-state values. It also calls other subroutines to do similar calculations for PPS, flow controllers and the steam generator controllers

SENS8T takes the actual sensed values from the controller cascades and compensates them for the inherent time lags imposed by the measuring devices

SGEN8T calculates the load-dependent setpoints as governed by the supervisory controller, using the user specified second-order polynomial coefficients

PPS8T subdriver routine for the plant protection system

PCON8T simulates the reactor power control and the control rod drive mechanism. It also calculates the reactivity worth of the reactor control rods

APPL8T calculates the scram reactivity worth of the primary and/or secondary control rods utilizing the user supplied polynomial coefficients for rod position as a function of time after reactor scram

FCON8T simulates the sodium flow-speed control and the pump drive mechanism

STGN8T subdriver for steam generator controller routines

SCUT9T controls timestep after scram

INTF9T checks the adequacy of all extrapolated interface conditions

FUEL5T driver for the fuel rod and structure calculations. By calling series of modules in succession; it calculates, quantities such as temperature and radii of the fuel, cladding, and structure nodes

POW6T calculates power to coolant for use in COOL6T

PRE5T transfers the temperature from storage arrays into local scratch arrays for the particular slice in question, at the start of each timestep

PROP5T calculates all properties for the fuel (rod) heat conduction calculations

XPAN5T recalculates the radii of the fuel and cladding, necessary because of the thermal expansion of the radial nodes. Two methods are
employed in calculating radii, equal area increment, and equal radii increment calculating radii; equal area increment, and equal radii increment
generate the thermal conductivity and emissivity for fuel and clad nodes and also computes the heat transfer coefficient for gaseous mixtures in the gap
FRAD5T calculates average power for all radial nodes in any rod slice. It also calculates the power generation multiplier to be used later in calculating the transient volumetric power generation
SGMA5T calculates the volumetric heat source for the fuel (rod) nodes, clad, coolant and structure in an axial slice
BOIL6T calculates liquid and bubble temperature in upper and lower slugs
COEF5T calculates appropriate coefficients for the transient temperature calculations of fuel rod
SOLV5T solves the fuel (rod) matrix equation using Gaussian elimination with fuel pivoting
PUT5T at the time this module is invoked, all formal calculations of the fuel and clad and structure have been completed for that timestep and for the given axial node. This module then move all temperatures and radii so far calculated from local scratch variables into storage arrays for subsequent timesteps
TSAV5T calculates certain fuel slice dependent quantities required in GROW5T, DOPP5T, and VOID5T
PROP6T calculates all properties used in the in-vessel coolant energy and fluid dynamics subroutines
INTR6T main driver for interassembly heat transfer
PREA6T calculates channel flow area
GEOM6T calculates coefficients for the various pressure loss terms used in FLOW6T
QCAC6T calculates interassembly heat transfer
INTA6T calculates interassembly heat transfer
TWIS6T calculates interassembly heat transfer
COOL6T driver for the transient coolant calculations. It provides initial conditions; determines step size; and then employs several submodules to calculate temperature, pressure, enthalpy, and mass flow rate of the coolant in all axial nodes of all channels. It then
stores values for fuel calculations

LPLN6T performs transient lower plenum calculations. It extrapolates boundary conditions. It determines its procedure by calculating coolant and metal temperature and pressures at the bottom of the core.

PIPE2T solves transient energy equations in the intermediate loop piping.

PSDRS performs transient lower plenum calculations. It extrapolates boundary conditions. It determines its procedure by calculating coolant and metal temperature and pressures at the bottom of the core.

COEFIC creates an ordered file containing information necessary to re-initialize all common blocks to a given master clock solution.

PRNT9T main printing routine for the transient.
Fig. B.4  Subroutines for Steam Generator (MINET Portion)

B-17
main driver for the steam generator calculation. It calls routines which computes accumulator conditions, backsubstitutes accumulator conditions to advance flow sequence variables, and determines the maximum change in water side variables during this step.

determines pointers for all arrays needed in the flow segment calculations

determines reference pressure for a flow segment

determines reference pressure for a flow segment

determines reference coefficients for feedwater flow rate

determines turbine inlet pressure

determines water properties as function of enthalpy and pressure

determines turbine inlet pressure

determines main driver for flow segment calculations

determines coefficients for energy and flow equation for water side of heat exchanger and advances sodium temperature

determines coefficients of total flow resistance in control volume

determines the coefficients of momentum flux pressure loss in control volume

determines friction factor as function of Reynolds number and surface roughness

determines two-phase friction multiplier on the water/steam side of the steam generator

determines coefficients of pressure drop in a fitting using form loss coefficient

determines water properties as function of enthalpy and pressure

determines sodium temperature at heat exchanger inlet from boundary conditions

writes error message

determines reference pressure for a flow segment

determines reference pressure for a flow segment

determines reference coefficients for feedwater flow rate

determines turbine inlet pressure

determines water properties as function of enthalpy and pressure

INFS3T
determines water properties as function of enthalpy and pressure

determines reference coefficients for feedwater flow rate

determines turbine inlet pressure

determines coefficients for energy and flow equations for a pump

determines water properties as function of enthalpy and pressure

determines coefficients for energy and flow equations for a pipe

determines coefficients of total flow resistance in control volume

determines the coefficients of momentum flux pressure loss in control volume

determines friction factor as function of Reynolds number and surface roughness

determines two-phase friction multiplier on the water/steam side of the steam generator

determines water properties as function of enthalpy and pressure

determines coefficients of pressure drop in a fitting using form loss coefficient

calculates surface heat fluxes and tube wall temperatures in heat exchanger

calculates the time derivatives of differential equations for intermediate loop hydraulics

sets inlet and outlet pressures of uniform mass flow rate sections in intermediate loops

computes pressures at eventual break in intermediate loop

computes pressure losses in appropriate sections of intermediate loop from the losses in individual components

determines heat transfer coefficient in film boiling

writes error message

determines heat transfer coefficient in forced convection to liquid

determines heat transfer coefficient in nucleate boiling of subcooled or saturated water

determines heat transfer coefficient in forced convection to superheated steam

computes intermediate pump variables and time derivative for pump speed

sets inlet and outlet pressures of uniform mass flow rate sections in intermediate loops
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSFW3T</td>
<td>Determines reference pressure for a flow segment</td>
</tr>
<tr>
<td>FEED3T</td>
<td>Determines reference coefficients for feedwater flow rate</td>
</tr>
<tr>
<td>PSTB3T</td>
<td>Determines turbine inlet pressure</td>
</tr>
<tr>
<td>TANK2T</td>
<td>Computes pressures and time derivative for level in surge tank</td>
</tr>
<tr>
<td>HNAF3T</td>
<td>Computes sodium side surface heat transfer coefficient</td>
</tr>
<tr>
<td>ACCM3T</td>
<td>Calculates coefficients for accumulator, eliminates flow segment terms for accumulator equations, and advances the accumulator variables</td>
</tr>
<tr>
<td>PSFW3T</td>
<td>Determines reference pressure for a flow segment</td>
</tr>
<tr>
<td>PSTB3T</td>
<td>Determines turbine inlet pressure</td>
</tr>
</tbody>
</table>
Fig. B.5 All Subroutines Employed into SSC-K
The Supper System Code of KAERI (SSC-K) is a best-estimate system code for analyzing a variety of off-normal or accidents in the heat transport system of a pool type LMR design. It is being developed at Korea Atomic Energy Research Institution (KAERI) on the basis of SSC-L, originally developed at BNL to analyze loop-type LMR transients. SSC-K can handle both designs of loop and pool type LMRs. SSC-K contains detailed mechanistic models of transient thermal, hydraulic, neutronic, and mechanical phenomena to describe the response of the reactor core, coolant, fuel elements, and structures to accident conditions. This report provides an overview of recent model developments for the SSC-K computer code, focusing on phenomenological model descriptions for new thermal, hydraulic, neutronic, and mechanical modules. A comprehensive description of the models for pool-type reactor is given in Chapters 2 and 3; the steady-state plant characterization, prior to the initiation of transient is described in Chapter 2 and their transient counterparts are discussed in Chapter 3. In Chapter 4, a discussion on the intermediate heat exchanger (IHX) is presented. The IHX model of SSC-K is similar to that used in the SSC-L, except for some changes required for the pool-type configuration of reactor vessel. In Chapter 5, an electromagnetic (EM) pump is modeled as a component. There are two pump choices available in SSC-K; a centrifugal pump which was originally imbedded into the SSC-L, and an EM pump which was introduced for the KALIMER design. In Chapter 6, a model of passive safety decay heat removal system (PSDRS) is discussed, which removes decay heat through the reactor and containment vessel walls to the ambient air heat sink. In Chapter 7, models for various reactivity feedback effects are discussed. Reactivity effects of importance in fast reactor include the Doppler effect, effects of sodium density changes, effects of dimensional changes in core geometry. Finally in Chapter 8, constitutive laws and correlations required to execute the SSC-K are described. It is noted that the user's manual will be revised later with the further development of SSC-K.
<table>
<thead>
<tr>
<th>시 지 정 보 양 식</th>
</tr>
</thead>
<tbody>
<tr>
<td>수행기관보고서번호</td>
</tr>
<tr>
<td>KAERI/TR-1619/2000</td>
</tr>
</tbody>
</table>

주제 / 부제: SSC-K 전산코드 사용자 지침서

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상 관 원 자: KAERI의 다양한 비정상 조건 및 사고를 분석하기 위하여 최적열수력 전산코드인 SSC-K (Supper System Code of KAERI)를 개발하고 있다. SSC-K는 미국 BNL에서 루프형 액체금속조의 안전해석을 위해 개발된 SSC-L을 기반으로 하여 KALIMER와 같은 물형 원자로에 적용할 수 있도록 개발되었다. 현재 SSC-K 코드는 루프형과 물형의 액체금속조를 모두 모의할 수 있다. SSC-K는 파도상태의 열수력, 액 및 기계적 모델을 포함하고 있으므로 사고시 노동과 방사재, 핵연료의 거동 및 구조물의 온도변화를 모의할 수 있다. 본 보고서는 SSC-K를 위하여 새로이 개발된 여러 형상적 모델들을 기술하고 있으며 부록에는 코드입력에 대한 설명을 포함하고 있다. 플롭 원자로 열수력 계산을 위해 개발된 정상상태 및 파도상태의 모델을 2장과 3장에 상세히 설명하였다. 4장에는 기존 SSC-L 코드의 IXH 모델을 플롭의 원자로 구성에 적합하도록 변경된 증강열전달교환기 (IHX) 모델에 대해서 기술하였다. 5장에는 전자몇프 모델을 설명하였으며, SSC-K는 기존의 원심형프 외에 KALIMER 설계에 도입된 전자몇프를 선택적으로 사용 가능하다. 6장에는 노동에서 발생되는 봉려열을 원자로 벽면과 압력용기 벽면을 정하여 주변의 공기로 제거하는 PDSRS 모델을 기술하였다. 7장에는 도플러와 소름 밀도 변화에 의한 반응도 모델 및 노동의 기하학적 변화에 의한 반응도 계 형 모델에 대하여 설명하였다. 마지막으로 8장에는 SSC-K에 사용되는 상관식 및 물성치에 대하여 기술하였다. 시험작성을 통하여 개발된 SSC-K 코드의 예측능력에 대한 타당성을 정성적으로 확인하였다. 현장적인 액체금속조 사고들에 대하여 SSC-K를 사용한 안전해석 결과는 별도의 보고서로 발간될 예정이다. 시험해석 결과에 의하여 개발된 SSC-K 코드는 향후 KALIMER 예비 안전해석에 사용할 수 있을 것으로 판단된다.

주제명 기워드:
LMFBR, SSC-K, Safety Analysis Code