Applicability of RELAP5-3D for Thermal-Hydraulic Analyses of a Sodium-Cooled Actinide Burner Test Reactor

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Introduction

- The Actinide Burner Test Reactor (ABTR) is envisioned as a sodium-cooled fast reactor that will burn the actinides generated in light water reactors
- RELAP5-3D is being considered as the thermal-hydraulic system code to support the development of the ABTR
- An evaluation was performed to determine the applicability of RELAP5-3D for analysis of the ABTR

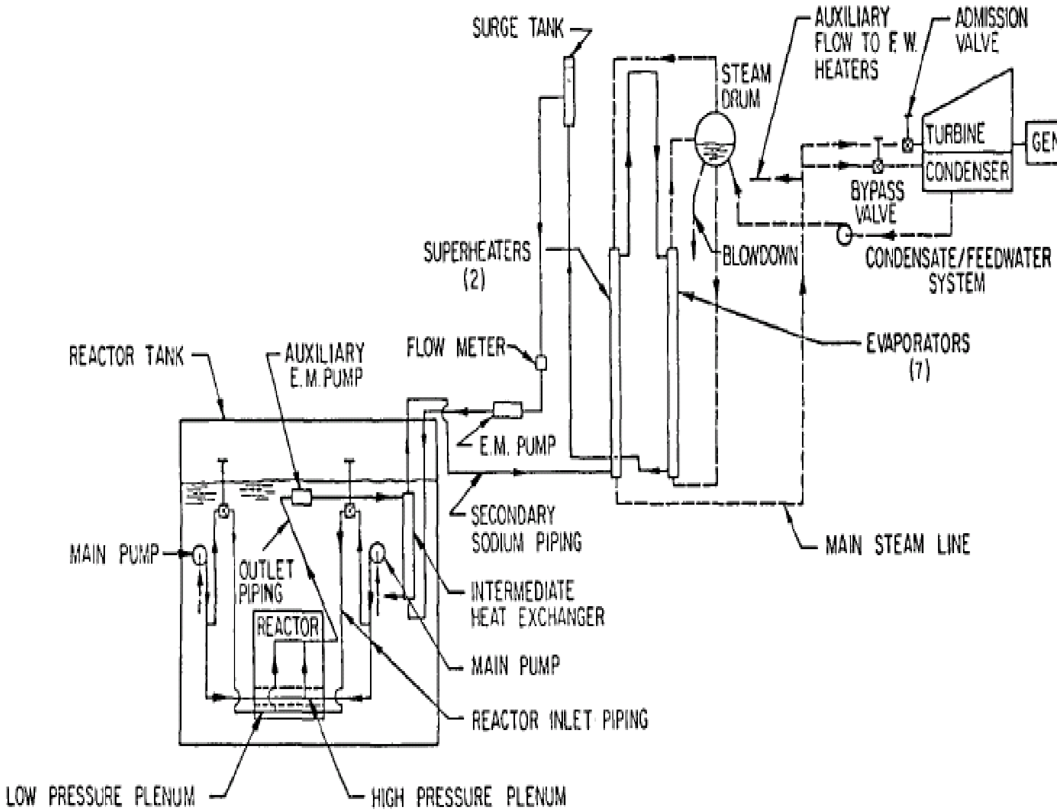
Introduction (cont'd)

- Evaluation was complicated by the fact that the conceptual design of the ABTR has not been developed
  - The Experimental Breeder Reactor-II (EBR-II) was used as a surrogate
- The ABTR design is expected to preclude the occurrence of boiling except for the most severe accidents
  - The applicability evaluation concentrated on single-phase phenomena
- Details are provided in INL/EXT-06-11518

Applicability evaluation steps

- **Identify the important phenomena expected during normal operation and important transients**
- **Identify the important models and correlations that affect the code's calculation of the important phenomena**
- **Evaluate the applicability of the important models and correlations**
- **Recommend new models and/or code improvements as needed**
- **Evaluate the accuracy of the thermodynamic and transport properties used by the code for sodium**

EBR-II Description



- Contained sodium-cooled primary and secondary coolant systems and a conventional steam system
- Primary coolant system was submerged in a large tank
- $371 < T_{fluid} < 473$ °C
- Wire-wrapped and orificed hexagonal subassemblies surrounded by reflector and blankets
- Fuel pins contained metallic uranium alloy fuel, sodium thermal bond, SS 316 cladding
- Centrifugal and EM pumps
- Air-cooled passive decay heat removal system

Identification of important transients

- Based on experiments conducted in EBR-II
  - Loss of forced convection without scram
  - Loss of heat sink without scram
- Station blackout is limiting event for the passive shutdown cooling system
- Figure of merit for evaluating the safety of EBR-II was the peak temperature at the interface between the fuel and the cladding
  - T < 715 °C for normal operation and anticipated transients
  - T < 815 °C, with less than 60 s operation above 715 °C, for unlikely transients

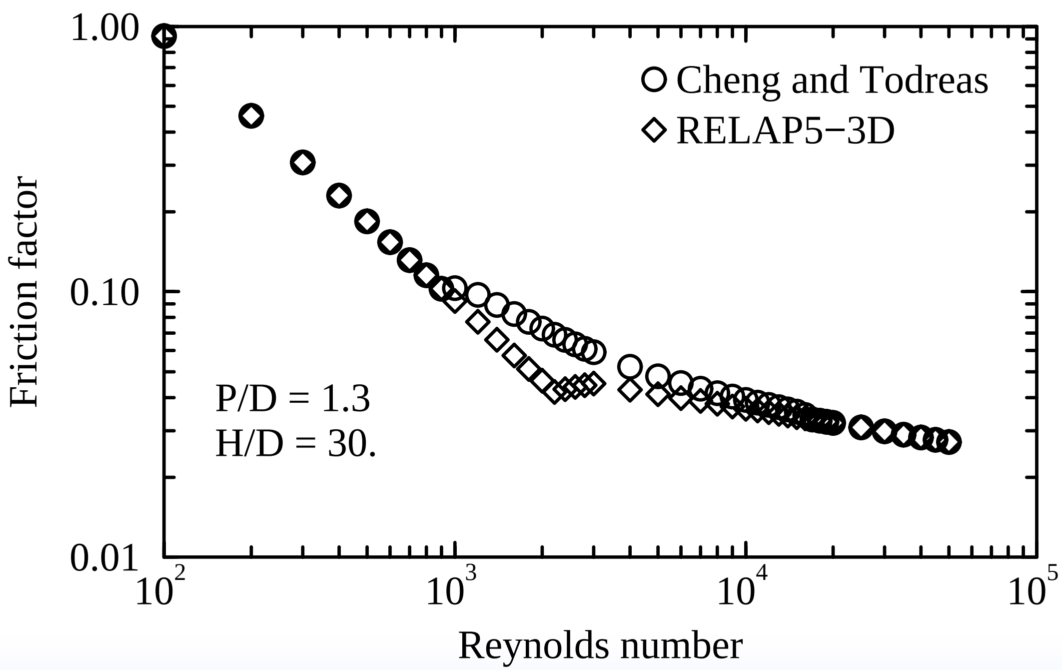
Identification of important phenomena

- Frictional characteristics of the inlet orifice and the wire-wrapped rod bundle
- Coastdown characteristics of the primary pumps
- Core inlet fluid temperature affected by mixing and thermal stratification in the tank and the performance of the secondary coolant system, power conversion unit, and passive decay heat removal system during long transients
- Heat transfer from the fuel rod to the coolant
  - Heat conduction and convective heat transfer
  - Axial and radial conduction in the fluid

Identification of important phenomena (Cont’d)

- **Reactivity feedback effects for transients without scram**
- **Decay power**
- **Natural circulation**

The wall friction model needs to be improved to represent the transition region of a wire-wrapped rod bundle



- The use of the shape factor

$$f_L = \frac{64}{Re\phi}$$

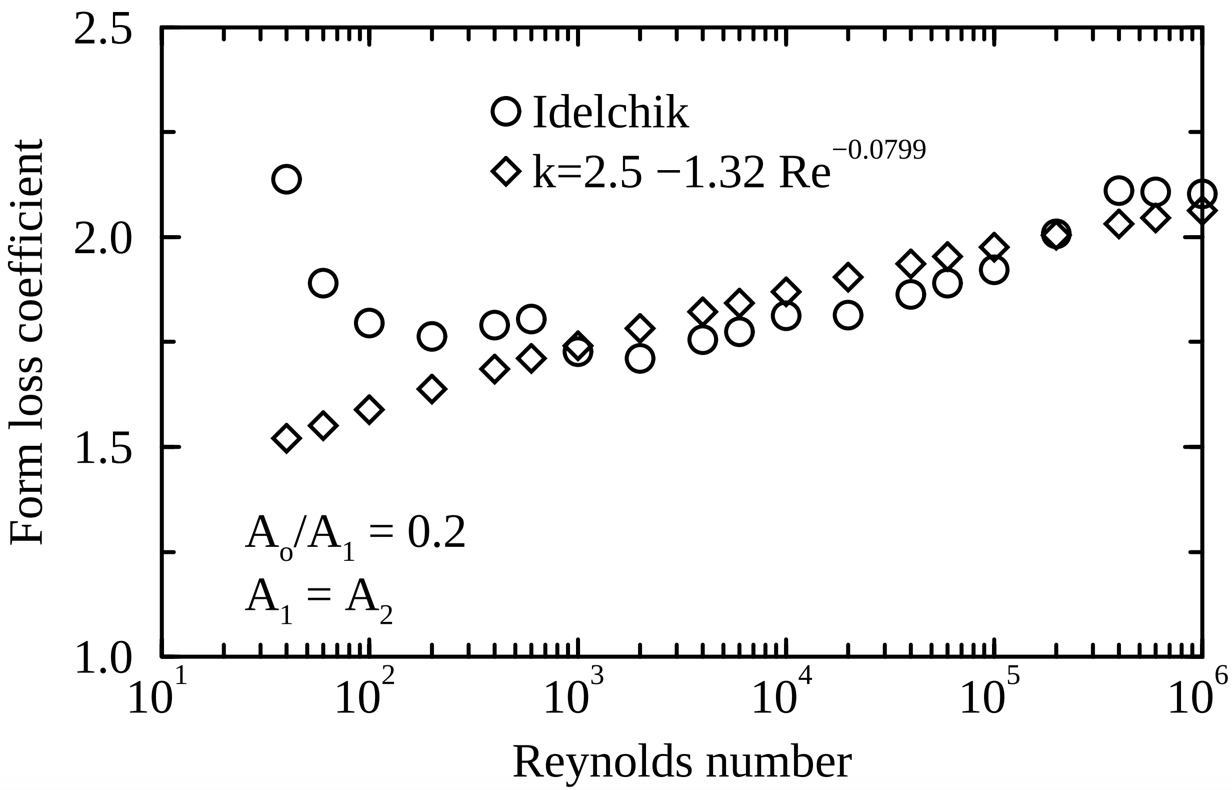
allows the laminar region to be matched exactly

- The alternate turbulent wall friction model

$$f_T = A + BRe^{-C}$$

matches the turbulent region exactly

A more general equation is required to accurately represent a sharp-edged orifice



- The allowed form

  $k = A + BRe^{-C}$

  matches Idelchik to within 10% for Re>200

- Negative values of B are currently not allowed

An electromagnetic pump model is probably needed to simulate the ABTR

- EBR-II used electromagnetic pumps in both the primary (auxiliary) and secondary coolant systems
  - The implementation of a previously proposed model should be adequate for analysis of the ABTR
- The existing centrifugal pump model should be adequate to characterize the behavior of the centrifugal pumps in the ABTR

No new models are needed to represent thermal stratification in the reactor tank

- **Existing code can not perform a mechanistic calculation of the mixing process**
- **The effects of thermal stratification can be bounded through nodalization studies**
- **Coupling with Fluent allows an integrated, mechanistic capability**

RELAP5-3D has the capability needed to represent the other systems of the ABTR including

- **Secondary coolant system (with the exception of the electromagnetic pump)**
- **Power conversion unit**
- **Passive decay heat removal system**

Minor modifications to the heat transfer models are required to represent the ABTR

- **The existing heat conduction model is adequate for the structures**
- **Gap conductance model not expected to be applicable for metallic fuel (results from a detailed fuel performance code are required)**
- **The default heat transfer correlation for liquid metals should be changed from**

$\mathrm{Nu} = 5.0 + 0.025\mathrm{Pe}^{0.8}$ **to** $\mathrm{Nu} = 7.0 + 0.025\mathrm{Pe}^{0.8}$

- **The rod bundle correlation should be changed from the Westinghouse correlation to the correlation of Borishanskii to better match data**

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The thermal conductivity of sodium is ~ 100 times greater than that of water

- Axial conduction in the fluid could be significant, particularly during transients with reduced flow
  - Axial conduction should be added to the code
  - Implementation of a previously proposed model should be adequate
- A scoping evaluation of an EBR-II experiment indicated that radial conduction between adjacent subchannels in a subassembly could be significant
  - Since RELAP5-3D will probably not be used to model subchannel effects, no changes are needed at this time

Core power depends on various feedback mechanisms

- Coolant density and fuel temperature (Doppler)
- Thermal expansion of various components including the fuel, upper and lower reflectors, control rod driveline, and upper grid plate
- Radial expansion of the core and bowing

Different approaches are available to represent these feedback mechanisms

- **Coupled thermal and mechanical calculations to determine the effect of temperature on the geometry and the effect of the geometry on the feedback**
  - **Implement detailed mechanical models in RELAP5-3D or link to a structural analysis code**
- **A simplified approach based on external mechanical calculations and changes in component temperatures**
- **No code changes are judged necessary at this time because the mechanical design of the ABTR has not yet been defined**

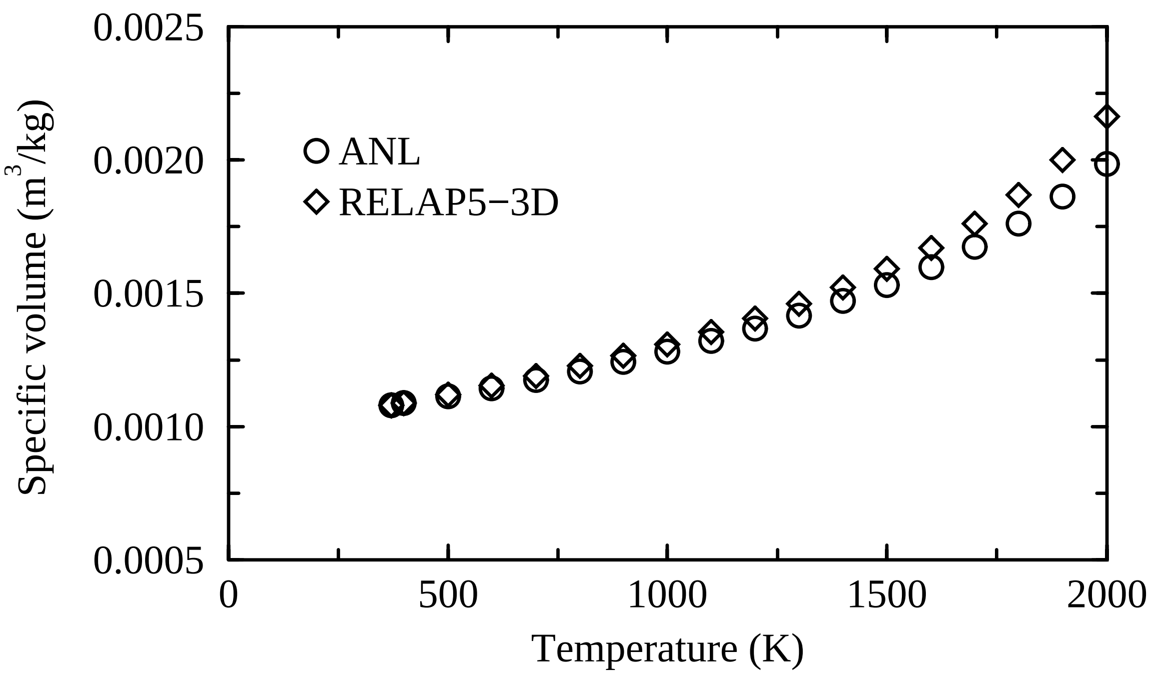
The decay heat model should be improved for the ABTR

- The decay heat will be affected by the minor actinides present in the fuel
- The decay heat characteristics of the driver and blanket subassemblies will differ considerably
  - The driver subassemblies are enriched with ^{235}U while the blanket assemblies are depleted of ^{235}U
  - The fraction of fission power generated in each isotope varies considerably between subassemblies

The accuracy of each fluid property was evaluated

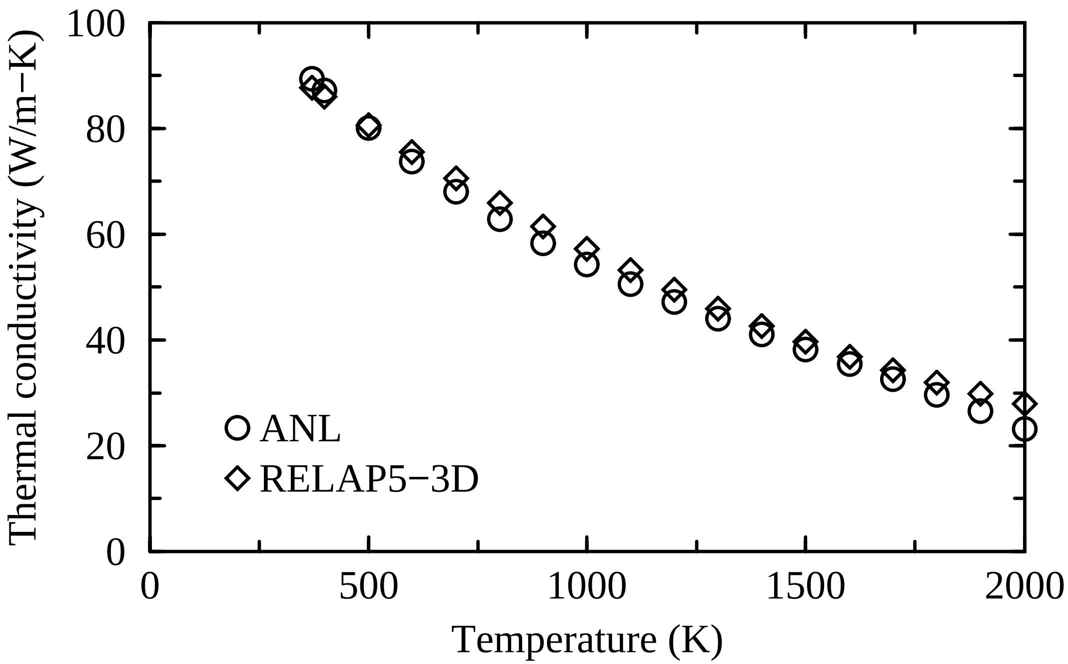
- The principal range of interest for the ABTR is expected to be between 600 and 1100 K
- Liquid properties are of the most interest for the ABTR
- Thermodynamic properties are obtained from a soft sphere model that utilizes five adjustable parameters
- Comparisons between the values calculated by RELAP5-3D were quantitatively compared to other sources of data and were given subjective judgments of excellent, reasonable, minimal, or insufficient based on the estimated uncertainty

RELAP5-3D fluid properties were generally in reasonable to excellent agreement



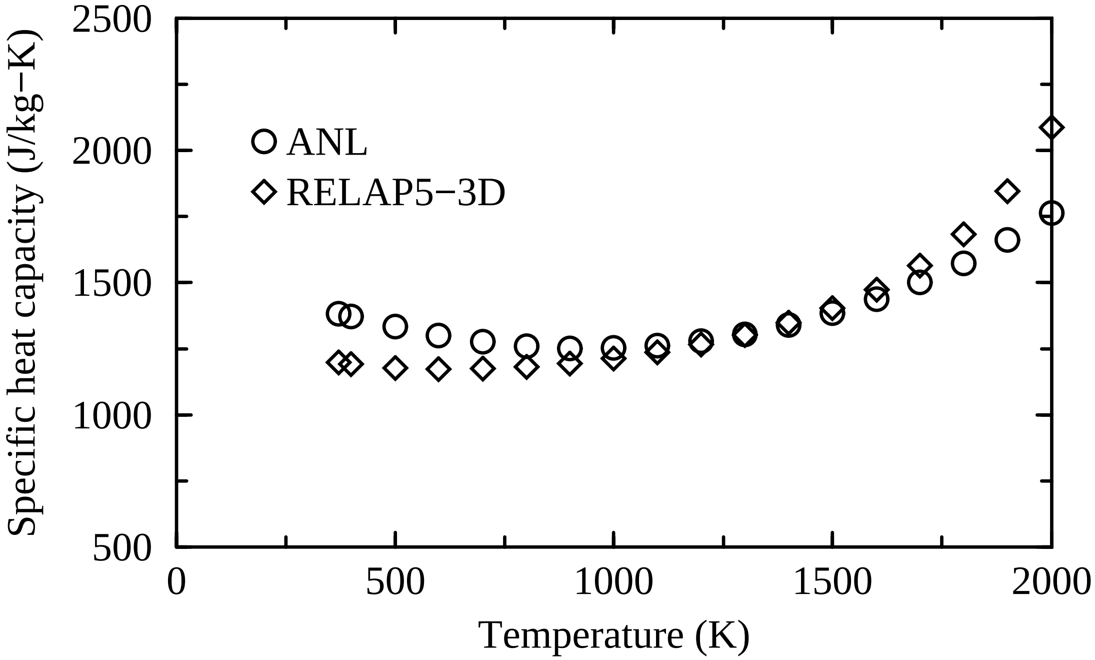
- Results for liquid specific volume agreed within a few percent for T < 1100 K and were judged in reasonable agreement

Transport properties were in excellent agreement



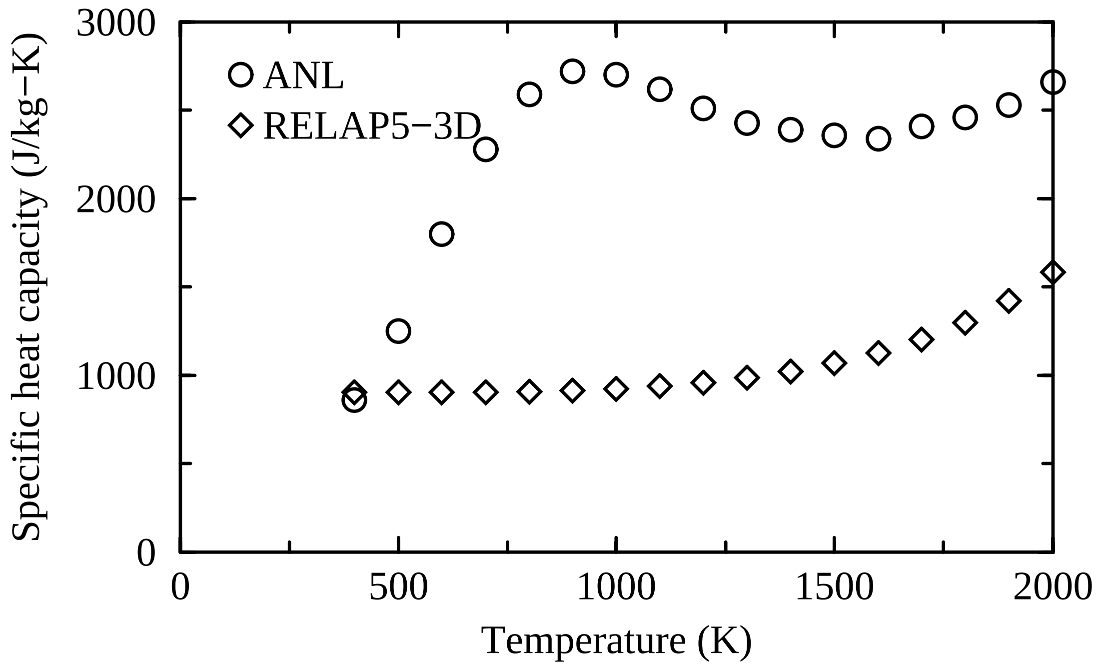
- Liquid thermal conductivity

However, the liquid specific heat capacity was judged to be in minimal agreement



- RELAP5-3D values were too low below 1100 K and too high about 1500 K
- At the expected normal operating temperature of 700 K, the RELAP5-3D value was 8% too low versus an estimated uncertainty of 2%
- The adjustable constants should be varied to better fit the data below 1100 K; larger errors could be tolerated above 1100 K

The vapor specific heat capacity was in insufficient agreement



- The impact of the large deviations is not expected to be significant because the liquid phase is of primary interest

Conclusions

- Peak temperature at the inside surface of the cladding is expected to be the primary figure of merit for the ABTR
- Transients initiated by loss of forced convection, loss of heat sink, and station blackout will be important in the design of the ABTR
- The evaluation showed that the existing models were generally adequate or relatively minor changes were required to simulate the ABTR
- However, two new models are needed
  - Electromagnetic pump
  - Axial conduction in the fluid

Conclusions (cont'd)

- Minor proposed code improvements include
  - Modify the transition region for a wire-wrapped rod bundle
  - Allow B < 0 in the user-input Reynolds-number dependent form loss coefficient
  - Change the constant in the default heat transfer correlation for liquid metals from 5 to 7
  - Change the bundle heat transfer correlation from that of Westinghouse to that of Borishanskii

Conclusions (cont'd)

- **Several long-term changes would result in an improved analytical capability, but are not required for immediate analyses**
  - **Implement mechanical models to calculate the effects of thermal expansion on the geometry of various core components for a more mechanistic calculation of reactivity feedback**
  - **Implement an improved decay heat model to account for the actinides that will be burned in the ABTR**
  - **Implement a more general equation defining the form loss coefficient as a function of Reynolds number for an orifice**

Conclusions (cont'd)

- **The sodium fluid properties in RELAP-3D are generally in reasonable to excellent agreement with other sources of data**
  - **The adjustable constants in the soft sphere model should be modified to better match liquid specific heat capacity data for temperatures below 1100 K**

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