Thermal-Hydraulic Analysis of the HFIR

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The High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (ORNL) is a high performance research reactor used to produce transuranium isotopes and perform material irradiation studies. HFIR was operated for about 20 years prior to its shutdown in November 1986 and has remained shutdown while the results of safety studies are completed and reviewed. This paper highlights results from ongoing studies which have revisited system thermal-hydraulic safety limits with present day analytical tools and experimental investigations. Long term decay heat removal requirements have been examined as well as the response of the system to small break loss of coolant accidents (SBLOCA).

In the event of a "worst case" station blackout, power for forced flow is only provided to primary coolant pump "pony" motors which supply sufficient flow to cool the core after shutdown. In this case, the primary heat sink is a large pool of water containing the reactor vessel and core. Forced flow is required until natural convection cooling is sufficient to (1) remove heat from the core, and (2) then transfer the heat to the pool. Based on pre-operation experimental investigations it was determined that forced flow was only needed for ∼2 h after shutdown; however, recent concerns that this was in fact adequate, motivated a revisit to this safety question.

The core must remain covered with liquid water in order to insure adequate natural convection cooling within a reasonable time after shutdown. Since the system is expected to depressurize to ∼0.15 MPa within a few hours following shutdown, the water in the vessel must remain below the saturation temperature (385 K). A global lumped parameter thermal model was used to predict the bulk vessel water peak temperature following shutdown with forced flow assumed for varying durations. For input to the lumped model, vessel-to-pool heat transfer was calculated assuming...
one-dimensional heat conduction through the vessel walls and using natural convection coefficients based on standard correlations. The TEMPEST code was used to characterize countercurrent flow (CCF) and heat transfer within the inlet piping through which significant heat transfer occurs to the pool heat sink. Analysis results indicate that if forced flow is provided through 8 h after shutdown, the probability is 90 percent that the water will remain below the saturation temperature; with 12 h of forced flow, the probability becomes 96 percent. It is hoped that an experiment in HFIR can be conducted to verify the analysis.

A RELAP/MOD2 input model of the HFIR core and vessel was created to study core cooling following termination of forced flow. The model contains many parallel channels representing lumped "average" fuel channels, hot fuel channels, and target, control cylinder, and beryllium reflector regions as shown in the schematic diagram in Fig. 1. Analyses have examined core cooling following cessation of forced flow assumed for various durations after shutdown. With 8 h of forced flow, analysis indicates the core will survive the transition from forced downflow to natural convection upflow through the fuel element. In addition, through the system heatup to the predicted peak vessel water temperature (taken to be the saturation temperature, 385 K) at ~14 h after shutdown, the core remains cool (near 385 K).

Although RELAP5 was developed for light water power reactors with geometries and operating conditions significantly different from those of HFIR, results of recent benchmarking activities evaluating code performance against low-flow and low-pressure critical heat flux (CHF) data in a narrow annular test section indicate the code conservatively predicts CHF at 61 to 89 percent of measured values. RELAP5 predicted density wave oscillations are consistent with the findings of Stenning, who determined that the period of a density wave should be approximately equal to the mass transport time. RELAP4/MOD6 has successfully predicted the period and amplitude of experimentally observed density waves in a previous application by Chen et al.

RELAP5 analysis has been complemented with an air/water CCF experiment using a HFIR fuel element mock-up which indicates that the fuel will remain adequately cooled with no forced flow at a decay heat level of 450 kW which corresponds to ~4.5 h after shutdown. Implicit in this result is the conservative assumption of a blocked bottom.
A thermal-hydraulic model of the HFIR system has been developed using RELAP5 and employed to investigate the system response to SBLOCA. \(^9\) Preliminary results indicate that the system can sustain a 5-cm-diameter break at the outlet of a main circulation pump with no resulting fuel damage. In fact, no boiling in the fuel region occurs. Analysis is in progress to determine the system response to larger-diameter breaks.
References


2. Morris, D. G., *Thermal Analysis of HFIR Station Blackout With Loss of Pool Inventory-Revision 1*, ORNL report to be published.


THERMAL-HYDRAULIC ANALYSIS OF THE HFIR*

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VARIETY OF THERMAL-HYDRAULIC ANALYSES ARE BEING PERFORMED FOR HFIR

● ANALYSES SUPPORT:
- HFIR RESTART
- UPGRADE OF THERMAL-HYDRAULIC ANALYTICAL CAPABILITIES
- REVISED FSAR

● ANALYSES INCLUDE:
- LONG-TERM DECAY HEAT REMOVAL
- SBLOCA, LBLOCA, AND OPERATIONAL TRANSIENTS
ANALYSIS HAS EXAMINED HFIR DHR REQUIREMENTS FOLLOWING STATION BLACKOUT

**OBJECTIVE:** DETERMINE REQUIRED DURATION OF FORCED FLOW FOLLOWING SHUTDOWN TO PREVENT FUEL MELTING

**"WORST" CASE STATION BLACKOUT (EXTERNAL EVENTS)**

- ONSITE POWER FOR PRIMARY FLOW
  - DIESELS
  - BATTERIES
- NO SECONDARY OR POOL COOLING SYSTEM FORCED FLOWS
- PRIMARY DEPRESSURIZED

**IF TIME \( \leq 8 \) TO 16 H, BATTERIES SUFFICIENT

**TWO NATURAL CONVECTION COOLING REQUIREMENTS**

- CORE TO PRIMARY (VESSEL)
- PRIMARY TO REACTOR POOL
VERTICAL SECTION OF HFIR VESSEL AND CORE
HFIR CORE COOLING FOLLOWING CESSION OF FORCED FLOW WAS STUDIED WITH RELAP5

- RELAP5/MOD2/CYCLE 36.06 WITH LOW PRESSURE UPDATES

- MODEL INCLUDES MANY PARALLEL CHANNELS REPRESENTING THE CORE
  - AVERAGE FUEL
  - HOT FUEL
    - POWER PEAKING FACTORS
    - 35 MIL CHANNEL GAP
  - TARGET
  - BE REFLECTOR
  - CONTROL CYLINDER
  - BYPASS

- "CALIBRATED" MODEL TO GET PROPER $\Delta P_{\text{CORE}}$, FLOW DISTRIBUTION FOR NOMINAL CONDITIONS
  - ORIFICES
  - ROUGHNESS

- MODEL NOT USED TO CALCULATE HEAT TRANSFER TO POOL HEAT SINK
RELAP5 SIMULATION

- OBJECTIVE: "SNAPSHOT" OF CORE COOLING AT A PARTICULAR POINT IN TIME (415-SECOND SIMULATION)

- ASSUMPTIONS/CONDITIONS
  - 8 H FORCED FLOW FOLLOWING HFIR SHUTDOWN
  - INITIAL TEMPERATURE \( \approx 62^\circ\text{C} \)
  - SYSTEM PRESSURE \( \approx 0.17 \text{ MPa} \)
  - DECAY HEAT POWER = 0.39 MW

- SIMULATION
  - 0 TO 200 S - ESTABLISH INITIAL FLOW, TEMPERATURE CONDITIONS
  - 200 TO 212 S - PUMP COASTDOWN TO NO FLOW
  - 212 TO 415 S - NO FORCED FLOW

{"SNAPSHOT"}
INNER FUEL ELEMENT HOT CHANNEL EXIT
MASS FLOWS AND VELOCITIES

![Graph showing mass flows and velocities over time.](image)
INNER FUEL ELEMENT HOT CHANNEL TEMPERATURES, VOID FRACTION, AND QUALITY AT TOP OF HEATED LENGTH

- TEMPF-1002
- TEMPG-1002
- SATTEMP-1002
- HTEMP-10000105

- VOID-1002
- QUALS-1002
RELAP5 ANALYSIS AND CCFL EXPERIMENT INDICATE NATURAL CONVECTION CORE COOLING ADEQUATE 4.5 H AFTER SHUTDOWN

- RELAP5 SIMULATIONS APPEAR REASONABLE
  - COOLING ADEQUATE AT SHORT TIMES AFTER SHUTDOWN
    - 0.85 MW (1.4 H)
    - 0.60 MW (3 H) WITH SATURATED UPPER PLENUM
  - CORE SURVIVES FLOW REVERSAL
  - CHF BENCHMARK INDICATES CONSERVATIVE CODE PERFORMANCE

- AIR/WATER CCFL EXPERIMENT PERFORMED WITH FULL SCALE MOCKUP
  - COOLING ADEQUATE ~ 4.5 H AFTER SHUTDOWN
  - RESULTS CONSISTENT WITH SINGLE CHANNEL MODEL
ANALYSIS OF HEAT TRANSFER TO POOL PERFORMED TO INSURE VESSEL WATER DOES NOT SATURATE

- AVOID VAPOR BUBBLE
  - BLOCK TARGET DOWNCOMER
  - UNCOVER CORE

- STEADY-STATE HEAT TRANSFER CALCULATIONS PERFORMED
  - TEMPEST CODE FOR INLET PIPING-TO-POOL HEAT TRANSFER
    - 3-D
    - SINGLE-PHASE FLOW
    - LAMINAR AND TURBULENT FLOWS
  - HAND CALCULATIONS FOR VESSEL-TO POOL HEAT TRANSFER

- LUMPED TRANSIENT MODEL
  - BEST-ESTIMATE
  - MONTE CARLO UNCERTAINTY ANALYSIS
COUNTERFLOW THROUGH THE HORIZONTAL PORTION OF THE INLET PIPING WAS ANALYZED WITH 3-D TEMPEST MODEL

MODEL CHARACTERISTICS:

- PIPE ASSUMED TO BE STRAIGHT
- EFFECTS OF INLET DIFFUSER NEGLECTED
- PIPE CONNECTED TO LARGE RESERVOIR
- H OUTSIDE ASSUMED CONSTANT
LOSS OF FORCED FLOW SAFELY ACCOMMODATED 12 H AFTER SHUTDOWN WITH HIGH CONFIDENCE

- INPUT UNCERTAINTIES INCLUDED (1 σ):
  - CONVECTION COEFFICIENT ~ 20%
  - CONDUCTION ~ 7.5%
  - DECAY HEAT ~ 5%
  - PRIMARY HEAT CAPACITY ~ 7.5%

- ANALYSIS RESULTS

<table>
<thead>
<tr>
<th>TIME (H)</th>
<th>B.E. MARGIN (°C)</th>
<th>CONFIDENCE (%)</th>
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</thead>
<tbody>
<tr>
<td>6</td>
<td>4.6</td>
<td>73.5 TO 76.7</td>
</tr>
<tr>
<td>12</td>
<td>11.</td>
<td>94.0 TO 95.6</td>
</tr>
<tr>
<td>16</td>
<td>13.</td>
<td>96.9 TO 98.0</td>
</tr>
</tbody>
</table>

- EXPERIMENTAL CONFIRMATION DESIRED

- HEAT TRANSFER TO SINK MORE LIMITING THAN CORE COOLING
HFIR RELAP5 SYSTEM MODEL DEVELOPED TO ASSESS SYSTEM RESPONSE TO LOCA AND OPERATIONAL TRANSIENTS

- INITIAL MODEL DEVELOPED
  - DOCUMENTING INPUT MODEL
  - INEL VERIFYING INPUT MODEL
  - VERIFYING CODE/MODEL AGAINST OTHER CALCULATIONS (HFIRSYS)
  - VALIDATING/CALIBRATING MODEL AGAINST DATA

- RELAP5 MODIFIED FOR USE
  - MOD2 WITH LOW PRESSURE UPDATES
  - MOD3
    - LOW PRESSURE UPDATES
    - "ANS UPDATES" FOR PLATE-TYPE REACTORS
    - FURTHER REVIEW/MODIFICATION

- CODE BENCHMARK STUDIES NEEDED
  - FLOW EXCURSION
  - HIGH FLOW CHF
  - OTHER
HFIR SYSTEM PRESENTS SIGNIFICANT THERMAL-HYDRAULIC MODELING CHALLENGES

- "HARD" SYSTEM LOCA
  - RAPID DEPRESSURIZATION
  - SUBATMOSPHERIC AT CORE EXIT
  - STRUCTURAL ELASTICITY SIGNIFICANT

- SIMULATIONS EXPENSIVE DUE TO HIGH VELOCITY FLOWS, FINE CORE AXIAL NODE DISCRETIZATION

  1 S REAL TIME - 100 S CRAY X-MP CPU TIME

- LOW PRESSURE SIMULATIONS DIFFICULT DUE TO LARGE WATER LIQUID TO VAPOR DENSITY DIFFERENCES
SUMMARY

- DHR FOLLOWING STATION BLACKOUT

  - CORE COOLING
    - RELAP5 SIMULATIONS
      APPEAR REASONABLE
      INDICATE NATURAL CONVECTION COOLING ADEQUATE AT SHORT TIMES AFTER SHUTDOWN
    - FLOODING EXPERIMENT DEMONSTRATES COOLING ADEQUATE ~ 4.5 H AFTER SHUTDOWN

  - HEAT TRANSFER TO SINK
    - COOLING ADEQUATE WITH DIESEL GENERATORS POWERING FLOW FOR LONG DURATION
    - CAN ELIMINATE DIESEL DEPENDENCE WITH HIGH CONFIDENCE
      ~ 95% WITH 12 H FORCED FLOW
      VERIFY WITH EXPERIMENT
      STEAM VENT

- RELAP5 SYSTEM ANALYSIS

  - INITIAL HFIR MODEL DEVELOPED
  - MODEL VERIFICATION AND VALIDATION IN PROGRESS
  - CODE REVIEW AND BENCHMARKS NEEDED
  - LOCA ANALYSIS INITIATED