BWR Control Blade/Channel Box Interaction Models for SCDAP/RELAP5 *

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ABSTRACT

The core of a boiling water reactor (BWR) consists of an array of fuel assemblies with cross-shaped control blades located between these assemblies. Each fuel assembly consists of a fuel rod bundle surrounded by a Zircaloy channel box. Each control blade consists of small stainless steel absorber tubes filled with B₄C powder surrounded by a stainless steel blade sheath. Under severe accident conditions, material interactions between the B₄C, stainless steel, and Zircaloy would have a significant impact on the melting and subsequent relocation of the control blade and channel box structures.

This paper describes a new BWR control blade/channel box model for the SCDAP/RELAP5 severe accident analysis code that includes the effects of these material interactions. The phenomena represented by this model and the modeling techniques are derived from ORNL analyses of the BWR severe fuel damage experiments. Two examples of the operation of this new model within SCDAP/RELAP5 are provided.

1. INTRODUCTION

Work began at Oak Ridge National Laboratory (ORNL) in January 1991 to improve the SCDAP/RELAP5 code for boiling water reactor (BWR) severe accident applications. To date, the ORNL improvements have been limited to SCDAP's core-region structural models. SCDAP/RELAP5 has been developed primarily at Idaho National Engineering Laboratory (INEL) to provide best-estimate predictive capability for use in light water reactor severe accident...
applications. INEL is the sole institution responsible for maintaining the official version of SCDAP/RELAP5.

The specific objective of the project described in this paper is to incorporate BWR control blade/channel box interaction models within SCDAP/RELAP5. A sketch of a typical BWR control blade and fuel assembly is shown in Figure 1. The cross-shaped control blade has four wings. Each wing consists of a stainless steel blade sheath that surrounds a row of small stainless steel absorber tubes filled with B$_4$C powder. The fuel assembly consists of an array of fuel rods that is surrounded by a Zircaloy channel box. The cross-shaped control blade is located between four fuel assemblies. Under severe accident conditions, material interactions occur between the B$_4$C, stainless steel, and Zircaloy.

Severe fuel damage experiments that include BWR control blade and channel box structures have been performed in-pile in the Annular Core Research Reactor at Sandia National Laboratory (the DF-4 test), and out-of-pile in the CORA test facility at Kernforschungszentrum Karlsruhe (KfK), Federal Republic of Germany. Posttest analyses have been conducted at ORNL for the DF-4 test$^2$ and the BWR series of CORA experiments (CORA-16 and CORA-17,$^3$ CORA-31,$^4$ CORA-33,$^5$ and CORA-28$^6$) using analytical tools that represent the specific geometry and boundary conditions of each experiment. Based on these experiment-specific analyses at ORNL, and KfK's separate effects tests,$^7$ a clear understanding of material interactions in BWR severe accidents has evolved.

The degradation process begins when the B$_4$C powder reacts with the stainless steel absorber tubes. This B$_4$C/stainless steel eutectic liquifies at a temperature of ~ 1505 K, which is lower than the melting temperature of pure stainless steel. Then, either by failing the stainless steel blade sheath or flowing through the water circulation holes in the sheath (shown in Figure 1), the molten B$_4$C/stainless steel mixture relocates downward and freezes to form a crust on the surface of the control blade. This crust builds up until a blockage spans the gap between the control blade and the channel box. The Zircaloy channel box reacts with the stainless steel in the blockage and melts at the stainless steel/Zircaloy liquefaction temperature of ~ 1523 K, which is much lower than the melting temperature of pure Zircaloy. This opens a relocation path for molten control blade material to move through the opening in the channel box wall and down the fuel bundle side of the channel box.

Control blade/channel box interaction models have been implemented within SCDAP/RELAP5 by taking portions of the experiment-specific models developed at ORNL for CORA-16 and CORA-17$^7$ and converting them into a new control blade/channel box component for SCDAP. The SCDAP development staff at INEL supports this modeling approach and provided the necessary information for implementing the interface with the RELAP5 hydrodynamic calculations. The new control blade/channel box component is provided as an additional "building block" that can be selected by the user when appropriate. SCDAP's original BWR control rod component (which does not include the channel box) remains as an available option.

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Figure 1. Sketch of typical BWR control blade and fuel assembly.
2. DESCRIPTION OF BWR CONTROL BLADE/CHANNEL BOX COMPONENT

The new control blade/channel box component is based on the nodal configuration shown in Figure 2. At each axial elevation, three radial temperature nodes are used for the control blade, whereas two temperature nodes represent the channel box wall. The actual control blade configuration of small tubes inside a stainless steel blade sheath is converted into an equivalent slab geometry (discussed in greater detail in Section 3).

The solid structures of the control blade/channel box component interact with two RELAP5 hydrodynamic volumes: one for the interstitial region and the other for the fuel bundle region. The gap between the blade sheath and the absorber tubes is modeled. This gap communicates with the interstitial coolant volume through a series of holes in the blade sheath (shown in Figure 1). The gap results in two additional surfaces for stainless steel oxidation and also imposes an additional thermal resistance between the blade sheath and the absorber tubes.

The thermal calculations for the control blade/channel box component take advantage of symmetry. The three control blade temperature nodes actually represent only half of a control blade; the other half is identical. The dashed line surrounding the component in Figure 2 represents an adiabatic surface. This adiabatic surface is shown as a triangular-shaped symmetrical region in the sketch of a BWR core in Figure 3. Figure 3 also highlights the need for modeling the channel box wall with two segments. One segment of the box wall is adjacent to a control blade, and the other is adjacent to another channel box. The region in the interstitial coolant volume beyond the tips of the control blades provides an important path for molten control blade material to relocate onto the core plate.

A finite difference formulation is used to model the thermal responses of the control blade and channel box structures. Energy equations representing conduction and convection heat transfer in the radial direction are solved implicitly to determine new values for the five nodal temperatures at each axial elevation. Axial conduction, relocation/solidification, oxidation, and radiation heat transfer are computed explicitly using previous timestep information and are included as constant terms in the energy equations.

An approximate solution method is used to solve the melting terms in the energy equations. At the end of each timestep, the new nodal temperatures calculated from the energy equations are compared with the associated melting temperatures. If a nodal temperature is greater than the melting temperature and the node also contains solid material, then the nodal temperature is adjusted downward to the melting temperature, and the associated sensible heat is used to melt an appropriate amount of the solid material. This temperature adjustment is not made if the node does not contain any solid material (i.e., if only liquid material is present).
Figure 2. BWR control blade/channel box component with equivalent slab geometry and five temperature nodes at each axial elevation.

Figure 3. Arrangement of fuel assemblies and control blades in BWR core.
Material interactions between $\text{B}_4\text{C}$/stainless steel and stainless steel/Zircaloy are modeled by using reduced melting temperatures. Material compositions are tracked in each solid node. When $\text{B}_4\text{C}$ and stainless steel, or stainless steel and Zircaloy, are present in a node, these material pairs are allowed to react, using Hofmann's reaction kinetics. After a material interaction has occurred in a node, a eutectic liquefaction temperature is used in the melting calculations rather than the melting temperature of the pure material. The liquefaction temperatures are $\sim 1505$ K for $\text{B}_4\text{C}$/stainless steel mixtures and $\sim 1523$ K for stainless steel/Zircaloy mixtures.

The relocation of molten material is assumed to be controlled by solidification rates. The effects of liquid viscosity and momentum are assumed to be negligible. As molten material relocates downward over an underlying solid structure, it will solidify and transfer heat to the underlying solid. In the control blade/channel box component, molten material is allowed to relocate downward until it either solidifies or moves past the bottom of the defined core.

The relocation logic in the control blade/channel box component allows for horizontal movement of molten material whenever a blockage (defined as a node completely filled by a uniformly distributed frozen crust) inhibits downward movement. For example, if there is a blockage in the interstitial volume between the control blade and the channel box, and the adjoining channel box node has failed, then molten control blade material is allowed to relocate through the original location of the channel box wall and into the fuel bundle region. If the adjoining channel box node has not failed, but the region beyond the tip of the control blade remains open, then molten material is allowed to relocate laterally from segment 1 to segment 2. If both horizontal directions are blocked, then molten material is allowed to pool up on top of the interstitial blockage.

The oxidation of Zircaloy, stainless steel, and $\text{B}_4\text{C}$ is included in the control blade/channel box models. Based on steam availability, oxidation heat generation rates and hydrogen production rates are calculated for each axial node. Zircaloy oxidation is modeled for temperatures $> 923$ K using several correlations that are applicable in different temperature regions. Oxidation of iron, chromium (which is the major contributor to total reaction energy), and nickel is considered for stainless steel. $\text{B}_4\text{C}$ oxidation/reduction predictions are obtained from a chemical equilibrium calculation involving 18 chemical species (see Section 2.5 of Reference 8).

Radiation calculations on the fuel bundle side of the channel box are performed in the normal manner by the SCDAP radiation model, with the two segments of the channel box treated as independent surfaces. Radiation calculations on the interstitial side of the channel box are performed internally by the control blade/channel box models. These radiation calculations are activated whenever the local fluid void fraction exceeds a user-specified value.

All hydrodynamic parameters used in the control blade/channel box component are obtained from the RELAP5 data base. These parameters include steam flow rates, fluid properties (pressures, temperatures, void fractions), and convective heat transfer coefficients. Radiation
heat transfer rates on the fuel bundle side of the channel box (both segments) are obtained from
the SCDAP radiation model. Control blade/channel box parameters returned to SCDAP/RELAP5 include hydrogen production rates, wall temperatures, and coolant flow area reductions
caused by frozen crust formation.

The new control blade/channel box component, consisting of 41 subprograms totaling about
10,000 lines of FORTRAN (see Section 3 of Reference 8), has been implemented and tested
within several developmental versions of SCDAP/RELAP5. These models are scheduled to be
released by INEL with the next production version of SCDAP/RELAP5.

Several limitations exist in the current implementation of these models, which will be remedied
for future versions of SCDAP/RELAP5. Recent control blade/channel box enhancements
developed for the experiment-specific analysis of CORA-33 have not been transferred to the
SCDAP version of the models. The current SCDAP models do not allow molten control blade/
channel box material to spread radially into the fuel bundle. Also, the current models are not
fully coupled with SCDAP's late-phase models for core debris, molten pool formation, and
lower plenum debris.

3. USER INTERFACE

Input data is specified on a group of cards that contain information for each control blade/
channel box component used in an input deck, and on cards that define SCDAP radiation
enclosures. The new SCDAP input format with RELAP5-style card numbers is employed.
Documentation for the control blade/channel box input cards will be included in new manuals
prepared by INEL, which are to be distributed with the next production version of SCDAP/RELAP5.

There are 11 cards (or card sets) that define the hydraulic connections, dimensions, initial
temperatures, and initial oxide thicknesses for each control blade/channel box component. The
dimensions specified by the user are sketched in Figure 4. The actual control blade dimensions
shown at the top of Figure 4 are converted by the model into the equivalent slab geometry
shown at the bottom of the figure. The equivalent slab thicknesses are calculated so that the
cross-sectional area of each layer in the equivalent slab geometry is identical to the cross-
sectional area in the actual geometry. The distance between the channel box and the fuel rods
(dimension 7 in Figure 4) is used in the relocation calculations to determine when a blockage
forms in the region between the channel box and the first row of fuel rods.

As is the case for all other SCDAP components, the internal modeling for the control blade/
channel box is performed using a set of local dimensions that represents the portion of channel
box and the half of control blade shown in Figure 4. The user must specify a multiplier that
Figure 4. Control blade/channel box dimensions specified by the user.
defines how many of these local configurations are needed to represent the region of the core being modeled.

Predicted results for the control blade/channel box models are available either in the printed output or as plotting variables in the plot file. Some of the printed output is generated during the processing of input data. This information is located near the beginning of a print file and includes most of the input data specified by the user. Predictions for structural temperatures, oxidation, relocation, and blockages are summarized in the printed output as a part of each "major edit" at user-specified time intervals.

The available plotting variables are: (1) structural temperatures, (2) intact structure and frozen crust thicknesses, (3) hydrogen production rates, and (4) a damage level indicator that identifies failure of the channel box wall. The locations of the intact structure and frozen crust thickness variables are shown in Figure 5. These eight variables can be used with the Nuclear Plant Analyzer (NPA) graphical package to generate animated drawings depicting the melting and downward relocation of the control blade and channel box structures.

4. PREDICTED RESULTS

The BWR control blade/channel box component has been successfully tested in several developmental versions of SCDAP/RELAP5. Calculations have been performed using the three input decks summarized in Table 1. The input deck for the "Test Calculation" is small and is intended to exercise efficiently the features of the control blade/channel box models. The input deck for General Electric Company’s Simplified Boiling Water Reactor (SBWR) is a large, full-

<table>
<thead>
<tr>
<th>Table 1. Summary of SCDAP/RELAP5 input decks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Calculation</td>
</tr>
<tr>
<td>No. of RELAP5 volumes</td>
</tr>
<tr>
<td>No. of RELAP5 junctions</td>
</tr>
<tr>
<td>No. of SCDAP components</td>
</tr>
<tr>
<td>Control blade/channel box</td>
</tr>
<tr>
<td>Fuel rod</td>
</tr>
<tr>
<td>Shroud</td>
</tr>
<tr>
<td>No. of SCDAP radiation enclosures</td>
</tr>
<tr>
<td>No. of SCDAP axial nodes</td>
</tr>
</tbody>
</table>
Figure 5. Locations of intact structure and frozen crust thickness variables.
plant simulation that employs three radial regions to represent the core. The FLHT-6 input deck is a preliminary simulation of the FLHT-6 BWR experiment to be conducted (Fall 1993) in Canada.

This section presents some predicted results for the Test Calculation and for an SBWR severe accident simulation using Version 80 of SCDAP/RELAP5. Because this is a developmental version (rather than a production version) of SCDAP/RELAP5, the predictions should be viewed as preliminary in nature. They are presented here mainly to demonstrate the operation of the control blade/channel box models.

4.1 TEST CALCULATION

The Test Calculation is designed as an efficient driver for the control blade/channel box models and does not represent a physical reactor core or experimental apparatus. A nodalization diagram is shown in Figure 6. A mixture of 99.5% argon and 0.5% steam at 1650 K enters at the top of two sets of RELAP5 volumes. The gas mixture flows downward and heats up the control blade and channel box structures from their initial temperatures of 900 K. The gas temperature and steam-starved conditions are specifically selected so that the control blade melts, but the channel box does not exceed the melting temperature of pure Zircaloy. The Test Calculation has been performed with several different versions of SCDAP/RELAP5, which allows meaningful comparisons of control blade/channel box results to be made before and after coding changes.

The sequence of events in the Test Calculation can be explained with the aid of Figures 7 and 8. Figure 7 shows the $\text{B}_4\text{C}$ and stainless steel blade sheath temperatures versus axial elevation. Figure 8 shows the control blade crust thicknesses (variable $R_{CO}$ in Figure 5) for axial nodes 4-9. Referring to Figure 7 at 6.0 min of problem time, the top node of the control blade is at a temperature just below the eutectic liquefaction temperature of $\text{B}_4\text{C}$/stainless steel. At 12.0 min, all of the $\text{B}_4\text{C}$ and absorber tube stainless steel from axial nodes 9 and 10 has relocated through the holes in the blade sheath and down the outside of the control blade, and the blade sheath at axial nodes 9 and 10 has reached the melting temperature of pure stainless steel.

Referring to Figure 8, the relocating material freezes to form a crust on the outside of the control blade. The control blade continues to melt and relocate downward, and a blockage forms at 13.0 min between the control blade and channel box at axial elevation 4 in RELAP5 volume 120-07 (see Figure 6). The stainless steel in the blockage interacts with the Zircaloy channel box, and the channel box begins to melt when it reaches the eutectic liquefaction temperature of stainless steel/Zircaloy. Channel box segment 1 at axial elevation 4 fails at 19.0 min, and control blade material begins to relocate into the fuel bundle region.

Referring to Figure 7 at 24.0 min, all of the $\text{B}_4\text{C}$ and absorber tube stainless steel from the top 5 axial nodes and all of the blade sheath stainless steel from the top 3 axial nodes has relocated
Figure 6. Nodalization diagram for control blade/channel box test calculation.
Figure 7. Control blade nodal temperatures for test calculation.

Figure 8. Control blade crust thicknesses for test calculation.
Control blade material continues to relocate downward and through the channel box into the fuel bundle region until 41.0 min, when the blockage between the control blade and channel box at axial elevation 4 melts, reopening the pathway for downward movement of control blade material. At 55.8 min, the entire control blade structure has melted and relocated below the defined core region. About 28% of the original control blade structure is calculated to rest ultimately beneath the fuel bundle side of the channel box.

### 4.2 SBWR LOCA SIMULATION

The RELAP5 hydrodynamic portion of the SBWR input deck was initially developed at INEL. This input deck was subsequently modified at ORNL to perform severe accident simulations by modeling core structures with SCDAP fuel rod and control blade/channel box components. The RELAP5 hydrodynamic model consists of 265 volumes and 317 junctions that represent the reactor coolant system, the main steam isolation valves (MSIVs), the depressurization valves (DPVs), the safety/relief valves (SRVs), the drywell, the suppression pool, the isolation condensers, the passive containment cooling system (PCCS), and the gravity-driven cooling system (GDCS). RELAP5 heat structures are used to model the sensible energy of solid structures outside the core region. The model also includes logic to open or close valves when certain operating conditions are met.

The SBWR core is divided into three radial regions and twelve axial nodes. Each radial region consists of two SCDAP components (fuel rod, control blade/channel box) and two RELAP5 pipe volumes (fuel bundle, interstitial). The radial regions are connected by cross-flow junctions between the interstitial volumes. Three SCDAP radiation enclosures are defined to model radiation between the fuel rod and channel box structures within each radial region.

The SBWR input deck has been used to perform a loss-of-coolant accident (LOCA) simulation representing a break in one of the 2-in. bottom head drain lines. The SBWR is designed to be protected from drain line breaks by automatic depressurization in combination with flooding the vessel with water from the GDCS reservoirs. Additionally, feedwater pumps (high pressure), control rod drive (CRD) cooling water pumps (high pressure), reactor water cleanup (RWCU) pumps (high pressure), and low pressure coolant injection (LPCI) pumps can be used to replenish the water flowing out the break.

Based upon the foregoing information, it is obvious that a drain line LOCA will result in core damage only if several coolant makeup systems (including the passive, safety-grade GDCS) have failed at the same time that the break occurs. The LOCA simulation was performed by stipulating that the isolation condensers remain operational, but that all other sources of cooling water for the core are unavailable. The LOCA assumptions are summarized below.

<table>
<thead>
<tr>
<th>Bottom head drain line</th>
<th>Broken</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedwater pumps</td>
<td>Independent failure</td>
</tr>
<tr>
<td>Component</td>
<td>Status</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>MSIVs</td>
<td>Operational, automatic closure</td>
</tr>
<tr>
<td>Isolation condensers</td>
<td>Operational, automatic initiation</td>
</tr>
<tr>
<td>CRD cooling water pumps</td>
<td>Independent failure</td>
</tr>
<tr>
<td>RWCU pumps</td>
<td>Independent failure</td>
</tr>
<tr>
<td>SRVs, DPVs</td>
<td>Operational, automatic initiation</td>
</tr>
<tr>
<td>PCCS</td>
<td>Operational, passive initiation</td>
</tr>
<tr>
<td>Short-term GDCS</td>
<td>Independent failure</td>
</tr>
<tr>
<td>Long-term GDCS</td>
<td>Independent failure</td>
</tr>
<tr>
<td>LPCI pumps</td>
<td>Independent failure</td>
</tr>
</tbody>
</table>

The simultaneous occurrence of these independent failures in conjunction with a drain line LOCA is recognized to have an extremely low probability.

The sequence of events predicted by the SBWR LOCA simulation for the radial region in the center of the core is summarized in Table 2. When control blade melting begins at 164.8 min, the reactor water level is below the bottom of active fuel. All core degradation occurs under "dry" conditions in a steam-starved environment. The simulation terminated at 203.7 min with a RELAP5 water property error in a PCCS condensate drain line. It is emphasized that these predictions are for demonstration purposes and should be viewed as preliminary in nature, because the calculations were performed using a developmental version of SCDAP/RELAP5. Future production versions of SCDAP/RELAP5 may not exhibit the same error.

The effects of control blade/channel box interactions in the LOCA simulation can be explained with the aid of Figures 9 and 10. These figures display the eight intact structure and frozen crust thickness variables (see Figure 5) at two points in time (174.5 min and 178.5 min). The segment 1 thicknesses are shown on the left side of the figures and the segment 2 thicknesses on the right side. Note that the array of fuel rods is illustrated in the figures as only a single fuel rod.

Referring to Figure 9, the B$_4$C and stainless steel in the absorber tubes interacts and melts away (at the eutectic liquefaction temperature) from axial nodes 4-9. The molten material relocates through the holes in the blade sheath and downward to form a blockage between the control blade and the channel box at axial node 3. After formation of the blockage, additional control blade relocation is diverted horizontally to segment 2, where it freezes on the interstitial side of the channel box at axial nodes 2 and 3. The stainless steel/Zircaloy interaction between the blockage and the channel box is complete, and the channel box at axial node 3 is beginning to melt (at the eutectic liquefaction temperature).

Referring to Figure 10, segment 1 of the channel box is completely melted at axial node 3. The blockage between the control blade and the channel box at axial node 3 has also melted and refrozen at axial node 2. A relocation path is now available for molten absorber tube and blade sheath material to move downward and then horizontally through the opening in the channel box wall to form a frozen crust on the fuel bundle side of the channel box. Figure 10 depicts a
Table 2. Sequence of events predicted by SBWR LOCA simulation for central region of core

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Time (min)</th>
<th>Description of event</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
<td>Reactor initial conditions are steady-state full power operation (2000 MW thermal). Severe accident simulation is initiated by opening a 2-in. diameter break in one of the bottom head drain lines, turning off the feedwater and CRD cooling water pumps, keeping the GDCS and suppression pool return lines closed, and stipulating that all other pump-driven sources of cooling water are unavailable.</td>
</tr>
<tr>
<td>6</td>
<td>0.1</td>
<td>Reactor scram occurs because of high drywell pressure. Turbine control valves close. Turbine bypass valves open automatically to control reactor pressure.</td>
</tr>
<tr>
<td>53</td>
<td>0.9</td>
<td>MSIVs close because the wide-range level instrumentation indicates Level 2. Isolation condenser return line opens.</td>
</tr>
<tr>
<td>2677</td>
<td>44.6</td>
<td>Automatic depressurization sequence begins because the wide-range level instrumentation indicates Level 1.</td>
</tr>
<tr>
<td>4747</td>
<td>79.1</td>
<td>LOCA-range level instrumentation indicates water level reaches the top of active fuel.</td>
</tr>
<tr>
<td>9185</td>
<td>153.1</td>
<td>Fuel rods rupture (caused by ballooning) at axial node 6.</td>
</tr>
<tr>
<td>9360</td>
<td>156.0</td>
<td>Water level reaches the bottom of active fuel (void fraction = 1.0).</td>
</tr>
<tr>
<td>9885</td>
<td>164.8</td>
<td>Control blades begin to melt at axial node 5.</td>
</tr>
<tr>
<td>10245</td>
<td>170.8</td>
<td>Blockages form between control blades and channel boxes at axial node 3.</td>
</tr>
<tr>
<td>10455</td>
<td>174.3</td>
<td>Channel boxes begin to melt at axial node 3 after interaction with stainless steel.</td>
</tr>
<tr>
<td>10650</td>
<td>177.5</td>
<td>Blockages form between channel boxes and fuel rods at axial node 2.</td>
</tr>
<tr>
<td>11031</td>
<td>183.9</td>
<td>Zr-U-O mixture from axial node 3 of fuel rods begins to relocate.</td>
</tr>
<tr>
<td>11937</td>
<td>199.0</td>
<td>Fuel rod debris begins to form molten pool at axial node 5.</td>
</tr>
<tr>
<td>12224</td>
<td>203.7</td>
<td>Simulation terminated because of RELAP5 water property error in condensate drain line from PCCS condenser.</td>
</tr>
</tbody>
</table>
Figure 9. Control blade melting and control blade/channel box blockage (segment 1) for SBWR LOCA simulation at 174.5 min.
Figure 10. Channel box failure (segment 1) and relocation through channel box wall for SBWR LOCA simulation at 178.5 min.
blockage that has formed at axial node 2 between segment 1 of the channel box and the first row of fuel rods. Because the control blade/channel box models do not currently allow material to spread radially into the fuel bundle, additional absorber tube and blade sheath material flowing through the opening in the channel box wall is diverted horizontally to segment 2 where it freezes on the fuel bundle side of the channel box at axial node 2.

5. SUMMARY

A new BWR control blade/channel box component has been developed for SCDAP/RELAP5. These models predict the severe accident response of the control blade and channel box structures, including the effects of material interactions between B₄C, stainless steel, and Zircaloy. The modeling approach is adapted from experiment-specific models developed at ORNL to analyze the CORA-16 and CORA-17 experiments. The new control blade/channel box component can be selected by the user when appropriate. SCDAP's original BWR control rod component remains as an available option.

Based on the experimental evidence, the following processes are modeled by SCDAP's control blade/channel box component. As the control blade and channel box structures heat up during an accident, the stainless steel and Zircaloy surfaces begin to oxidize. Melting of a control blade begins at the inner surfaces of the absorber tubes, where the B₄C reacts with the stainless steel. The absorber tubes liquify at a temperature of ~1505 K, which is lower than the melting temperature of pure stainless steel. Stainless steel from the control blade then relocates downward and forms a blockage between the control blade and the channel box, where it reacts with the Zircaloy. The Zircaloy channel box forms a eutectic mixture with the stainless steel in the blockage and liquefies at a temperature of ~1523 K, which is much lower than the melting temperature of pure Zircaloy.

The control blade/channel box component has been implemented and tested within several developmental versions of SCDAP/RELAP5. Predicted results are available either in the printed output or as plotting variables for use with the Nuclear Plant Analyzer graphical package. The control blade/channel box component is scheduled to be distributed by INEL (with documentation) as part of the next production version of SCDAP/RELAP5. Current limitations in the control blade/channel box models will be resolved in future versions of SCDAP/RELAP5.

6. REFERENCES


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BWR Control Blade/Channel Box Interaction Models for SCDAP/RELAP5

F.P. Griffin

Code Modifications in Support of Severe Accident Analyses for SBWR Designs Program*

Oak Ridge National Laboratory

Presented at
Twenty-First Water Reactor Safety Information Meeting
Bethesda, Maryland
October 25, 1993


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Background

- Work began at Oak Ridge National Laboratory in January 1991 to improve SCDAP/RELAP5* for BWR severe accident applications.

- To date, all improvements have been to SCDAP's core-region structural models.

- Objective: To incorporate models that represent material interactions between control blades and channel boxes as observed in BWR experiments.

*Idaho National Engineering Laboratory is responsible for maintaining the official version of SCDAP/RELAP5*
Under BWR Severe Accident Conditions, Interactions Occur Between B4C, Stainless Steel, and Zircaloy.
BWR Severe Fuel Damage Experiment Results Guide the Development of New Models

- Experiment analyses have been performed at ORNL*
  - SNL's DF-4
  - German CORA-16, 17, 31, 33, and 28
  - PNL's FLHT-6 (pretest analyses)
  - SNL's Ex-reactor series (pretest analyses)

- Based on these experiments and KfK's separate effects tests, a clear understanding of material interactions has evolved

*By L.J. Ott as part of the BWR Core Melt Progression Phenomena Program
Conceptualization of Structural Liquefaction, Material Dissolution and Eutectic Relocation for the BWR Control Blade/Channel Box

CONTROL BLADE

CHANNEL BOX

B$_4$C

SS

Zr

ZrO$_2$

ORNL-DWG 92M-2816AC ETD
Blockage with SS/B₄C/Zr Interaction

Channel Box Breach with SS/B₄C/Zr Eutectic Relocation

SS/B₄C/Zr INTERACTION

BLOCKAGE

CRUST

EUTECTIC

FLOWING SLUG

BREACH

ORNL-DWG 92M-2818AC ETD
SCDAP/RELAP5 Modeling Approach

- A new BWR control blade/channel box component has been developed using portions of the CORA experiment-specific models developed at ORNL.

- The control blade and channel box structures are modeled within a single SCDAP component.

- SCDAP’s original BWR control rod component remains as an available option.
Each Channel Box Wall is Adjacent to Either A Control Blade Or Another Channel Box Wall
The New Control Blade/Channel Box Component Has an Equivalent Slab Geometry and 5 Temperature Nodes at Each Axial Elevation

- Fuel Bundle coolant volume – steam/water
- Interstitial coolant volume – steam/water
- Channel box – Zircaloy
- Blade sheath – SS
- Gap – steam/water
- Absorber tubes – SS
- Absorber – B$_4$C
Features of the New Control Blade/Channel Box Component

• Oxidation of Zircaloy, stainless steel, and B₄C

• 2-D conduction (radial, axial)

• Melting with material interactions
  - B₄C/stainless steel eutectic at ~1505 K
  - Stainless steel/Zircaloy eutectic at ~1523 K

• 3-D relocation (axial, radial, azimuthal)

• Radiation with other SCDAP structures

• Hydrodynamic boundary conditions are exchanged with RELAP5
Control Blade/Channel Box User Interface

• Input cards employ new SCDAP format with RELAP5-style card numbers

• Printed output is generated at each user-specified Major Edit

• Plotting variables are written to the plot file at user-specified time intervals

• Documentation is currently provided in ORNL letter reports and will be included in new manuals prepared by INEL
The Thickness Variables Are Useful in the Nuclear Plant Analyzer (NPA) Graphical Package for Animation
The Control Blade/Channel Box Component Has Been Successfully Tested at ORNL Using Three Input Decks

<table>
<thead>
<tr>
<th>Test Calculation</th>
<th>SBWR</th>
<th>FLHT-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of RELAP5 volumes</td>
<td>26</td>
<td>265</td>
</tr>
<tr>
<td>No. of RELAP5 junctions</td>
<td>24</td>
<td>317</td>
</tr>
<tr>
<td>No. of SCDAP components</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- BWR blade/box</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>- Fuel rod</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>- Shroud</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>No. of SCDAP radiation enclosures</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>No. of SCDAP axial nodes</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>

ORNL-DWG 93M 3864C ETD
Test Calculation for Control Blade/Channel Box Component

<table>
<thead>
<tr>
<th>Source Volume (99.5% Argon, 0.5% Steam, 1650 K)</th>
<th>Source Junction (0.2 m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Temperature = 900 K</td>
<td></td>
</tr>
</tbody>
</table>

| Fuel Bundle Hydrodynamic Volumes               |                           |
|------------------------------------------------|
| Initial Temperature = 900 K                   |                           |

| BWR Channel Box                                |                           |
|------------------------------------------------|
| Initial Temperature = 900 K                   |                           |

| Interstitial Hydrodynamic Volumes              |                           |
|------------------------------------------------|
| Initial Temperature = 900 K                   |                           |

| Sink Volume                                    |                           |
|------------------------------------------------|
| Initial Temperature = 900 K                   |                           |

| BWR Control Blade                              |                           |
|------------------------------------------------|
| Initial Temperature = 900 K                   |                           |

| Sink Volume                                    |                           |
|------------------------------------------------|
| Initial Temperature = 900 K                   |                           |
Drawings Generated by NPA Demonstrate the Proper Operation of the Control Blade/Channel Box Component Within SCDAP/RELAP5

- Example results based upon the test calculation
  - Absorber tube melting and relocation (720 s)
  - Segment 1 blockage with melt diverted to segment 2 (1080 s)
  - Channel box failure after interaction with blockage (1440 s)
Test Calculation

- Absorber Tubes (B4C, SS)
- Blade Sheath (SS)
- Control Blade Crust
- Channel Box (Zr)
- Channel Box Crust
- Fuel Rod (not modeled)
Test Calculation

- Absorber Tubes (B4C, SS)
- Blade Sheath (SS)
- Control Blade Crust
- Channel Box (Zr)
- Channel Box Crust
- Fuel Rod (not modeled)
Test Calculation

Segment 1

Time

Segment 2

Absorber Tubes (B4C, SS)
Blade Sheath (SS)
Control Blade Crust
Channel Box (Zr)
Channel Box Crust
Fuel Rod (not modeled)
The Control Blade/Channel Box Models Will be Released With the Next Production Version of SCDAP/RELAP5

- Models reflect status of experiment-specific analyses performed for CORA-16 and 17; enhancements developed for CORA-33 have not been incorporated

- Models do not include radial spreading of molten control blade/channel box material into fuel bundle

- Models are not fully coupled with SCDAP's late phase models (core debris, lower plenum debris)
Summary

- A new BWR control blade/channel box component has been developed for SCDAP
  - Includes effects of material interactions between B$_4$C, stainless steel, and Zircaloy
  - Will be released by INEL (including documentation) with next production version of SCDAP/RELAP5

- Current limitations are scheduled to be remedied for future versions of SCDAP/RELAP5