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RELAP5-3D CODE FOR SUPERCRITICAL-PRESSURE, LIGHT-WATER-COOLED REACTORS

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ABSTRACT

The RELAP5-3D computer program has been improved for analysis of supercritical-pressure, light-water-cooled reactors. Several code modifications were implemented to correct code execution failures. Changes were made to the steam table generation, steam table interpolation, metastable states, interfacial heat transfer coefficients, and transport properties (viscosity and thermal conductivity). The code modifications now allow the code to run slow transients above the critical pressure as well as blowdown transients (modified Edwards pipe and modified existing pressurized water reactor model) that pass near the critical point.

1. INTRODUCTION

The RELAP5 series of codes has been developed at the Idaho National Engineering and Environmental Laboratory for over 25 years under sponsorship of the U. S. Department of Energy, the U. S. Nuclear Regulatory Commission, members of the International Code Assessment and Applications Program, members of the Code Applications and Maintenance Program, and members of the International RELAP5 Users Group. Specific applications of the code have included simulations of transients of light water reactor systems such as loss of coolant, anticipated transients without scram, and operational transients such as loss of feedwater, loss of offsite power, station blackout, and turbine trip. RELAP5-3D (Ref. 1), the latest in the series of RELAP5 codes, is a highly generic code that, in addition to calculating the behavior of a reactor coolant system during a transient, can be used for simulation of a wide variety of hydraulic and thermal transients in both nuclear and nonnuclear systems involving mixtures of vapor, liquid, noncondensable gases, and nonvolatile solute.

Nearly all of the light water applications have been performed at pressures less than the critical pressure, consistent with the design and normal operation of current light water reactors. The code contains fluid properties of supercritical light water, but it has been used successfully for only a few supercritical cases (Ref. 2). Experience has shown that the code does not execute as reliably at supercritical conditions as it does for subcritical conditions.

2. SLOW TRANSIENTS

A series of 27 slow transient calculations were performed to evaluate potential code problems for supercritical applications. The test problems represented a pipe that initially contained subcooled water at less than critical pressure. Boundary conditions were varied so that the pressure in the pipe increased along a line of constant temperature until reaching a maximum value that exceeded the critical pressure of 22.12 MPa. The maximum value varied between 22.2 and 90 MPa from calculation to calculation. The pressure was then held constant at the maximum value, and the temperature increased until it was above the critical temperature of 647.3 K. The pressure and temperature were then decreased back below the critical values. The initial pressure and temperature were 0.4 MPa and 322 K, respectively. The final state corresponded to superheated vapor at a pressure of 5 MPa.

The loci of points of calculated pressure versus temperature are shown in Figures 1 through 3 for the 27 cases. Each figure contains a dashed line that represents the saturation curve as a function of temperature. The transient began in the lower left corner of the graph and ended in the lower right corner of the graph. Figure 1 shows that two of eight cases did not reach the lower right corner, which indicates that the code failed, when the maximum pressure was between 25 and 90 MPa. Figure 2, which contains results from 10 cases with a maximum pressure between 23.1 and 24 MPa, shows that only one case completed successfully. Figure 3 shows that all of the calculations failed when the maximum pressure was between 22.2 and 23 MPa. Overall, 20 of the 27 cases failed with the original code, and the probability of failure increased dramatically near the critical point.

Several code updates were implemented to correct the code execution failures indicated in Figures 1 through 3. Specifically, the steam tables were changed to use more consistent values for the reset water property derivatives representing the specific heat and the coefficients of volume expansivity and isothermal compressibility at the critical point. The steam tables were also generated using more pressure and temperature points near the critical point. The specific volume and isothermal compressibility were interpolated using linear, rather than cubic expressions. Changes were also made to the extrapolations for metastable states near the critical point. Additional protections were provided to prevent problems with square roots and log functions. The calculations described previously were repeated with the updated code. All 27 cases executed successfully with the updated code as illustrated in Figures 4 through 6.

3. BLOWDOWN TRANSIENTS

A series of 85 blowdown transient calculations were performed based on the geometry of the Edwards pipe experiment (Ref. 3). This experiment simulated a pipe pressurized with water that was blown down to the atmosphere through a large, fast-opening hole in one end of the pipe. Although the experiment was performed at subcritical conditions, the initial pressure was changed to 25 MPa for this evaluation. The initial temperature varied between 500 K and 800 K from calculation to calculation. Eight of these 85 problems encountered water property failures and did not run to completion with the existing code. The failures generally occurred near the critical point.

Several code updates were implemented to correct the code execution failures. One change was to modify the interfacial heat transfer coefficient for vapor near the critical point. Changes were also made to the extrapolations for metastable states near the critical point. Modifications were also made to the transport properties of thermal conductivity and viscosity to eliminate discontinuities as the temperature changed from supercritical to subcritical. The modified transport properties were based on the 4th edition of the 1967 ASME steam tables (Ref. 4).

The combined code modifications now allow all 85 modified Edwards pipe blowdown calculations to run to completion. Figures 7 and 8 show the pressure and break mass flow rate for the case with initial conditions of 25 MPa and 647 K.

An existing pressurized water reactor model, known as typpwr, from the RELAP5-3D assessment library (Ref. 5), was modified so that the initial conditions were supercritical on the primary side of the reactor. The modified model had an initial pressure of 25 MPa and initial temperatures ranging from 583 K to 704 K on the primary side. The modified model was run successfully using the modified code through a loss-of-coolant accident (LOCA) initiated by a small break. Figures 9 and 10 show the primary system pressure and break mass flow rate for this small-break LOCA calculation.

4. FUTURE WORK

Future work will include code modifications for heat transfer processes at supercritical pressure. Heat transfer to fluids at supercritical pressure is a complicated topic, and a number of detailed reviews of work on this heat transfer can be found in the literature as discussed in Ref. 6. Other code modifications may be necessary as the code is validated against experimental data.

The code may also be compared to calculations from other codes, such as SCRELA (Ref. 7).

5. CONCLUSIONS

The RELAP5-3D code can now reliably run slow transients above the critical pressure as well as blowdown transients that pass near the critical point. In the future, the code will be modified to better represent heat transfer processes at supercritical pressure.

6. ACKNOWLEDGEMENT

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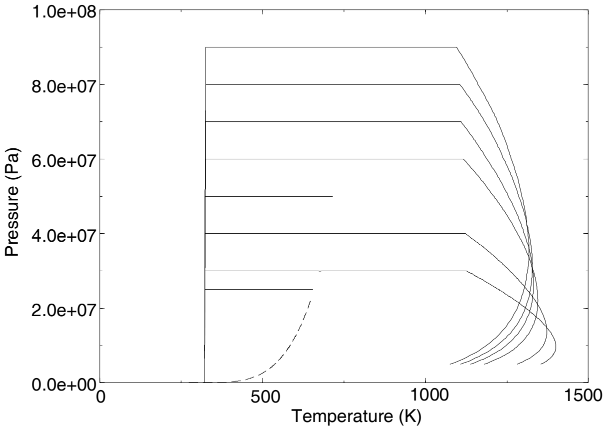

Figure 1. Pressure-temperature plots for cases with the maximum pressure between 25 and 90 MPa (no updates).

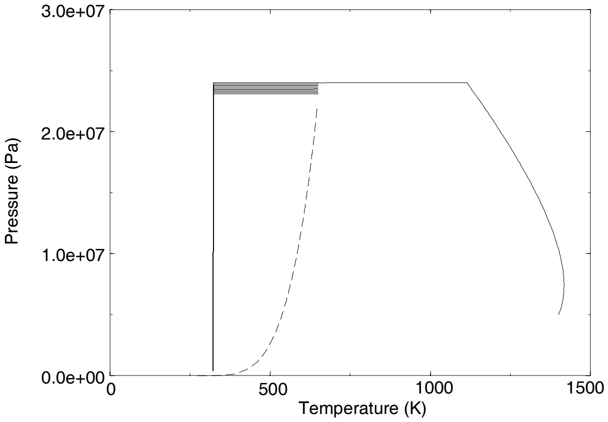

Figure 2. Pressure-temperature plots for cases with the maximum pressure between 23.1 and 24 MPa (no updates).

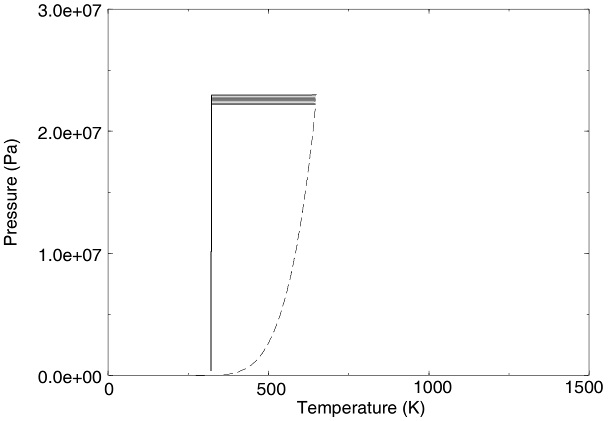

Figure 3. Pressure-temperature plots for cases with the maximum pressure between 22.2 and 23 MPa (no updates).

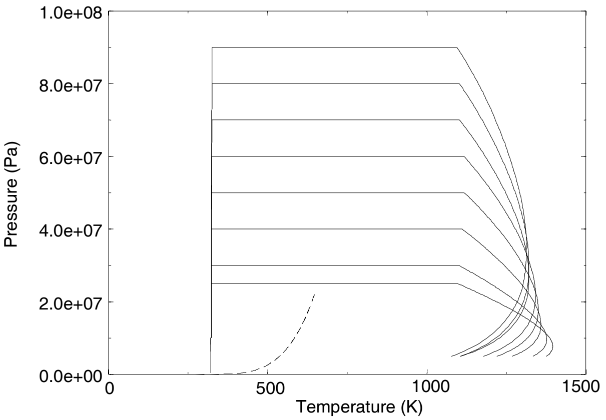

Figure 4. Pressure-temperature plots for cases with the maximum pressure between 25 and 90 MPa (with updates).

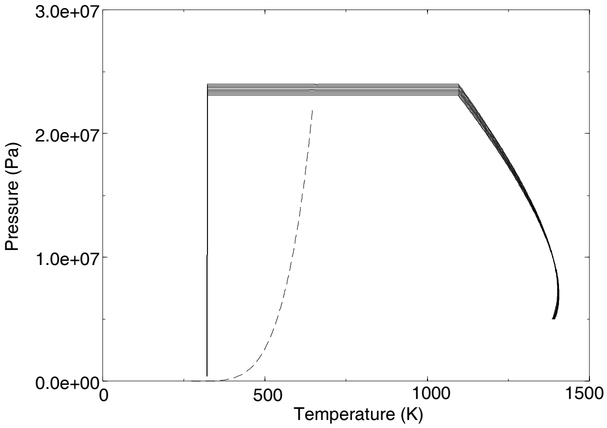

Figure 5. Pressure-temperature plots for cases with the maximum pressure between 23.1 and 24 MPa (with updates).

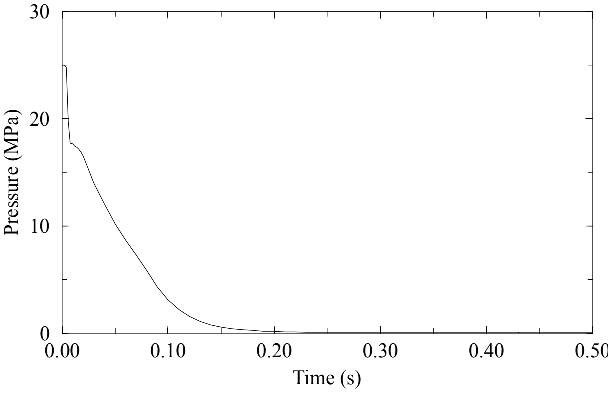

Figure 7. Pressure during a blowdown of Edwards pipe.

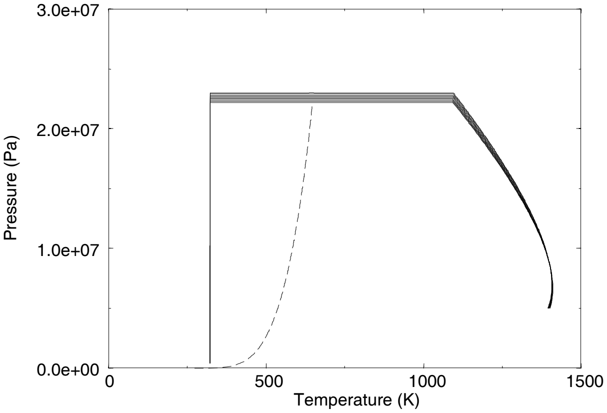

Figure 6. Pressure-temperature plots for cases with the maximum pressure between 22.2 and 23 MPa (with updates).

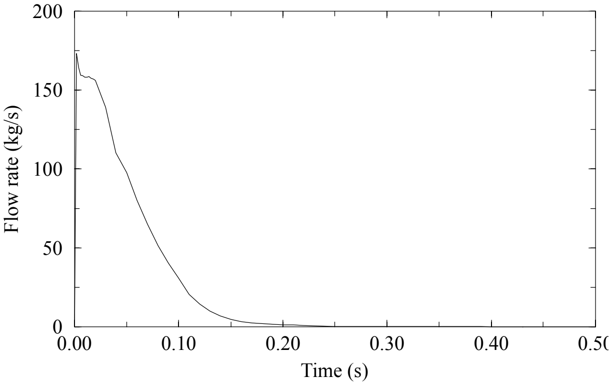

Figure 8. Break flow rate during a blowdown of Edwards pipe.

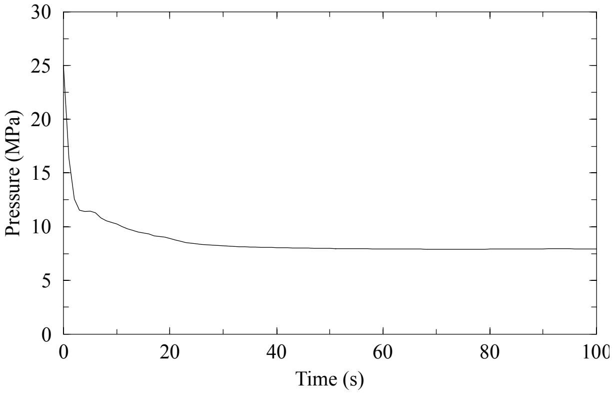

Figure 9. Primary system pressure during a small-break LOCA.

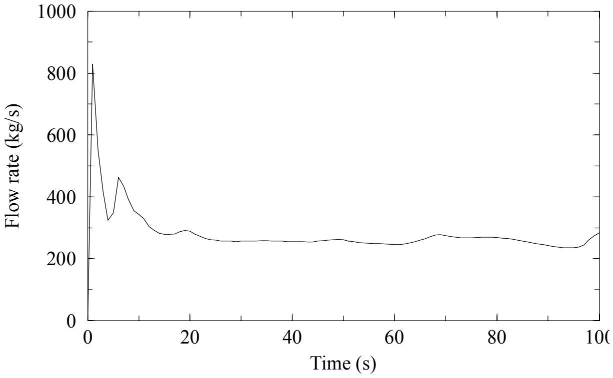

Figure 10. Break flow rate during a small-break LOCA.