RELAP5-3D VERSION 4.0.3: INSTALLATION AND TESTS FOR APPLICATIONS TO SPACE REACTORS

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ABSTRACT

To attend the TERRA project (“TEcnologia de Reatores Rápidos Avançados”), currently conducted by the Nuclear Energy Division (ENU) of the IEAv, this work presents the RELAP5-3D, Version 4.0.3, prepared in July 12, 2012, also known as r3d403is, received recently by the IEAv from the Idaho National Laboratory (INL). This version of RELAP5-3D is configured for the International User Group Source Code Group and is developed and maintained at the INL for the US Department of Energy. RELAP5-3D, 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. Enhancements include all features and models previously available in the ATHENA configuration version of the code which are as follows: addition of new work fluids and a magneto-hydrodynamic mode. Following the instructions from the README file, the RELAP5-3D, version 4.0.3 was installed creating the necessary subdirectories, by using the LINUX platform and applying both Intel Fortran 95 and C-language compilers. Many input examples were executed and the same results were observed as compared to the received documentation. A sample of the Edwards-O’Brien test was evaluated to verify if the code could simulate a LOCA type accident properly. The test executed by the RELAP5-3D demonstrated good agreement with test data including a new output involving the mass flow during the test.

1. INTRODUCTION

The Nuclear Energy Division (ENU) of the Institute for Advanced Studies (IEAv) is currently conducting the TERRA project (“TEcnologia de Reatores Rápidos Avançados”), Technology for Advanced Fast Reactors project. The project is based on three main research areas: a) thermal cycles for the establishment of the concept for a Closed Brayton Cycle Loop (CBCL), by building a demonstrative simulator [1, 2], b) fuel elements and nuclear reactor core computer design to be the heat source for the thermal cycle [3, 4], and c) heat pipes for passive heat rejection. The TERRA project is in a first phase, where these areas are being worked in an independent way. New developments on thermal cycle’s research were presented, where the authors have discussed the CBCL and a redesign of the NOELLE 60290 in order to operate in a closed cycle. Also, they gave an overview of the full cycle design [1].
The RELAP5-3D code, the newest one from the RELAP5 series codes, is very important to attend the TERRA project due to additional capabilities as space reactor simulations, gas cooled reactor applications, fast breeder reactor model [5].

Specific applications of the code have included simulations of transients in light water reactor (LWR) systems such as loss of coolant, anticipated transients without scram (ATWS), and operational transients such as loss of feedwater, loss of offsite power, station blackout, and turbine trip.

All characteristics available in the ATHENA version of the code were included as addition of new work fluids and a magneto-hydrodynamic mode.

Next items of this work will show more details on the RELAP5-3D features including the improvements from the version 2.4.3, steps of the installation in the computational machines, and one of the samples for the code validation.

2. CODE FEATURES

RELAP5-3D, Version 4.0.3, prepared in July 12, 2012, also known as r3d403is, was received recently by the IEAv from the Idaho National Laboratory (INL) [5].

The RELAP5-3D code has been developed for best estimate transient simulation of light water reactor coolant systems during postulated accidents. The code models the coupled behavior of the reactor coolant system and the core for loss-of-coolant accidents, and operational transients, such as anticipated transient without scram, loss of offsite power, loss of feedwater, and loss of flow. A generic modeling approach is used that permits simulating a variety of thermal hydraulic systems. Control system and secondary system components are included to permit modeling of plant controls, turbines, condensers, and secondary feedwater systems.

The RELAP5 series of codes has been developed at the INL under sponsorship of the U.S. Department of Energy, the U.S. Nuclear Regulatory Commission, members of the International Code Assessment and Applications Program (ICAP), members of the Code Applications and Maintenance Program (CAMP), and members of the International RELAP5 Users Group (IRUG). Specific applications of the code have included simulations of transients in light water reactor (LWR) systems such as loss of coolant, anticipated transients without scram (ATWS), and operational transients such as loss of feedwater, loss of offsite power, station blackout, and turbine trip. RELAP5-3D, 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.

The mission of the RELAP5-3D development program was to develop a code version suitable for the analysis of all transients and postulated accidents in LWR systems, including both large- and small-break loss-of-coolant accidents (LOCAs) as well as the full range of operational transients.
The RELAP5-3D code is based on a nonhomogeneous and nonequilibrium model for the two-phase system that is solved by a fast, partially implicit numerical scheme to permit economical calculation of system transients. The objective of the RELAP5-3D development effort from the outset was to produce a code that included important first-order effects necessary for accurate prediction of system transients but that was sufficiently simple and cost effective so that parametric or sensitivity studies are possible.

The code includes many generic component models from which general systems can be simulated. The component models include pumps, valves, pipes, heat releasing or absorbing structures, reactor kinetics, electric heaters, jet pumps, turbines, compressors, separators, annuli, pressurizers, feedwater heaters, ECC mixers, accumulators, and control system components. In addition, special process models are included for effects such as form loss, flow at an abrupt area change, branching, choked flow, boron tracking, and noncondensable gas transport.

The system mathematical models are coupled into an efficient code structure. The code includes extensive input checking capability to help the user discover input errors and inconsistencies. Also included are free-format input, restart, renodalization, and variable output edit features. These user conveniences were developed in recognition that generally the major cost associated with the use of a system transient code is in the engineering labor and time involved in accumulating system data and developing system models, while the computer cost associated with generation of the final result is usually small.

The development of the models and code revisions that constitute RELAP5-3D has spanned more than two decades from the early stages of RELAP5-3D numerical scheme development (circa 1976) to the present. RELAP5-3D represents the aggregate accumulation of experience in modeling core behavior during accidents, two-phase flow process, and LWR systems. The code development has benefited from extensive application and comparison to experimental data in the LOFT, PBF, Semiscale, ACRR, NRU, and other experimental programs.

The RELAP5-3D version contains several important enhancements over previous versions of the code. The most prominent attribute that distinguishes the RELAP5-3D code from the previous versions is the fully integrated, multi-dimensional thermal-hydraulic and kinetic modeling capability. This removes any restrictions on the applicability of the code to the full range of postulated reactor accidents. Enhancements include a new matrix solver for 3D problems, new thermodynamic properties for water, and improved time advancement for greater robustness. Enhancements also include all features and models previously available in the ATHENA configuration version of the code, which are as follows: addition of new working fluids (e.g., ammonia, blood, carbon dioxide, DowThermA, glycerol, helium, helium-xenon, hydrogen, lead-bismuth, lithium, lithium-lead, molten salts, nitrogen, potassium, R134a (SUVA), sodium, sodium-potassium, and xenon) and a magneto-hydrodynamic model. The multi-dimensional component in RELAP5-3D was developed to allow the user to more accurately model the multi-dimensional flow behavior that can be exhibited in any component or region of a LWR system. Typically, this will be the lower plenum, core, upper plenum and downcomer regions of an LWR. However, the model is general, and is not restricted to use in the reactor vessel. The component defines a one, two, or three-dimensional array of volumes and the internal junctions connecting them. The geometry can be either Cartesian or cylindrical. An orthogonal, three-dimensional grid is defined by mesh interval input data in each of the three coordinate directions. The multi-
dimensional neutron kinetics model in RELAP5-3D is based on the NESTLE code, which solves the two or four group neutron diffusion equations in either Cartesian or hexagonal geometry using the Nodal Expansion Method (NEM) and the non-linear iteration technique. Three, two, or one-dimensional models may be used. Several different core symmetry options are available including quarter, half, and full core options for Cartesian geometry and 1/6, 1/3, and full core options for hexagonal geometry. Zero flux, non-reentrant current, reflective, and cyclic boundary conditions are available. The steady-state eigenvalue and time dependent neutron flux problems can be solved by the NESTLE code as implemented in RELAP5-3D. The new Border-Profile Lower Upper (BPLU) matrix solver is used to efficiently solve sparse linear systems of the form $AX = B$. BPLU is designed to take advantage of pipelines, vector hardware, and shared-memory parallel architecture to run fast. BPLU is most efficient for solving systems that correspond to networks, such as pipes, but is efficient for any system that it can permute into border-banded form. Speed-ups over the previously used sparse matrix solver are achieved in RELAP5-3D running with BPLU on multi-dimensional problems, for which it was intended. For one-dimensional problems, the BPLU solver runs as fast or faster than the previously used sparse matrix solver.

3. EDWARDS-O’BRIEN BLOWDOWN TEST

The Edwards-O’Brien blowdown test [6] is a classic separate effects code benchmark problem and is identified as the Committee on the Safety of Nuclear Installations (CNSI) Standard Problem number 1 for performing validation of nuclear reactor safety computer codes.4.1-2 The test was conducted to investigate and measure pressurized two-phase water blowdown behavior in a straight pipe geometry.

The objective of performing this code benchmark is to validate the code capability to calculate basic rapid blowdown phenomena given a simple straight pipe geometry. This sample was evaluated to verify if the code could simulate a LOCA type accident properly.

The code assessment includes two predominant transient flow regimes and behavior. The initial part of the transient involves single-phase choked flow at the break location while the pipe undergoes rapid depressurization and propagation of a pressure wave along the pipe. As the pipe rapidly depressurizes, flashing occurs along the pipe, resulting in two-phase break flow until the pipe is depressurized and essentially empty.

The facility is an electrically-heated straight pipe, filled with water and pressurized. The sealed pipe section is 4.096 m long with a 73 mm inside diameter. The pipe is instrumented with seven fast response pressure gauges mounted along the length of the pipe and seven temperature transducers with a response time of 15 ms. The pipe is also instrumented with two water density sensors to measure local void fraction during the test. The initial conditions for this test are 7 MPa and 502 K. The test is initiated by breaking a glass rupture disk located in the end of the pipe, resulting in a break opening time of approximately 1 ms. The effective break flow area is reduced by approximately 13% from the full pipe diameter. Various publications have documented that this reduced break area was due to a small piece of the glass rupture disk remaining at the break location.

The hydrodynamic nodalization scheme that was used in the RELAP5-3D is described by the diagram shown in Fig. 1. The instrumented horizontal pipe section of the test facility is
modeled explicitly using a pipe (Component 3) with 20 unequal-length cells and a length of 2.04801x10^1 m each. All of the pipe cells have a cross sectional flow area of 4.56037x10^-3 m^2 and a wall roughness of 1.177911x10^-6 m. The pipe is initialized with zero flow and is full of subcooled water with a non-uniform temperature distribution, which was taken from Reference [7]. The temperature data were taken from the gauge stations and linearly interpolated to obtain the initial temperatures in each cell. Initial pressure in the pipe component is established at 7.0 MPa. A time-dependent volume (Component 5) provides the user-specified atmospheric boundary condition adjacent to the pipe break location for the test simulation. A trip-controlled motor valve (Component 4) is used to connect the pipe to the boundary volume. The valve flow area is set at 3.96752x10^-3 m^2 to model the effective area of the test rupture disk.

Transient runs were made using the semi-implicit solution option. The transient runs were initiated from a zero flow initial condition. The code runs were terminated at 0.4 s. The time step size used was 1.0x10^-4 s.

Pressure results from the two calculations are compared to the test data at position GS-5 in Fig. 2. The RELAP5-3D calculated pressure response is in good agreement with the Edwards-O’Brien test pressure data, with only an initial undershoot immediately after break initiation and an over prediction of the pressure response in the 0.3 to 0.4 s time period.

![Figure 1: Diagram of the RELAP5-3D Edwards-O’Brien model.](image)

![Figure 2: Measured and calculated pressures for the Edwards-O’Brien blowdown test.](image)
The RELAP5-3D calculated void fraction response is shown in Fig. 3 in comparison to the Edwards-O’Brien test data at position GS-5. The calculated void fractions are in good agreement with the test data. The code-calculated response does not predict the oscillatory behavior shown in the test data in the 0.15 to 0.25 s time period. These void fraction oscillations are also not representative of the test pressure data. The RELAP5-3D code calculations under predict the void fraction in last half of the transient, which is consistent with the code calculations over predicting the pressure in the last half of the transient.

The RELAP5-3D input data were modified to also calculated and evaluate the mass flow rate during the test as it can be seen in Fig. 4.

![Figure 3: Measured and calculated void fractions for the Edwards-O’Brien test.](image)

![Figure 4: Mass Flow Rate for the Edwards-O’Brien test.](image)
4. CONCLUSIONS

The RELAP5-3D code pressure results are in reasonable agreement with the Edwards-O’Brien test data. The results were observed to be the same as compared to the received documentation.

For the first time, modifying the test data, we could evaluate the mass flow rate for the test.

It should be noted that measured break flow data were not available for this test. However, the fact that the pressure is well-calculated indicates that the break flow is likely well-calculated also.

Future works are been planned and prepared to simulate a CBCL components behavior coupled to a micro nuclear reactor as the heat source, to attend the TERRA project in the first phase, applying the RELAP5-3D new capabilities, including new work fluids.

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