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ASSESSMENT OF THE TRACE REACTOR ANALYSIS CODE AGAINST SELECTED PANDA TRANSIENT DATA

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ABSTRACT

The TRACE (TRAC/RELAP Advanced Computational Engine) code is an advanced, best-estimate thermal-hydraulic program intended to simulate the transient behavior of light-water reactor systems, using a two-fluid (steam and water, with non-condensable gas), seven-equation representation of the conservation equations and flow-regime dependent constitutive relations in a component-based model with one-, two-, or three-dimensional elements, as well as solid heat structures and logical elements for the control system. The U. S. Nuclear Regulatory Commission is currently supporting the development of the TRACE code and its assessment against a variety of experimental data pertinent to existing and evolutionary reactor designs. This paper presents the results of TRACE post-test prediction of P-series of experiments (i.e., tests comprising the ISP-42 blind and open phases) conducted at the PANDA large-scale test facility in 1990s. These results show reasonable agreement with the reported test results, indicating good performance of the code and relevant underlying thermal-hydraulic and heat transfer models.

INTRODUCTION AND BACKGROUND

PANDA [1,2] is a large-scale thermal-hydraulic test facility, located on the grounds of the Paul Scherrer Institute (PSI) in Switzerland, and dedicated to investigating containment system phenomena relevant to Advanced Light Water Reactor (ALWR) designs, including the General Electric (GE) Simplified Boiling Water Reactor (SBWR). The facility comprises a number of large, vertical, cylindrical vessels interconnected by smaller lines. Valves in the system lines can be controlled by the operators in order to establish desired initial conditions during the preconditioning period of an experiment, or to model system behavior during the transient period. Figures 1 and 2 show schematic depictions of the PANDA facility system layout.

A single cylindrical vessel, with 1.23 m ID and 19.23 m inside height, is used to model the Reactor Pressure Vessel (RPV). A cylindrical shroud is present inside of the RPV, from near the bottom of the vessel to approximately midway up its height, in order to separate this region of the vessel into downcomer and riser portions. Inverted U-tube shaped electrically heated elements are located near the bottom of the riser in order to model power input by the reactor core. Two valved Main Steam Lines (MSLs) connect the upper portion of the RPV to the drywell vessels.

The drywell consists of two identical vessels, each 3.96 m ID and 8.0 m height, connected by a large horizontal pipe. There are also two corresponding suppression chamber vessels, 3.96 m ID and 10.11 m height, normally partially filled with water. The suppression chamber vessels are connected to one another via large connecting pipes in both the liquid and gas spaces). Main Vent Lines (MVLs) connect the drywell vessels to their corresponding suppression chambers below the nominal water level to model pressure suppression during simulated Loss of Coolant (LOCA) transients, and the suppression chambers gas spaces are also connected back to the drywells via Vacuum Breaker Lines (VBLs) that open at a pressure differential of 3.24 to 3.90 kPa.

One cylindrical vessel – 1.98 m diameter and 6.06 m height, partially filled with water – represents the water tank of a Gravity Driven Cooling System (GDCS) that can inject to a depressurized RPV through a drain line containing a check valve. The gas space of the GDCS tank is connected via Equalization Lines to the gas spaces of the two suppression chamber vessels.

Three divisions of a Passive Containment Cooling System (PCCS) are present in the PANDA facility, for passively removing heat from the containment by condensing drywell steam inside of heat exchangers submerged in an external water pool. The pool consists of portions of a rectangular tank, partially filled with water and largely open to the environment at the top. In this pool are submerged the heat exchangers, consisting of horizontal, cylindrical drums at the top and bottom, connected by vertical pipes inside of which steam is condensed. The upper drums are connected to the tops of the drywells via PCCS Supply Lines. Liquid water condensed inside of the heat exchanger tubes collects in the bottom drums, where it returns to the RPV downcomer via a common PCCS Drain Line. Any noncondensable gas drawn into the PCCS will be returned to the suppression chambers via PCCS Vent Lines connecting the bottom drums to the suppression chambers (below the nominal water level). Note that, while the three divisions of the PCCS are nearly identical, PCCS-1 is connected to the first drywell and suppression chamber, while PCCS-2 and –3 are connected to the second drywell and suppression chamber, resulting in some overall containment asymmetry.

The ISP-42 test [3] consisted of six separate experiments, denoted Phases A through F, devoted to investigating particular phenomena of relevance to an ALWR containment during design basis accidents, or to studying individual time frames of an ALWR accident scenario. The present report documents only Phases A and B of the ISP-42 test.

The Phase A (PCCS Startup) experiment studied containment behavior in response to the beginning of steam injection to an initially cool, dry containment (e.g., such as during the initial phase of a LOCA). In this phase of the test, initial conditions in the containment atmosphere and suppression pool water were cool, with the atmosphere consisting mostly of noncondensable gas (oxygen). The RPV, preconditioned separately, consisted of saturated liquid and steam, with a water level approximately midway up the height of the downcomer. At time zero of the experiment, the main steam lines were opened, and a constant heater power of 1000 kW was imposed on the system, permitting hot steam to flow into the drywell vessels. Among the phenomena studied in this experiment were steam and noncondensable gas mixing in the drywells; condensation of steam on the drywell walls; and startup of the PCCS in response to rising steam fraction in the drywells, along with the consequent effect on drywell pressure.

Phase B (GDCS Discharge) of the test was devoted to examining the intermediate period of a LOCA scenario from the beginning of GDCS injection to the depressurized RPV. Operator intervention consisted of opening all PCCS lines at 29 s; opening the GDCS drain line at 48 s; and controlling the heater power to a specified value from 1400 kW at the start to 800 kW by the end of the experiment. Following heatup and resumption of boiling in the RPV, restoring the source of steam to the drywells, PCCS startup and eventual quasi-equilibrium conditions in the containment were reached by the end of this phase of the test (about 5000 s).

TRACE (the TRAC/RELAP Computational Engine, formerly known as TRAC-M) [4] is a thermal-hydraulic and heat transfer simulation code in development by the U.S. Nuclear Regulatory Commission (USNRC) for calculating the best-estimate progression of transients and accidents in Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs). The thermal-hydraulic portion of the code features a six-equation computational model (conservation of mass, energy, and momentum over two fields, with or without noncondensable gases) for the steam-water component, and a seventh field equation for non-condensable gas mass balance, along with the necessary closure relations. Systems are modeled by assembling a collection of individually sub-nodalized components, which may be one-, two-, or three-dimensional, and may incorporate specialized models (e.g., the CHANNEL component for core heat transfer). Provisions are also present for modeling of solids such as vessel and pipe walls as heat structure (HTSTR) components, and use of signal and control variable networks for the status of valves, power input to structures, etc. Models used inside the TRACE code draw upon the long experience with the earlier TRAC and RELAP codes, and also incorporate other recently implemented models for such phenomena as drywell wall condensation.

As part of ongoing efforts by the USNRC to assess the performance of the TRACE code, a TRACE input model was developed by Energy Research, Inc. (ERI) for the purpose of simulating the PANDA facility in its ISP-42 test configuration. This model was then used to simulate Phases A and B of the test, and code results were compared with the available experimental data.

MODELING

A TRACE input model was developed by ERI for the purpose of simulating the ISP-42 test, based on the facility description and drawings contained in [1]. Figure 3 shows the resulting system nodalization that was settled upon. This input model has a fairly detailed nodalization and includes the following features:

- Use of VESSEL components for all of the major cylindrical vessels in the facility, including the RPV, two drywells, two suppression chambers, GDCS tank, and three compartments of the PCCS pool.

- Two-dimensional cylindrical nodalization (in the axial and radial directions) for most VESSEL components (with the exception of the GDCS tank), including two radial rings and several axial levels. This was done to permit circulation between the downcomer and riser in the RPV and PCCS pool, as well as to allow natural circulation patterns in the containment compartments.

- Heat structure (HTSTR) components to model the walls of all major vessels, as well as the heating elements in the RPV, and the walls of the PCCS heat exchanger tubes. Heat transfer rates at the external boundary of the vessel walls were chosen to match the measured heat losses through insulation provided in [1].

- Application of TRACE's falling film heat transfer model on the inside of the PCCS tube walls.

- Control functions for determining the open status of the various lines, as specified by the documented procedures for individual experiments.

Heat transfer for the PCCS was modeled mechanistically, using structure components with hydraulic boundary conditions at the inside of the tubes (steam from the drywell, with code-calculated heat transfer rates from condensation using the falling film model) and at the outside pool (code-calculated heat transfer rates using pool boiling, given that initial conditions for the pool in these experiments are generally saturated from the beginning).

The resulting TRACE model for PANDA consisted of 734 fluid cells and 497 heat structure mesh points, summed over the entire system. In preliminary calculations performed to assess the performance of the model, the sensitivity of the results with respect to maximum timestep size and the degree of nodalization of the large vessels had been examined. Although no significant sensitivity of the results was found as a function of maximum timestep size up to about 1.0 s, it was sometimes found that the calculations proceeded more stably at sudden transients with a maximum timetep size of 0.1 s. Therefore, all of the final results presented here were obtained using a maximum timetep size of 0.1 s. (Note that TRACE adaptively adjusts the local timestep size within specified bounds according to the maximum error in thermodynamic convergence. Also, various limiters and relaxation-type relations are imposed on closure equations in such a way that TRACE is designed to display little sensitivity to timestep size.) Some nodalization sensitivity studies performed with respect to the mesh spacing in the large vessels indicated that the differences in the results, relative to the differences between simulation and data, are generally small.

RESULTS

TRACE calculations were performed separately for each Phase of the ISP-42 test, with initial conditions, the controlled status of various valves, and tabular input for heater power changed to correspond to the documented conditions for each experiment. Version 4.280 of the code was employed. The calculations were performed on a PC with an AMD Athlon™ 64 X2 4600+ processor and 2 GB of RAM, and the simulations required on average approximately 2x real time to finish (e.g., 12921 s of CPU time for the 6000 s simulation involved in Phase A) while using between 40 and 50 MB of RAM.

In each case, a 50 s Generalized Steady-State (GSS) calculation was performed prior to the main transient calculation, with main steam lines closed, in order to reach initial quasi-equilibrium. Due to heat losses from the system through the insulated vessel walls (about 4% of nominal heater power), true steady-state conditions were not possible in such a calculation. Nevertheless, calculated system pressures and temperatures at the end of the GSS were found to match the test conditions to an acceptable degree of tolerance.

<u>Phase A:</u>

Results of the TRACE simulation of ISP-42 Phase A (PCCS Startup) are summarized in Figures 4 through 6.

The progression of this transient, in both the experiment and the TRACE results, can be divided into two time frames: (1) the early time frame, during which steam injection from the RPV purges noncondensable gases from the drywells to the suppression chambers through the PCCS vent lines, and (2) the late time frame (after approximately 3000 to 4000 s) in which PCCS performance ramps up and reaches near-equilibrium heat removal from the system, at which time the drywells atmosphere is nearly all steam.

In both TRACE and measurements, the flow rate of steam to the drywells during the course of the experiment balanced the controlled heater power input to the RPV. Figure 4 shows the calculated and measured total pressure in DW1, along with partial pressure of noncondensable gas at locations near the bottom, middle (i.e., near the MSL), and top (i.e., near the PCCS inlet) of the vessel. The general course of the transient is that noncondensable gas fraction decreases at all locations due to purging through the PCCS vents. TRACE results contrast somewhat with the experimental measurements, however, in that conditions are predicted to be well mixed (i.e., uniform noncondensable partial pressure) at all times. In the measurements, some apparent pocketing of noncondensable gas is observed near the bottom and top of the drywell, and some noncondensable gas remains near the top of the drywell even by the end of the experiment, by which time almost none is present in the TRACE simulation. Note that both calculated and observed behavior in DW2 is nearly identical to that in DW1.

Figure 5 shows the cumulative mass of steam that condenses on the walls of DW1 and pools in the bottom of the vessel. TRACE calculations match the measurements well up until about 1500 to 2000 s, where the condensation rate diverges significantly, such that, by the end of the experiment, TRACE shows about 300 kg less steam condensed in the drywell.

Performance of the PCCS is reflected in Figure 6, which shows the cumulative drain rate of condensed water from all PCCS divisions. It can be seen that the TRACE results for PCCS performance in Phase A are in reasonable agreement with the experimental measurements.

Although heat rejection to the PCCS is accurately predicted by TRACE in Phase A, drywell condensation is calculated to be somewhat less than was measured in the experiment. Due to the consequent overall slower rate of heat removal from the system prior to PCCS startup, the total system pressure calculated by TRACE (Figure 4) is therefore slightly higher than was measured during the intermediate time frame, by a difference of 0.2 bar. However, the TRACE-predicted long-term equilibrium pressure following full PCCS startup (after about 4000 s) is a good agreement with the experimental data.

Phase B:

Results of the TRACE simulation of ISP-42 Phase B (GDCS Discharge) are summarized in Figures 7 through 9.

In this Phase of the ISP-42 test, four time frames can be observed in both the TRACE calculation and the experimental measurements: (1) an early time frame prior to the operator-initiated GDCS injection, and before injected GDCS water reaches and quenches the heating elements; (2) an intermediate time frame, in which water injected from the GDCS renders RPV conditions subcooled, until such time that the heating elements can return this water to saturation conditions; (3) a transitional time frame, following resumption of boiling in the RPV and restoration of a steam source to the drywells, during which the system pressurizes and PCCS performance ramps up; and (4) a late time frame in which the system eventually reaches near-equilibrium with power input to the RPV heating elements.

At 48 s, the GDCS drain line is opened as a result of operator action, and injection to the RPV downcomer begins. Gravity-driven injection rates as calculated by TRACE compare well with those measured during the experiment, as shown in Figure 7.

In the reported experimental measurements of steam generation rate, this appears to result in a nearly instantaneous quench of the heating elements, whereas results of the TRACE calculation show that it requires approximately 200 s for the cool injected water to flow down the downcomer and reach the heating elements. Note that, in the present TRACE model, the RPV downcomer has no azimuthal nodalization, so that any injected water must in effect mix around the entire circumference of the vessel, precluding smaller jets that could more effectively penetrate through the downcomer and into the heating elements. However, a limited number of sensitivity calculations performed to date involving a two-dimensional downcomer have indicated that the difference between calculation and experimental data in this respect still cannot be entirely explained by this aspect. Furthermore, since the data indicate that pressure in the RPV begins to rapidly fall even before injection begins, potential issues related to the recorded test data cannot be excluded.

As a result of this delay in quenching of the heating elements as simulated by TRACE, an additional quantity of boiled water is added as steam to the drywells, which is reflected in Figure 8 as a drywell total pressure that is persistently about 0.2 bar higher in the TRACE calculation as compared with the experimental measurement. As a further consequence of the lower pressure measured during the experiment in the intermediate time frame, one opening of the wetwell-to-drywell vacuum breakers was observed, whereas TRACE calculates no VBL activity over the entire course of the simulation.

Beginning at around 3200 to 3300 s, saturation conditions are reached again in the RPV, and injection of steam from the RPV to the drywells therefore resumes, as shown in Figure 8. At the same time, flow through the PCCS also begins to pick up, with nearly equilibrium conditions observed by the end of the experimental measurements and TRACE simulation at around 4500 to 5000 s. Figure 9 shows the cumulative mass of water condensed inside all divisions of the PCCS. It can be seen that measured PCCS heat rejection rate (i.e., the slope of the line in Figure 9) is observed in the experiment to be about the same as in the TRACE results, although a longer PCCS startup time in the calculation results in a difference of about 200 kg of condensed steam by the end of the experiment. This explains the pressure difference of about 0.2 to 0.3 bar observed in the drywell between the TRACE results and measurements in the late time frame.

SUMMARY AND CONCLUSIONS

A TRACE model of the PANDA facility was constructed that was found to be capable of modeling Phases A and B of the ISP-42 test. TRACE was able to qualitatively predict the timing and expected time frames of each experiment, as well as calculate final system pressure during PCCS operation to within 0.2 to 0.3 bar. Three areas of discrepancy were observed:

(1) TRACE condensation on the drywell walls during some time frames or regimes appears to be less than was measured during the experiment, with the result that calculated drywell pressures are higher.

(2) PCCS performance, while calculated accurately in Phase A, is somewhat less than measured experimentally in Phase B. It is unknown at this time whether this difference is a modeling issue or is possibly rooted in the condensation or boiling correlations used for the PCCS in TRACE.

(3) Penetration of injected GDCS water in the downcomer to the vicinity of the heating elements is less than was measured experimentally, resulting in later quench of the heating elements and a higher early drywell pressure in TRACE, as shown by observed time-dependent temperature profiles in the downcomer region and inferred from the very early time of quench observed in the test data. The observed discrepancies between the TRACE predictions and the Phase B experimental data have not been fully resolved as of this date.

Continued work on TRACE modeling of the PANDA facilities will consist of investigating some of the identified issues as well as performing simulations of the remaining experimental phases of ISP-42 (i.e., Phases C through F). This is expected to shed further light on the capability of TRACE to model ALWR systems.

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LIST OF ACRONYMS

ALWR	Advanced Light Water Reactor
BWR	Boiling Water Reactor
DW	Drywell
ERI	Energy Research, Inc.
GDCS	Gravity Driven Cooling System
GE	General Electric
GSS	Generalized Steady State
LOCA	Loss of Coolant Accident
MSL	Main Steam Line
MVL	Main Vent Line
NRC	Nuclear Regulatory Commission
PCCS	Passive Containment Cooling System
PSI	Paul Scherrer Institute
PWR	Pressurized Water Reactor
RPV	Rector Pressure Vessel
SBWR	Simplified Boiling Water Reactor
TRACE	TRAC/RELAP Advanced Computational Engine
VBL	Vacuum Breaker Line

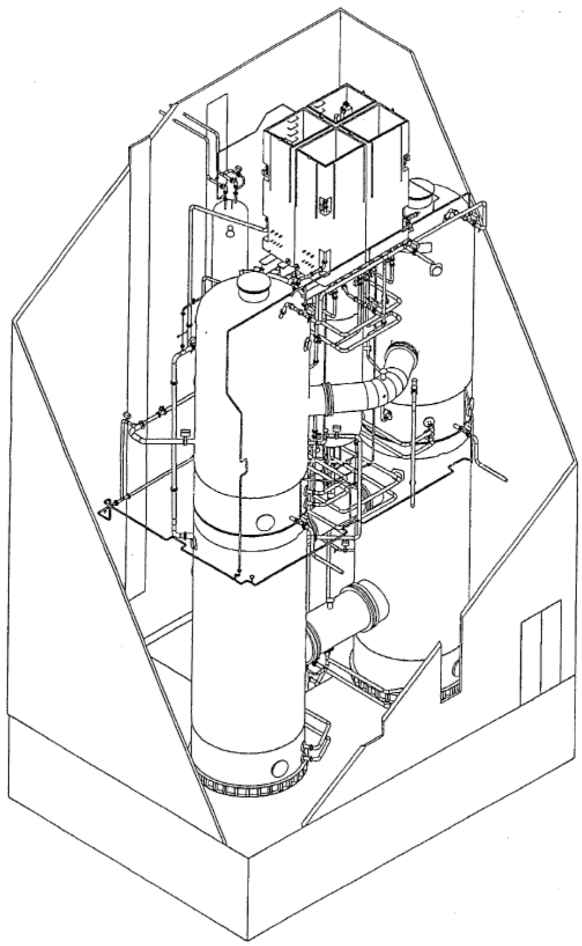

Figure 1: PANDA Facility (from [1])

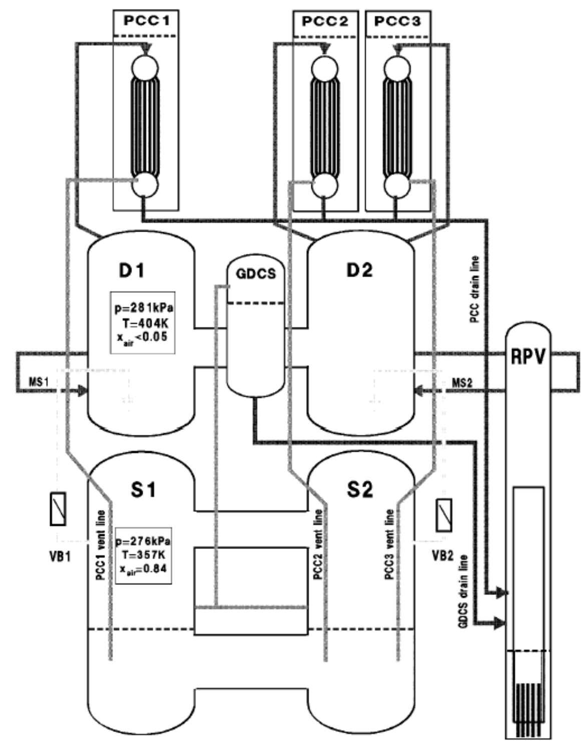

Figure 2: PANDA Facility Schematic (ISP-42 Phase B configuration, from [2])

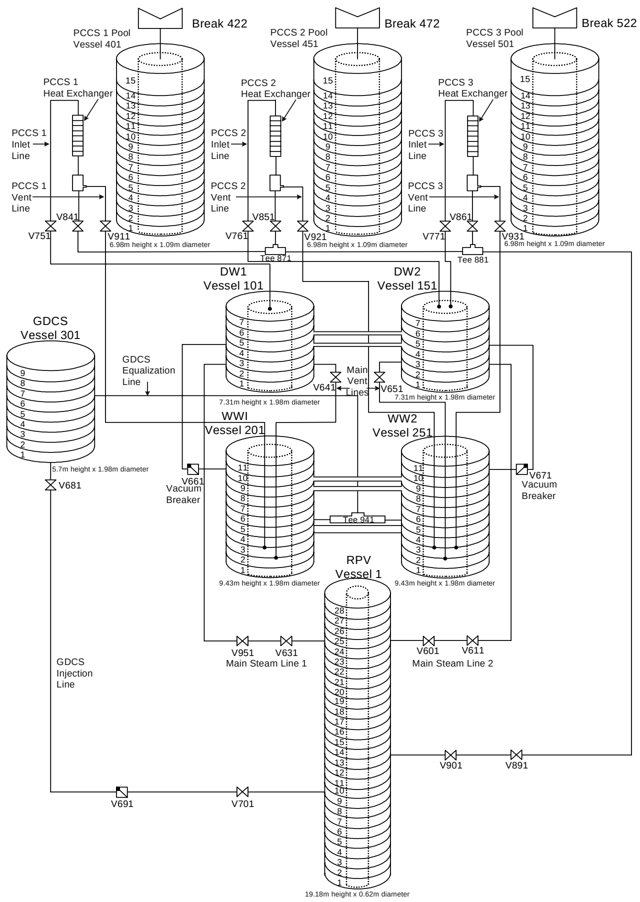

Figure 3: TRACE Nodalization of PANDA Facility

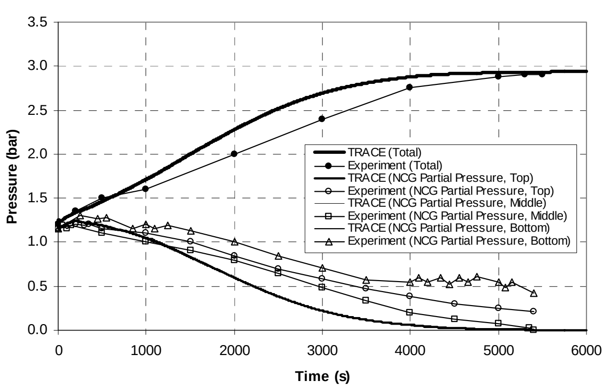

Figure 4: ISP-42 Phase A – Pressure in Drywell 1

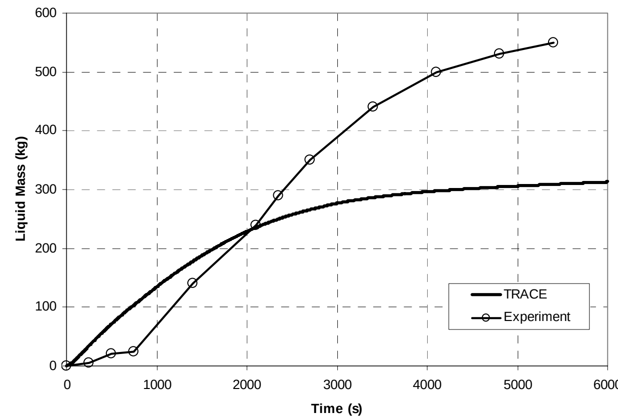

Figure 5: ISP-42 Phase A – Integrated Condensation in Drywell 1

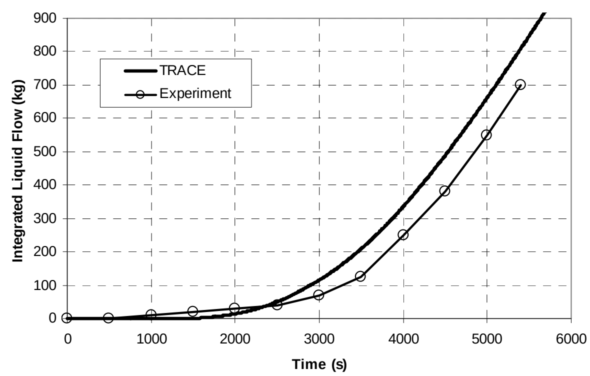

Figure 6: ISP-42 Phase A – Integrated Condensate Drain Flow from All PCCS Divisions

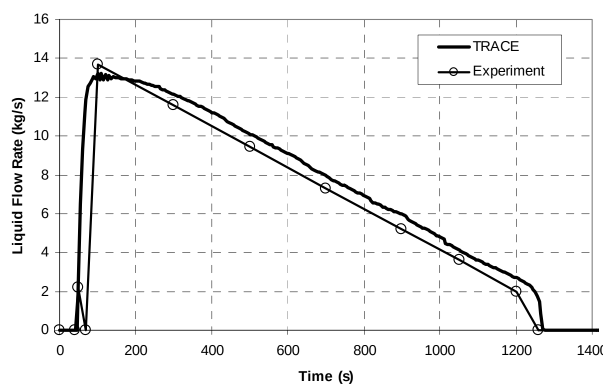

Figure 7: ISP-42 Phase B – Injection Rate from GDCS to RPV

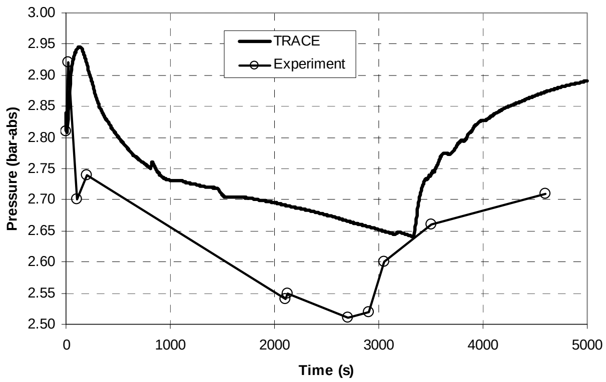

Figure 8: ISP-42 Phase B – Pressure in RPV

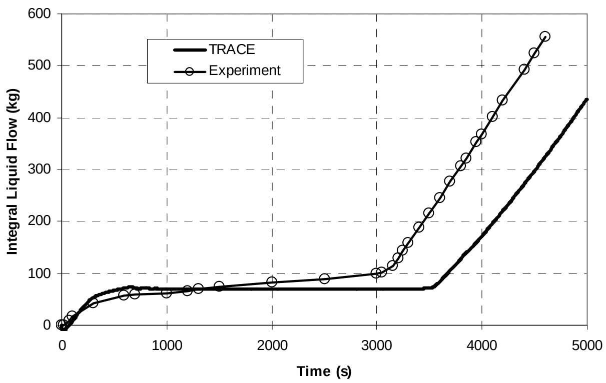

Figure 9: ISP-42 Phase B – Integrated Condensate Drain Flow from All PCCS Divisions