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THE PUMA TEST PROGRAM AND DATA ANALYSIS

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ABSTRACT

The PUMA test program is sponsored by the U.S. Nuclear Regulatory Commission to provide data that are relevant to various Boiling Water Reactor phenomena.

This paper briefly describes the PUMA test program and facility, presents the objective of the program, provides data analysis for a large-break loss-of-coolant accident test, and compares the data with a RELAP5/MOD 3.1.2 calculation.

I. PUMA TEST PROGRAM AND FACILITY DESCRIPTION

PUMA is an acronym for Purdue University Multi-Dimensional Integral Test Assembly.[1] The PUMA test program[2,3] is sponsored by the U.S. Nuclear Regulatory Commission (NRC). It consists of two phases of operation. The "completed" first phase includes the design, construction, and preoperational testing of the PUMA facility. The "ongoing" second phase is to perform tests and collect data, analyze data, and document the results.

The design of the PUMA test facility was initiated in July 1993, when NRC awarded a contract to Purdue University in West Lafayette, Indiana. The facility construction and instrumentation were completed in August 1995. A PUMA facility readiness review was conducted by a team of NRC staff in November 1995. As a result, a number of improvements were implemented on documentation and operation. Preoperational facility testing was completed in May 1996. On June 3, 1996, the facility inauguration and first integral test were conducted. Tests are being performed at PUMA to provide data that are relevant to the Boiling Water Reactor (BWR) phenomena to meet NRC's needs.

Figure 1 is a sketch of the PUMA facility (drawn to scale). PUMA has the essential BWR-relevant components, which include a reactor pressure vessel (RPV), a containment consisting of a drywell (DW) and wetwell (WW, namely, the suppression pool and the gas space above the pool), an Automatic Depressurization System (ADS) consisting of the safety/relief valves (SRVs), and an Isolation Condenser System (ICS). In addition, PUMA also has the innovative, passive safety components, which are relevant to an advanced BWR design by GE Nuclear Energy,[4] including the Gravity-Driven Cooling System (GDCS), Passive Containment Cooling System (PCCS), and depressurization valves (DPVs) as part of the ADS. The GDCS, PCCS, and DPVs can be isolated from other PUMA components. The RPV has a height of 6.126 m (20.1 ft) and an inside diameter of 0.6 m (1 ft 11.6 in.). Heights and diameters of other components can be estimated from Fig. 1 by comparing them with the RPV.

A detailed scaling analysis was performed by Ishii et al.[1,5,6] to design PUMA based on an advanced BWR design.[4] PUMA is a reduced-height (1/4 of the prototype height), reduced-time (1/2 of the prototype), and real-pressure (approximately same as the prototype at 150 psia or less) facility. The volume of each PUMA component is 1/400 of the prototype, and the core power is 1/200 of the prototype. The RPV can be safely operated at 1.034 MPa (150 psia), and the DW and WW can be safely operated at 0.483 MPa (70 psia). PUMA has a maximum core power of 385 KW.

There are about 400 instruments at various locations to measure pressures, temperatures, water levels, void fractions, non-condensable gas concentrations, and flow rates in PUMA.

II. OBJECTIVE OF THE PUMA TEST PROGRAM

The PUMA test program provides BWR-relevant data that can be used (1) to validate the models in thermal-hydraulic codes, (2) to enhance understanding of various phenomena, and (3) to assess scaling methodologies (by comparing the PUMA data vs. data from the full-height PANDA or GIRAFFE test facility[1]).

III. DATA ANALYSIS FOR A LARGE-BREAK LOSS-OF-COOLANT ACCIDENT TEST

A large-break loss-of-coolant accident (LBLOCA) test was performed at PUMA on July 22, 1996. The break was located at a main steam line at a high elevation in the RPV. The test lasted for 8 hours. The initial test conditions were scaled from the RELAP5 calculations[7,8] for an advanced BWR design.[4] Note that for the prototype, the LBLOCA is assumed to occur at full pressure of 7.17 MPa (1040 psia), and the reactor is tripped with the core at decay power; the RPV is blown down to 1.034 MPa (150 psia). The corresponding mass and energy (in terms of pressure, temperature, mass concentration, etc.) in each component calculated by RELAP5 for the prototype were then scaled down to use as the "ideal" values for initial PUMA test conditions.

The "actual" initial test conditions for the LBLOCA test were: the RPV steam dome at 1.048 MPa (152 psia, vs. the ideal value of 150 psia) and 185.3 °C (vs. the ideal 186 °C); the upper DW at 0.233 MPa (33.8 psia, vs. the ideal 34 psia) and 126 °C (vs. the ideal 127 °C); the suppression pool gas space at 0.234 MPa (34 psia, vs. the ideal 33.5 psia) and 58.7 °C (vs. the ideal 63 °C); and the suppression pool water bulk temperature at 52.6 °C (vs. the ideal 53 °C). The differences between the actual and ideal values are small. Data uncertainties for those shown in this paper were estimated to be within 5.0 KPa (0.73 psi) for pressures, 3.2 °C for temperatures, and 0.023 m (0.91 in.) for water levels.

It should be pointed out that a post-test facility examination revealed leaks at or near the RPV (with a mass error estimated to be -0.56% at the end of the 8-hr test). Those leaks are not expected to be significant enough to qualitatively challenge the following conclusions that are based on the analysis of the LBLOCA data.

1. Core Was Always Covered With Water During the Test

Figure 2 shows a collapsed water level measurement in the PUMA RPV downcomer between 0.108-m and 6.153-m elevations (above the inner surface of the RPV lower head). The top of the active fuel (TAF) is at 1.623-m elevation, which corresponds to 1.515 m (= 1.623 - 0.108 m) in Fig. 2. The entire core was always covered with water during the 8-hr test. The minimum collapsed water level (at 214 s when the GDCS coolant injection was initiated as shown in Fig. 3) was 1 m above the TAF. Between 214 s and 800 s, the collapsed water level was on the rise. It reached 5.22 m at 800 s, when the RPV water began to overflow to the DW through the break and DPVs. From 800 s to 28,800 s (8 hr), the collapsed water level slowly decreased to below 5.1 m. For this test, the GDCS covered the core with water and maintained adequate core cooling.

2. Drywell and Wetwell Pressures and Temperatures Were Well Below Design Limits

Figure 4 shows the DW and WW gas space pressures during the 8-hr test. Both the DW and WW pressures were well below the containment design limit of 0.483 MPa (70 psia). The overall trend after 5000 s was a gradual decrease in both the DW and WW pressures. (Note that if there were no leaks in this test, the DW and WW pressures would be somewhat higher. But they are expected to remain well below the DW and WW design limits based on an energy balance calculation.)

Figure 5 shows the DW and WW gas temperatures. The maximum DW temperature was 136 °C, which is 35 °C below the design limit of 171 °C. The maximum WW gas temperature was around 66 °C, which is well below the design limit of 121 °C. The overall trend was a slow change in the DW and WW gas temperatures after 2000 s to 4000 s. For this test, the PCCS maintained adequate containment cooling.

3. There Was a Close Coupling of RPV, DW, and WW Pressures After RPV Blowdown

Figure 6 shows the RPV, DW, and WW gas pressures for the first 500 s of the test. Figure 7 shows the same pressures for the entire 8-hr test. During the initial RPV blowdown from 1.048 MPa (152 psia), both the DW and WW pressures increased until they approached the decreasing RPV pressure. The DW pressure began to decrease with the RPV pressure at around 240 s. About 20 s later, the WW pressure also began to decrease with the RPV pressure. After 260 s, all three pressures followed the same trend throughout the rest of the 8-hr test. There was a close coupling of RPV, DW, and WW pressures after RPV blowdown.

4. PCCS Condensers Had Different Condensation Rates

Figure 8 shows the steam condensation rates in two PCCS condensers (Units A and C) in PUMA. The condensation rates (or the work loads) were different in the two condensers. The condensation rate in the third condenser (Unit B, not shown) was different from those shown in Fig. 8. The non-uniform steam condensation in the three PCCS condensers could not be predicted by computer code calculations; it might be caused by variations of the non-condensable gas concentration in the condensers.

5. ICS Condensed Much Less Steam Than PCCS After 4600 Seconds

Figure 9 compares the steam condensation rate in an ICS condenser (Unit C) with that in a PCCS condenser (Unit A). For the first 4200 s, the steam condensation rate in the ICS condenser was higher than that in the PCCS condenser. But the trend was reversed after 4200 s. From 4600 s to 28,800 s (8 hr), the steam condensation rate in the ICS condenser became much smaller than that in the PCCS condenser. The other two ICS condensers (Units A and B, not shown) also condensed much less steam than the PCCS condenser (shown in Fig. 9) after 4600 s. Unlike PCCS, there was no venting of non-condensable gas from the ICS condensers to the suppression pool in this test. This could be a reason why the ICS condensed much less steam than the PCCS after 4600 s.

6. Cyclic Openings of Vacuum Breakers Did Not Stop Steam Condensation in PCCS

Figure 10 shows the opening periods of one of the three vacuum breakers (the other two vacuum breakers had the same behavior). There were three opening periods between 10,000 s and 20,000 s, in which the vacuum breakers cycled open and closed many times. Comparing Fig. 10 with Fig. 8, the vacuum breaker cycling between 10,000 s and 20,000 s did not stop steam condensation in the PCCS condensers. Note that Fig. 10 also shows a vacuum breaker opening period between 272 s and 763 s, in which the opening was continuous and occurred during the initial GDCS injection to the RPV.

IV. COMPARISON OF A RELAP5/MOD 3.1.2 CALCULATION WITH DATA

A RELAP5/MOD 3.1.2 calculation was performed on a Sun Sparc LX workstation at NRC to simulate the PUMA LBLOCA test. It took about 15 days of the workstation time to simulate 3200 s of the test (with 220 computational cells). The calculation was a repeat of a pre-test calculation performed by Parlatan et al.;[8] it is based on the ideal values for initial test conditions (see Section III) and assumes no leaks in the RPV. However, those differences are not expected to significantly affect the following comparisons.

1. Comparison of RPV Pressures

Figure 11 compares the PUMA data with the RELAP5-calculated RPV pressure up to 3200 s, when the calculation was terminated. The overall comparison is good, although RELAP5 somewhat underpredicts the RPV pressure after about 800 s.

2. Comparison of DW and WW Pressures

Figure 12 compares the PUMA data with the RELAP5-calculated DW pressure. Figure 13 compares the WW gas pressures. The RELAP5-calculated DW and WW pressures are qualitatively similar to the data.

But there are quantitative discrepancies. First, the initial DW or WW pressure rise (between the initial pressure and the peak at 240 s to 300 s) calculated by RELAP5 is approximately only 1/6 of that in the data (with a pressure rise at about 3 psi). It is worth noting that during this time period, the vertical vent pipe (between the DW and WW) was partially cleared to allow direct venting of DW steam to the suppression pool. Secondly, although the calculated pressure drop (between the peak and the minimum pressure at about 750 s for the data and at 1750 s for the calculation) is about the same as the data (around 8 to 9 psi), the calculation takes approximately 1000 s longer to reach the same pressure drop compared to the data. Those discrepancies could be due to the impact of several factors, which include the suppression pool surface temperature, steam condensation with the presence of non-condensable (namely, air) at the pool surface, PCCS and ICS heat removal rates, heat loss at the wall, and vacuum breaker operation. Further study is needed to determine the possible causes for those discrepancies.

3. A Physical Process Not Predicted in the Calculation

Contrary to the data, the calculation does not predict water accumulation in the lower DW, which was caused by (1) RPV water overflow to the DW during GDCS injection and (2) steam condensation in the DW. Further study is needed to determine the possible causes for this discrepancy.

V. CONCLUSIONS

The NRC-sponsored PUMA test program provides BWR-relevant data for code assessment. Data analysis for an LBLOCA test has led to several important conclusions (see Section III): (1) the core was always covered with water and adequate core cooling was maintained by the GDCS for the entire 8-hr test; (2) containment (DW and WW) pressures and temperatures were maintained well below the design limits by the PCCS; and (3) there was a close coupling of RPV, DW, and WW pressures after RPV blowdown.

Comparison of the first 3200 s of the LBLOCA data with a RELAP5/MOD 3.1.2 pretest calculation has revealed a reasonably good agreement between the calculated RPV pressure and data (see Section IV). But this is not the case for the DW and WW pressures. In addition, the comparison has identified that water accumulation in the DW is not predicted at all in the calculation. Further study is needed to determine the possible causes for those discrepancies.

VI. ACKNOWLEDGEMENTS

We wish to thank Dr. Shripad Revankar and other PUMA staff at Purdue University for the data.

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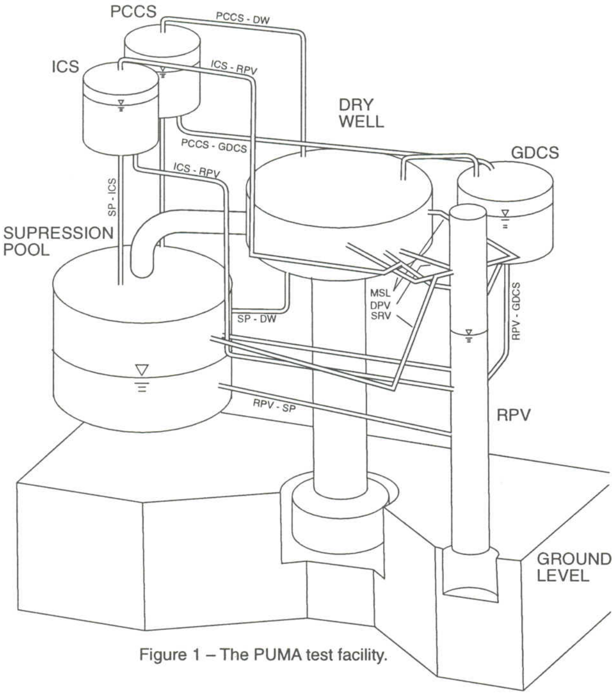

Figure 1 – The PUMA test facility.

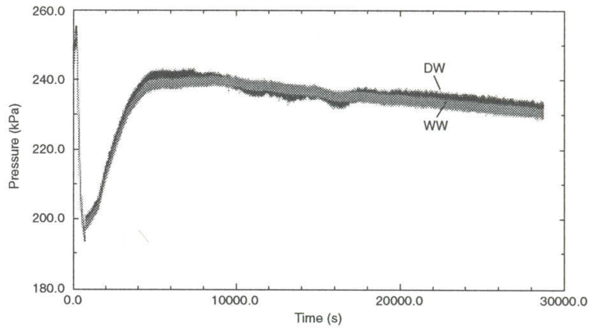

Figure 4 – Drywell and wetwell pressures for an LBLOCA test.

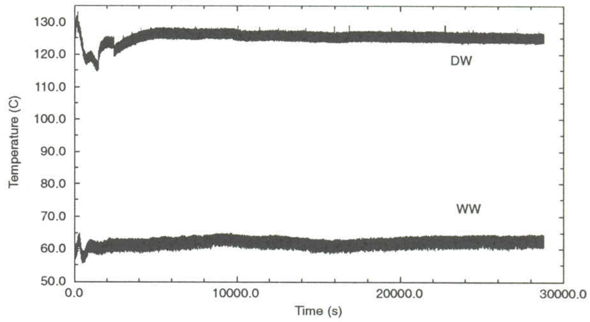

Figure 5 – Drywell and wetwell gas temperatures for an LBLOCA test.

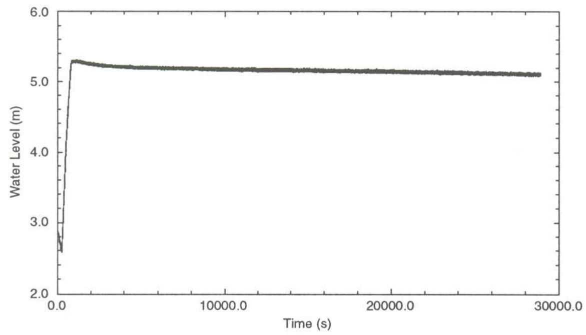

Figure 2 – Collapsed water lavel in the PUMA RPV measured from 0.108 m to 6.153 m (above the inner surface of lower head) for an LBLOCA test.

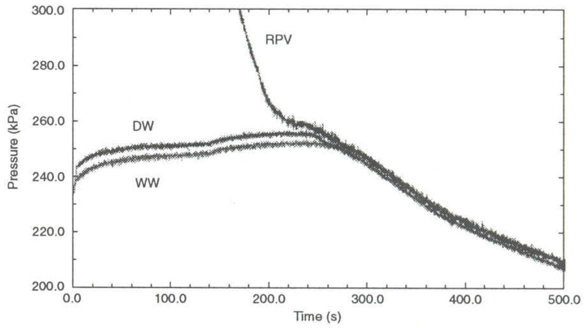

Figure 6 – RPV, drywell, and wetwell pressures for the first 500 s of an LBLOCA test.

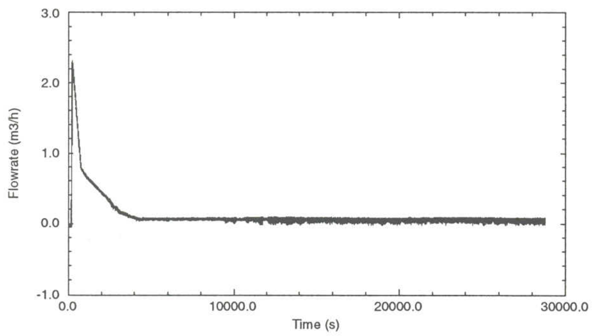

Figure 3 – Water volumetric flow rate in GDCS drain line A for an LBLOCA test.

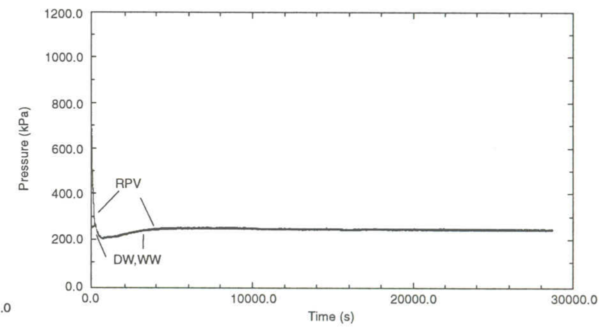

Figure 7 – RPV, drywell, and wetwell pressures for an LBLOCA test.

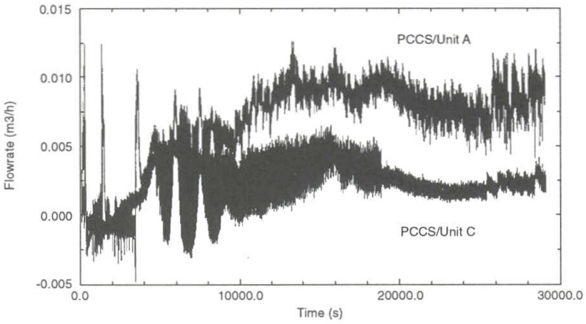

Figure 8 – Water volumetric flow rates in the PCCS/Unit A and Unit C drain lines for an LBLOCA test.

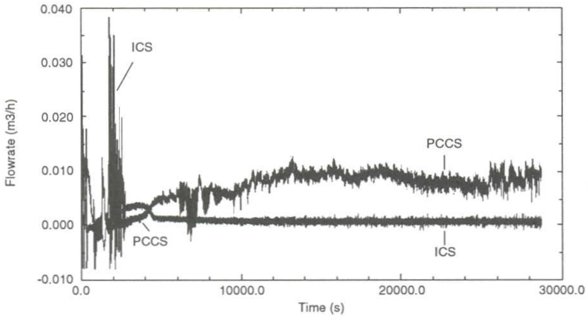

Figure 9 – Water volumetric flow rates in the ICS/Unit C and PCCS/Unit A condenser drain lines for an LBLOCA test.

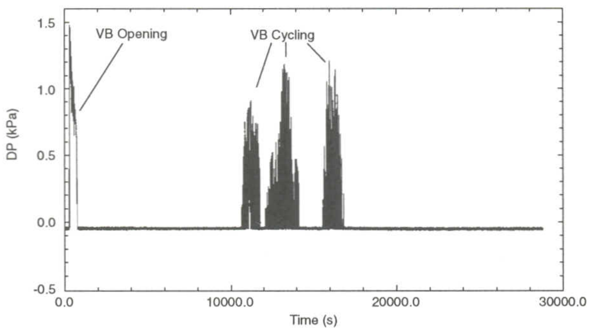

Figure 10 – Differential pressure across vacuum breaker A for an LBLOCA test.

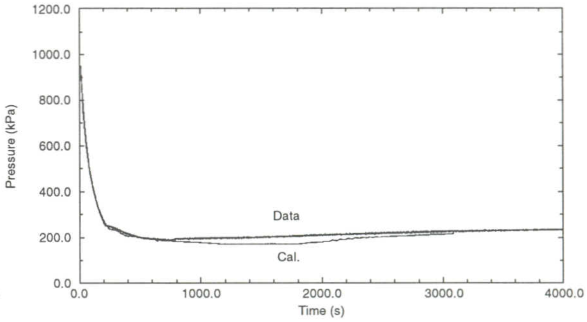

Figure 11 – Comparison of RPV pressures: PUMA data vs. RELAP5 pretest calculation for an LBLOCA test.

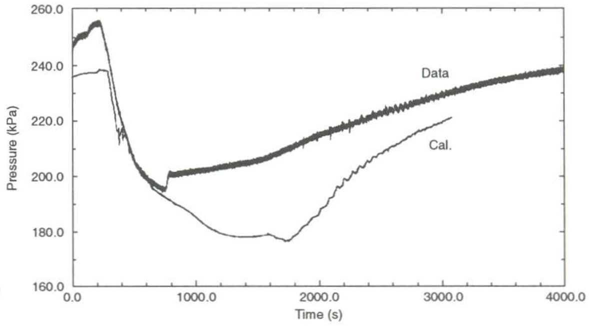

Figure 12 – Comparison of drywell pressures: PUMA data vs. RELAP5 pretest calculation for an LBLOCA test.

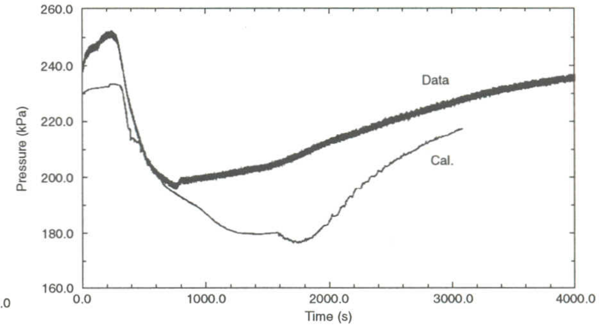

Figure 13 – Comparison of wetwell pressures: PUMA data vs. RELAP5 pretest calculation for an LBLOCA test.

17. Draft Call for Papers

CALL FOR PAPERS
(Beijing, China 1997)
FIFTH International Topical Meeting on Nuclear Thermal Hydraulics, Operations, & Safety (NUTHOS-5)
April 14-18, 1997
Beijing, China

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Presentation Outline

- The PUMA Test Facility
- Objective of the PUMA Test Program
- Data Analysis for a PUMA Main Steam Line Break (MSLB) Test
- Comparison of a RELAP5 Pretest Calculation with PUMA Data
- Conclusions

The PUMA Test Facility

- PUMA = Purdue University Multi-Dimensional Integral Test Assembly

- Is a Low-Pressure (1.034 MPa or 150 PSIA), Integral and Separate-Effects Test Facility That Provides Data Relevant to Boiling Water Reactor (BWR) Phenomena.

- Is Funded and Owned by U. S. Nuclear Regulatory Commission (NRC), and Is Run by Purdue University (in West Lafayette, Indiana) Under a Contract with NRC.

- Became Operational in June 1996, About Three Years After Purdue University Received NRC Funds To Build the Facility.

- Has About 400 Instruments to Measure Various Pressures, Temperatures, Water Levels, Flow Rates, and Oxygen Concentrations.

- PUMA Has the Following BWR-Relevant Components:
  - RPV (Reactor Pressure Vessel)
  - Drywell
  - Wetwell (Suppression Pool and the Gas Space Above)
  - ICS (Isolation Condenser System)
  - ADS (Automatic Depressurization System)
- Plus Three SBWR-Unique and Isolable Components:
  - GDCS (Gravity-Driven Cooling System)
  - PCCS (Passive Containment Cooling System)
  - DPVs (Depressurization Valves as Part of ADS)

Objective of the PUMA Test Program

- Provide Valuable Data To:
  - Validate the Models in Thermal-Hydraulic Computer Codes
  - Enhance Understanding of Various Phenomena
  - Assess Scaling Methodologies (by Comparing PUMA Data with Data from Other Facilities Such As PANDA and GIRAFFE)

Data Analysis for a PUMA Main Steam Line Break (MSLB) Test

[This PUMA Test Was Initiated at t = 0 with Mass and Energy Distributions Approximating the RELAP5-Calculated SBWR Conditions at 1.034 MPa (150 PSIA). The SBWR Calculation Began at the SBWR Operating Pressure of 7.17 MPa (1040 PSIA) with the Initiation of a MSLB Loss-of-Coolant Accident and Ended When the RPV Pressure Decreased to 1.034 MPa (150 PSIA).]

- Core Was Always Covered with Water During the 8-Hour Test. [The Gravity-Driven Cooling System (GDCS) Kept Core Covered and Cooled.]

- Drywell and Wetwell Pressures and Temperatures Were Well Below Design Limits. [The Passive Containment Cooling System (PCCS) Maintained Adequate Containment Cooling.]

- **After RPV Blowdown, Pressures in the RPV, Drywell, and Wetwell Came Together and Were Closely Coupled.**
- **GDCS Injected Water to the RPV at 214 Seconds and Afterwards.**
- **Different Steam Condensation Rates Were Observed in the PCCS Condensers.**

Comparison of a RELAP5 Pretest Calculation with PUMA Data

A RELAP5/MOD3.1.2 Pretest Calculation Was Performed on a Sun Workstation at NRC for Approximately 3200 Seconds of the PUMA MSLB Test. The Calculation Was Compared with the Data, and Code Deficiencies Were Identified.

- Comparison of the Calculated RPV Pressure with the Data Is Reasonable (Note That 100 KPa = 14.5 PSIA). However, To Look More Closely,
  - RELAP5 Somewhat Underpredicts the Pressure After 800 Seconds.
  - A Reasonable Comparison in RPV Pressure May Not Be Sufficient to Reveal the Adequacy of RELAP5. Comparison of Drywell and Wetwell Pressures with Data Was Also Performed.

- **The Calculated Drywell and Wetwell Pressures Are Qualitatively Similar to the Data. But Quantitative Comparison with the Data Is Less Than Reasonable. It Reveals Deficiencies in RELAP5/MOD3.1.2.**

  - **The Calculation Significantly Underpredicts the Initial Pressure Rises between the Initial and Peak Pressures, During RPV Blowdown (The Calculated Pressure Rise = 1/6 of the Data Value).**

  - **After the Peak Pressure Is Reached, the Calculation Significantly Underpredicts the Rate of Pressure Decrease. To Reach the Same Pressure Drop between the Peak and the Lowest Pressures, It Takes Approximately 1500 Seconds in the Calculation vs. Only 500 Seconds in the Data (The Calculated Pressure Decrease Rate = 1/3 of the Data Value).**

- After the Lowest Pressure Is Reached, the Calculation Significantly Overpredicts the Rate of Pressure Increase. It Takes 1250 Seconds (Between 1750 to 3000 Seconds) in the Calculation vs. 3250 Seconds in the Data (From 750 to 4000 Seconds) to Reach the Same Pressure Increase. (The Calculated Pressure Increase Rate = 2.6 of the Data Value).

- The Above Discrepancies Could Be Caused by Deficiencies in RELAP5 Models That Calculate Containment Pressure Rise Due to RPV Blowdown, Steam Condensation Rate with the Presence of Noncondensable Gas (Namely, Air) in the Suppression Pool and at the Pool Surface, Pool Surface Temperature, PCCS and ICS Heat Removal Rates, Containment Heat Loss, Etc.

- Other Deficiencies in RELAP5/MOD3.1.2
  - It Does Not Predict Water Accumulation in the Drywell.
  - It Numerically Introduces Flow Circulation In the Suppression Pool of the Wetwell. (This Problem Is Addressed in RELAP5/MOD3.2, Which Is a Replacement for RELAP5/MOD3.1.2.)

Conclusions

- Data Analysis for a PUMA MSLB Test

  - The Core Was Always Covered with Water During the 8-Hour Test, and Adequate Core Cooling Was Maintained by the Gravity-Driven Cooling System (GDCS).

  - The Drywell and Wetwell Pressures and Temperatures Were Maintained Well Below Design Limits by the Passive Containment Cooling System (PCCS).

  - RPV, Drywell, and Wetwell Pressures Were Closely Coupled After RPV Blowdown.

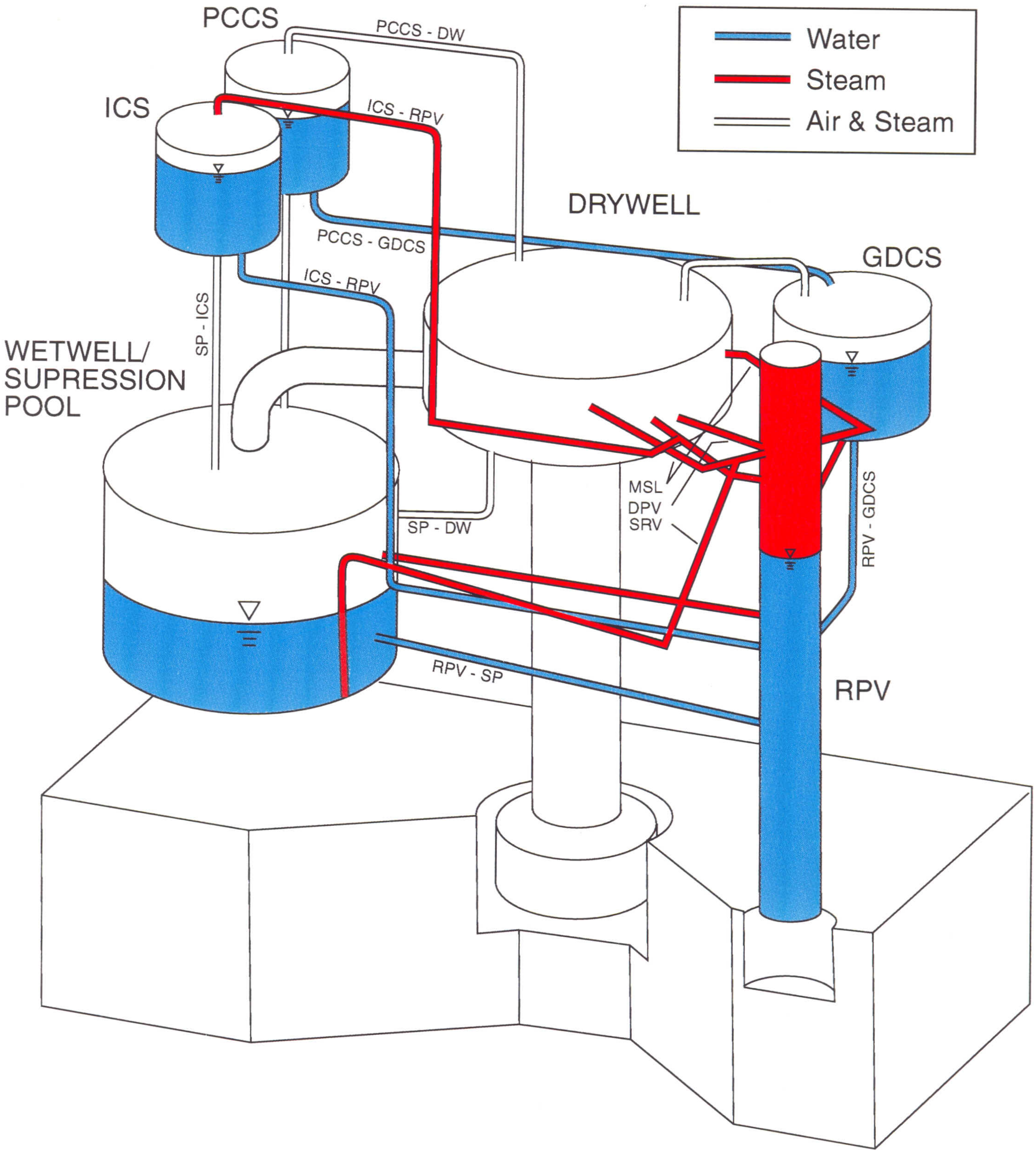
Conclusions (Cont'd)

- Comparison of a RELAP5 Pretest Calculation with PUMA Data

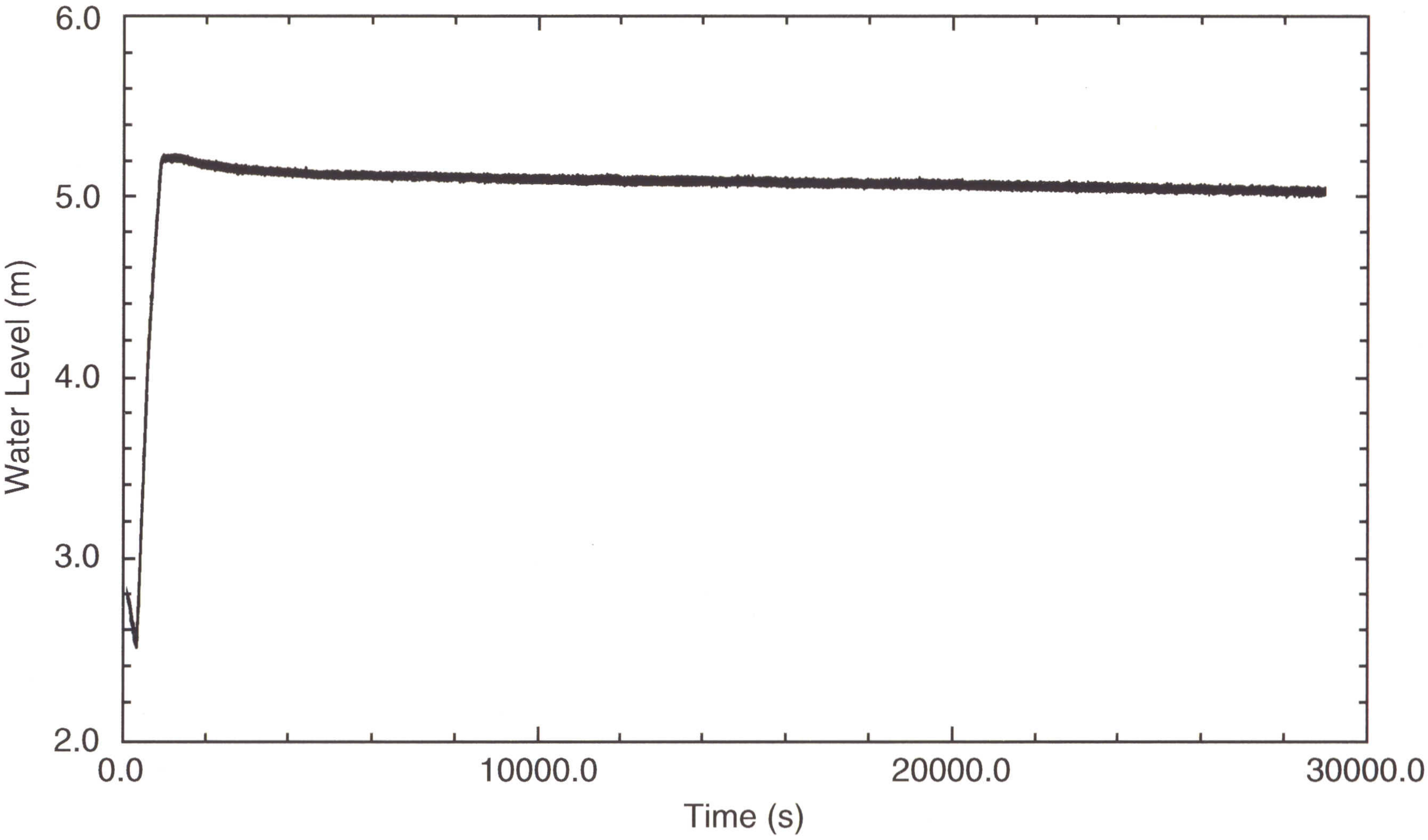
    - Reasonable Agreement Exists between the Calculated RPV Pressure and the Data. However, the Agreement between the Calculated Drywell or Wetwell Pressure and the Data Is Less Than Reasonable.

    - Possible Causes for Discrepancies in Drywell and Wetwell Pressures and Code Deficiencies Have Been Identified for Consideration for Future Improvements.

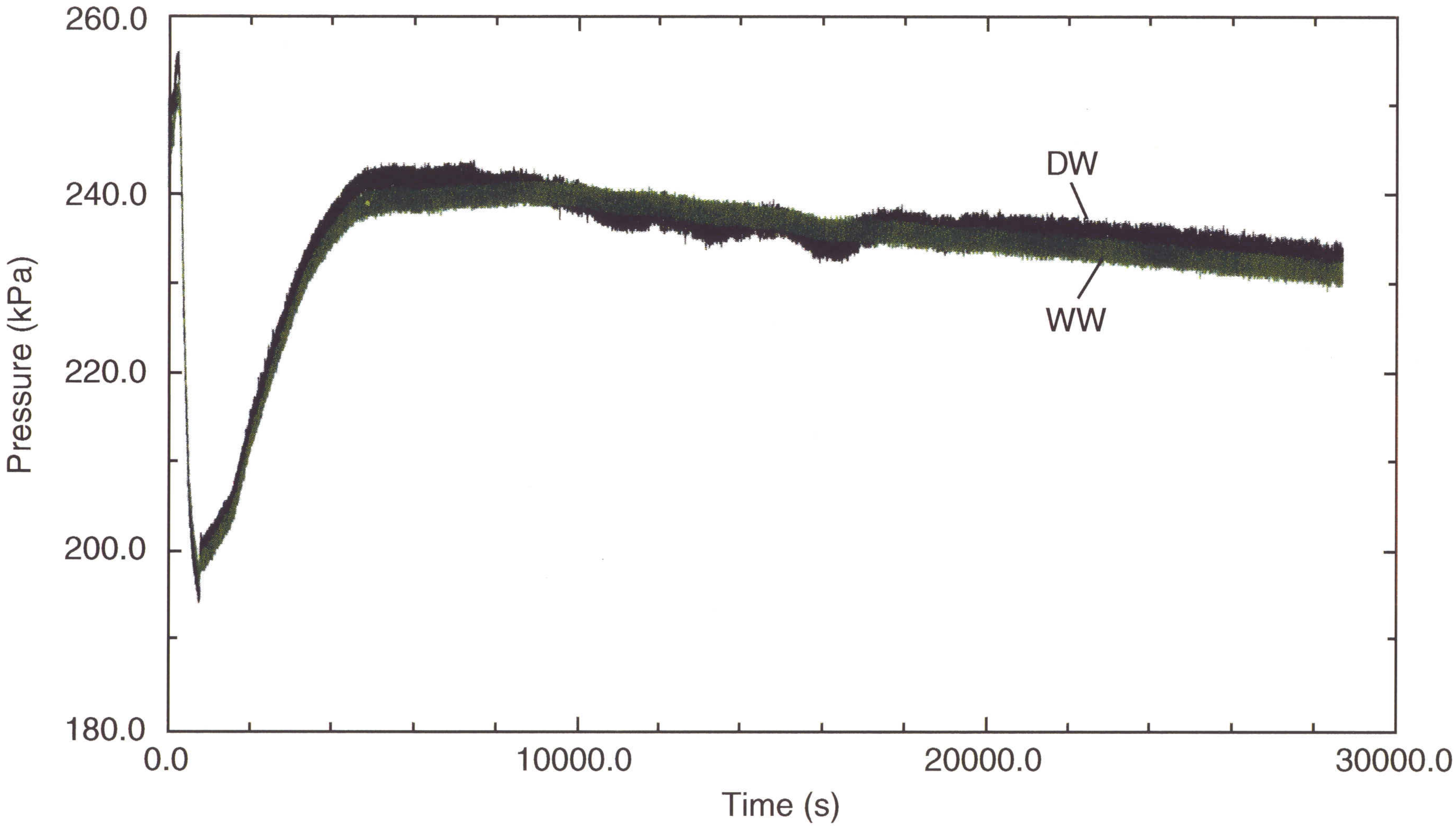
The PUMA Test Facility



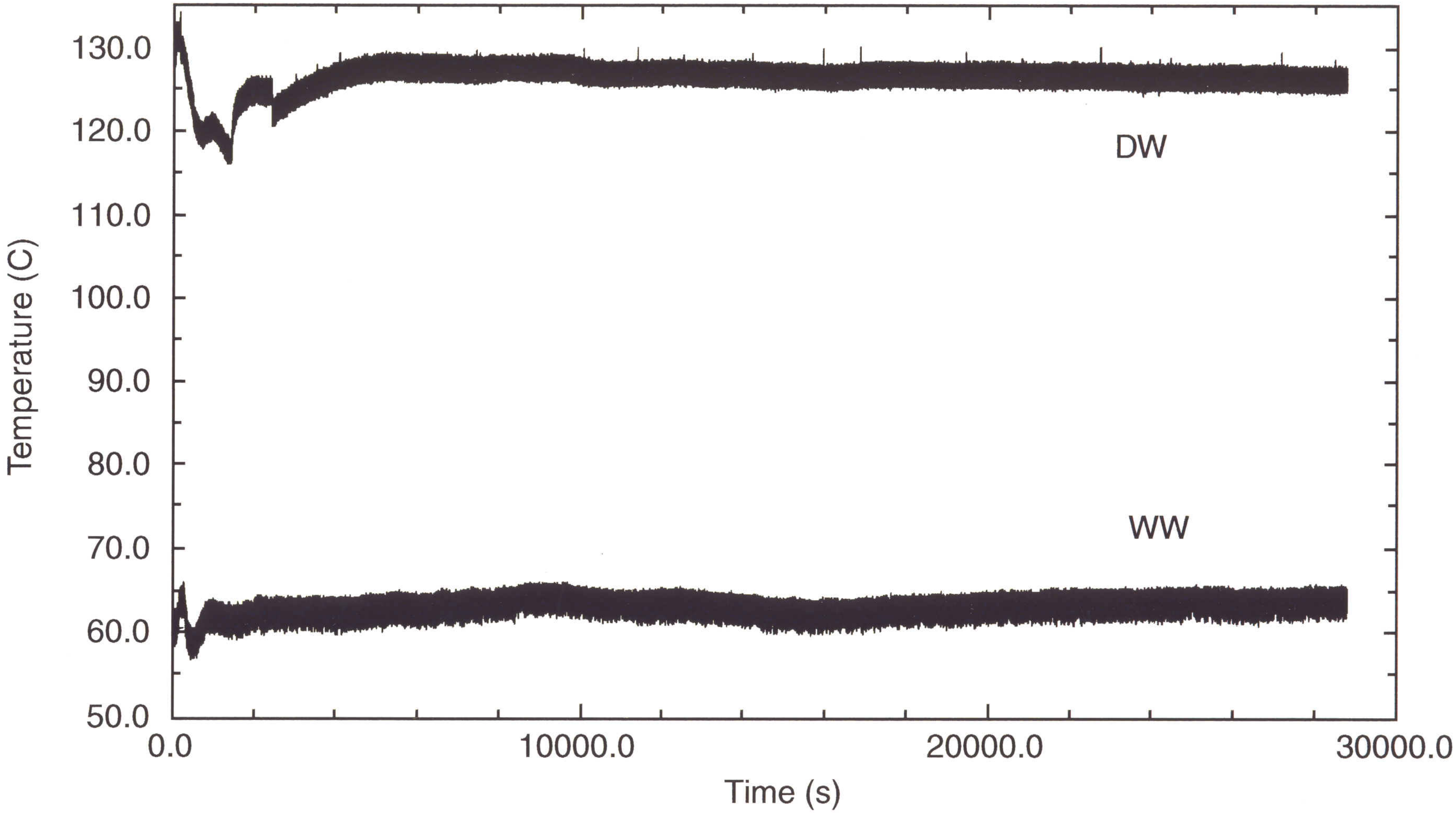
Core Was Always Covered with Water During the 8-Hour Test (Shown is the RPV Collapsed Water Level with Top of the Core at 1.515 m)



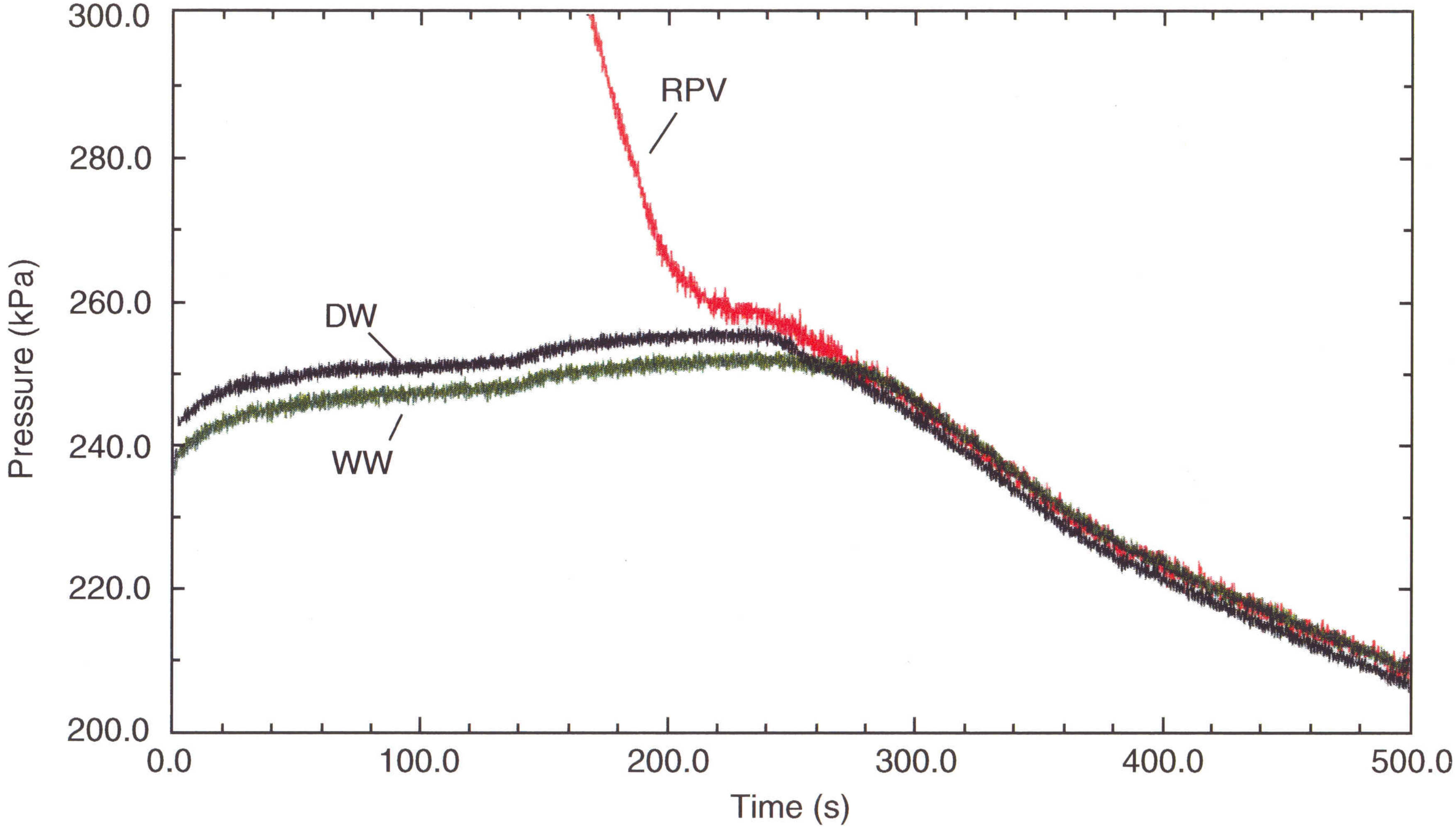
Drywell and Wetwell Pressures Were Well Below the Design Limit of 483 KPa (70 PSIA)



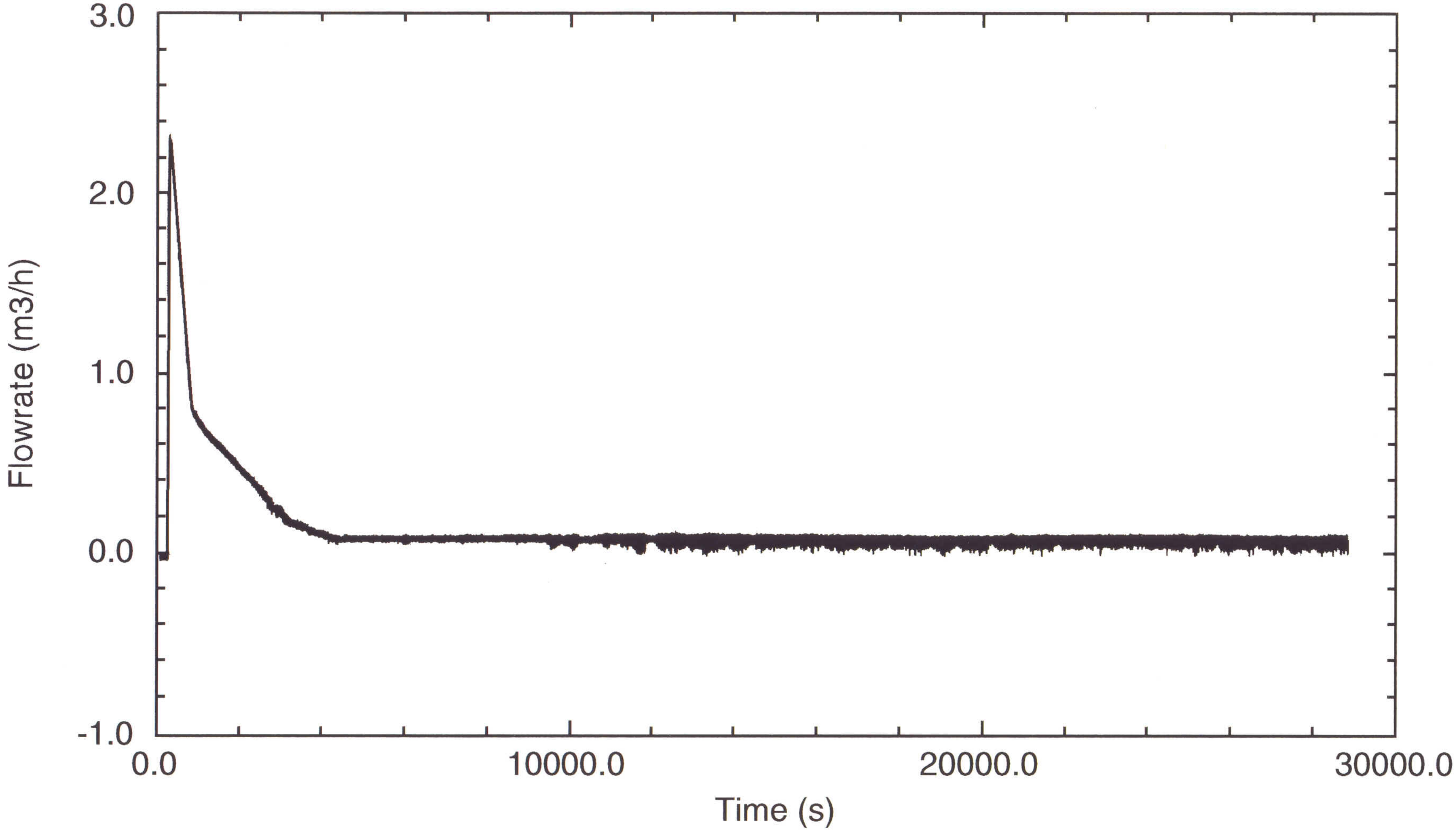
Drywell and Wetwell Temperatures Were Well Below Design Limits (171°C for Drywall, 121°C for Wetwell)



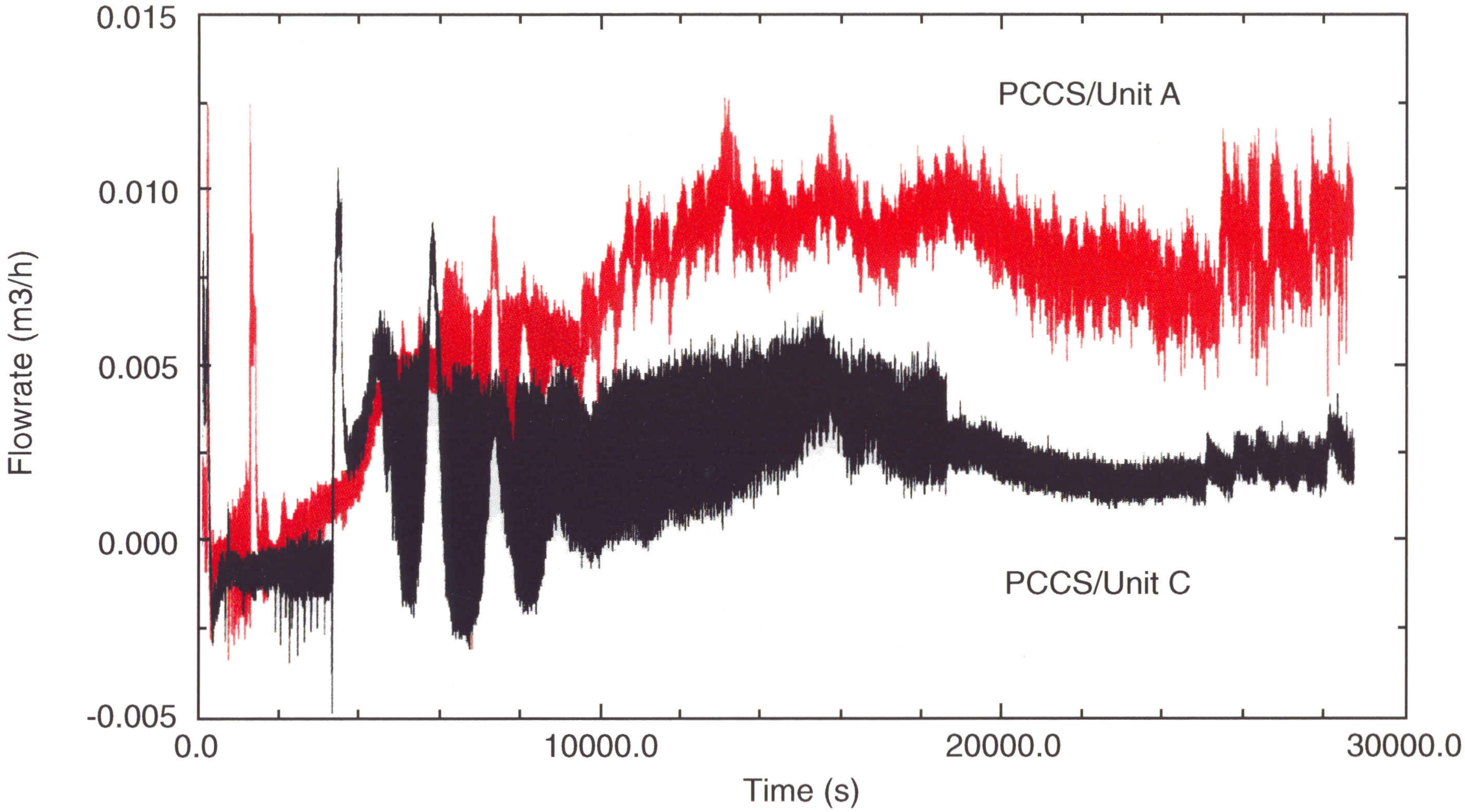
After RPV Blowdown, Pressures in the RPV, Drywell, and Wetwell Came Together and Were Closely Coupled



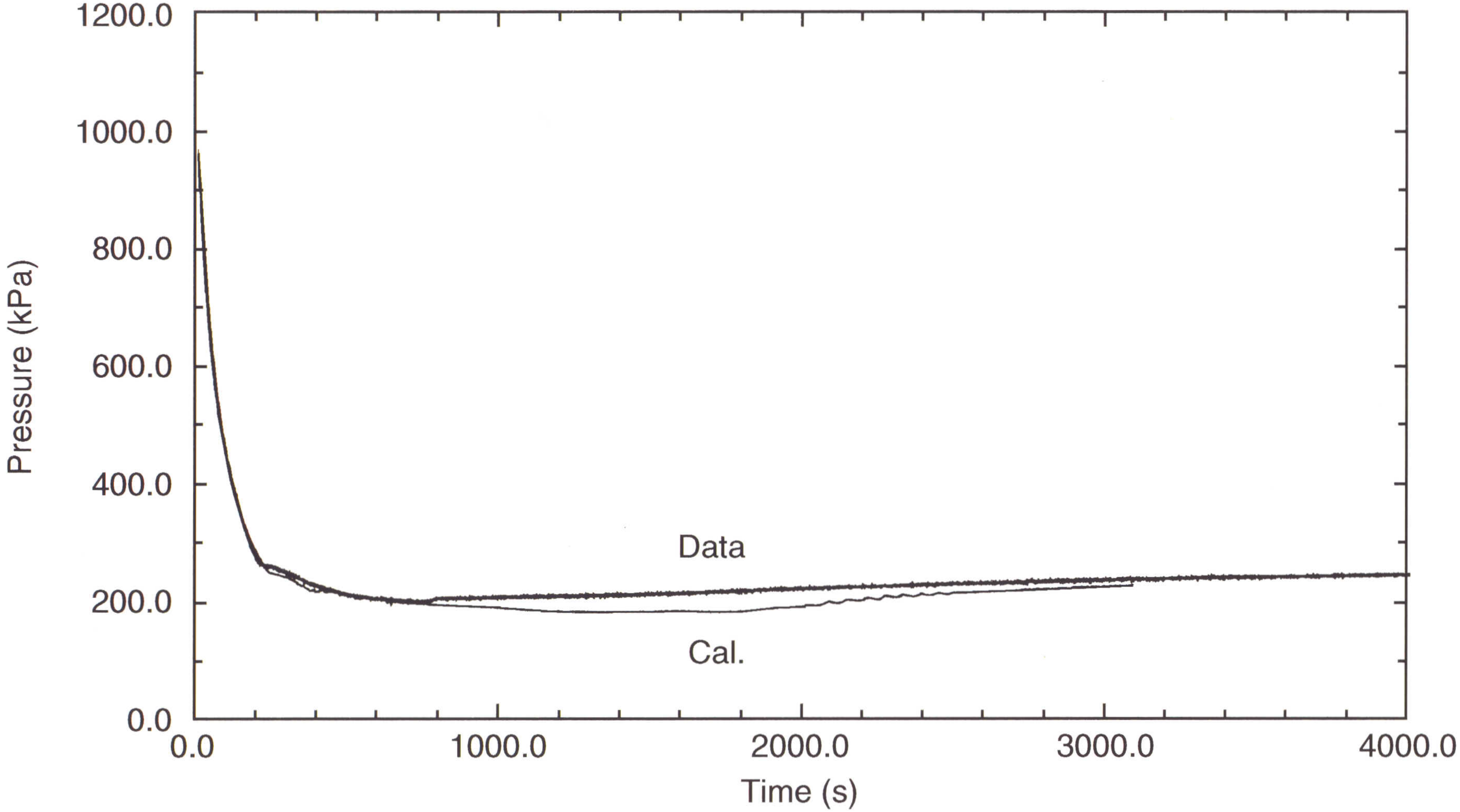
GDCS Injected Water to the RPV at 214 Seconds and Afterwards



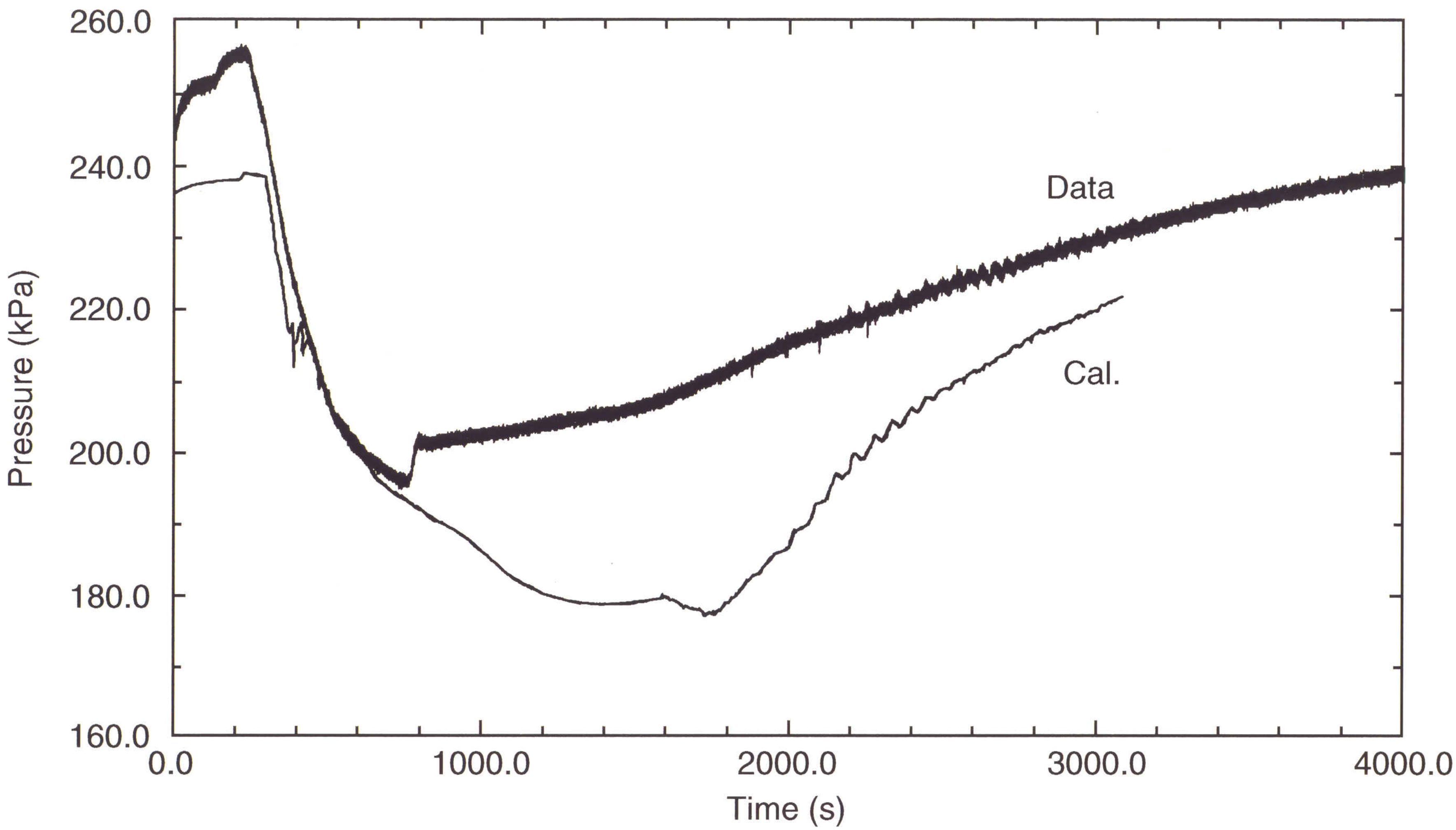
Different Steam Condensation Rates Were Observed in the PCCS Condensers



Comparison of the RELAP5-Calculated RPV Pressure with PUMA Data for A MSLB Test



Comparison of the RELAP5-Calculated Drywell Pressure with PUMA Data for A MSLB Test



Comparison of the RELAP5-Calculated Wetwell Pressure with PUMA Data for A MSLB Test