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SUBJECT: Transmittal of EPRI Report TR-108812, "Response of Isolated Piping to Thermally Induced Overpressurization during a Loss of Coolant Accident (GL96-06)", December 1997

As per your request, enclosed for your information are four copies of the subject non-proprietary EPRI report.

Sincerely,

Avtar Singh
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Y001

EPRI

EPRI TR-108812
White Paper Report
December 1997

Response of Isolated Piping to Thermally Induced Overpressurization during a Loss of Coolant Accident (GL96-06)

Prepared by
Electric Power Research Institute
Charlotte, NC

Response of Isolated Piping to Thermally Induced Overpressurization during a Loss of Coolant Accident (GL96-06)

TR-108812

White Paper Report
December 1997

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REPORT SUMMARY

USNRC Generic Letter GL 96-06 raises the concern that during a postulated Loss of Coolant Accident (LOCA), piping inside containment will be heated beyond its normal operating temperature that would cause water trapped in piping (isolated by closed valves) to expand and challenge pipe integrity. EPRI has performed piping tests which demonstrate that a realistic design margin exists in the existing plant containment penetration systems under the postulated LOCA conditions. This design margin can be used as a basis to justify that plant modifications are unwarranted.

Background

USNRC Generic Letter GL 96-06 issued on September 30, 1996 raises the concern that during a postulated accident condition, piping inside containment will be heated beyond its normal operating temperature. The concern is that water trapped in piping (isolated by closed valves) in the containment penetration systems would expand and potentially challenge pipe integrity. GL 96-06 requires that utilities evaluate affected piping systems and identify long term corrective actions to be taken to comply with the plant's design basis. In order to address the technical issues and to obtain schedule relief from the USNRC in the implementation of plant design modifications, EPRI has performed piping tests to demonstrate the design margin in existing plant configurations.

Objectives

The objectives of this project are as follows:

- To perform a limited testing and analysis effort to establish a credible technical basis that can be brought forward to the NRC in order to obtain schedule relief from the implementation of plant design modifications, and
- To obtain data that can be used to validate non-linear analysis models and acceptance criteria for utility pipe and valve integrity evaluations.
- To establish a technical basis for the support of future ASME Section III strain limits that may be used when evaluating energy controlled conditions.

Approach

Testing involved heating test specimens from ambient temperature to a temperature representative of plant accident conditions (approximately 300- 320° F). The test specimens typically consisted of a section of pipe with end caps (or plates) completely filled with water. In order to eliminate end-cap effects, the specimen straight pipe sections were at least 5 pipe diameters long. The following specimens were tested: Type 304 Stainless Steel, 3-inch NPS schedule 40 pipe, Type 304 Stainless Steel, 3-inch NPS pipe with a schedule 40/80 transition weld, and A106-Gr B Carbon Steel, 8-inch NPS schedule 40 pipe. All welds in the pipe were standard ASME welds. Recorded data included: water pressure and temperature, pipe temperature and dimensional measurements which can be used to determine strains in the pipe. Two hydrostatic burst tests were performed on the 3-inch stainless steel and 8-inch carbon steel pipes to measure the margin to burst.

Results

Four straight pipes, three of 3-inch Stainless Steel and one of 8-inch Carbon Steel, were tested for thermal expansion from 70 to about 320 degree F, except for the carbon steel pipe which was tested to 265 degree F. The maximum hoop strains measured for the uniform thickness pipes were in the range of 2.4 to 2.9%. For the 3-inch Stainless Steel pipe that was of non-uniform thickness (with a Schedule 40/80 transition weld in the middle), the maximum hoop strain measured in the thinner section (Schedule 40 part) was of 5.4%. Elastic-plastic analyses were performed demonstrating good correlation between test and analysis. A simple thermodynamic model was also applied to evaluate the thermal-mechanic behavior. The analysis results confirmed the test measurements. Furthermore, the thermal dynamic model showed that the thermal expansion of the water and the volume increase of the pipe compensate the pressurization of the pipe limiting the maximum pressure built-up for a given temperature increase.

Hydrostatic burst tests were also performed. The burst hoop strain for the stainless pipe was of 36.3% and the carbon steel pipe of 8.7%. Both materials have high ductility with stainless having a much higher ductility margin. Comparing with the thermal expansion temperature controlled behavior (2-3% hoop strain), it is clear that there is sufficient margin that pipe integrity is maintained in a thermally induced overpressurization situation.

EPRI Perspective

This effort is a joint EPRI-industry effort and received support from domestic and international utilities. The issues and concerns raised in GL 96-06 were urgent and anticipated to have an industrywide impact. The EPRI GL 96-06 effort has successfully achieved one of its key goals to provide a basis for obtaining schedule-relief from NRC on mandated plant modifications. NRC has issued on November 13,1997 the Supplement 1 to GL 96-06 which officially allows plants to revise their commitments to plant modifications. The supplement specifically cites- " .....ongoing tests by the Electric Power Research Institute to support a generic resolution of the overpressurization of piping issues", as a basis for the revision to plant commitments. A second major achievement is that NRC has recognized that analytical solutions employing the permanent use of the acceptance criteria contained in the ASME Code, Section III, Appendix F(or other acceptance criteria) may present viable alternatives to plant modifications and can be used where appropriate. The EPRI testing/analysis results provide a viable technical basis for such analysis and acceptance criteria.

The results of this project provide a basis to support those utility personnel involved in resolution of the GL 96-06 issues, specifically the containment penetration piping overpressurization issue, for their nuclear plants.

Interest Categories

Risk and Reliability
Component Reliability
Piping, Reactor Vessel, and Internals

Keywords

Component Integrity
Piping
Piping Thermal Expansion
Piping Overpressurization
Piping Design and Analysis

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1

INTRODUCTION

1.1 Background

NRC Generic Letter (GL) 96-06 raised concerns that during postulated accident conditions, isolated piping inside containment will be heated beyond its normal operating temperature. Expansion of the trapped water is hypothesized to result in pressures in excess of design allowables.

Accordingly, GL-96-06 requested that utilities evaluate the operability of affected piping and identify long-term corrective actions that will be taken in order to comply with the plant's design basis. These corrective actions normally involve implementing hardware and/or procedural modifications designed to relieve the predicted overpressure. From the regulatory point of view, this approach can meet the FSAR plant design basis in a direct manner. However, hardware modifications (for example rupture disks and pressure relief valves) will require capital expense and future maintenance adding burden to assure their reliability and operability. Also, the addition of these relief devices may have a negative effect on initiating event (that is, LOCA) frequencies and plant safety.

On April 30, 1997 the industry met with the NRC. The Staff expressed concerns that many plants were not committing to implement design modification until their next scheduled refueling outages in 1998 and 1999. In the absence of any meaningful data, the Staff indicated that proposed delays beyond one year might not be acceptable. It appeared that, given appropriate test data and supporting analyses, the NRC could reconsider its position.

As an alternative to the rules in NC/ND-3621.2, ASME Section III has proposed strain limit criteria that can be used when evaluating piping pressure increases due to thermal expansion effects when caused by a one-time event for which Service Level C or D limits are applicable. As currently written, Code Case N584 recommends that the strains resulting from these events be limited to a maximum circumferential (hoop) membrane strain of 5%. This code case is currently being reviewed by an ASME Section III project team.

In parallel with ongoing effort by the ASME Section III, EPRI initiated the first of a two-phase testing and evaluation program designed to develop technical methods and criteria utilities can use to justify the long-term operability of existing in-plant containment penetration systems (including pipes and valves) affected by overpressurization caused by external overheating due to postulated LOCA. Non-linear evaluation methods and acceptance criteria (that is, strain limits) were evaluated against the test results of these prototypical piping configurations.

1.2 Purpose

This white paper will present the results of EPRI's Phase 1 Generic Letter 96-06 Testing Program and compare the results against non-linear analytical predictions. These test results will be used to assess the alternative strain limit criteria proposed in the ASME Section III Code Case N584, ***Rules for Evaluating Fluid Thermal Expansion Effects, Section III, Division 1, Class 2 and*** *3.*

It is expected that some issues (not specifically addressed in phase 1) will be raised when these results are reviewed and discussed in the ASME Section III Code Committees and the NRC; however, EPRI believes that the results presented in this white paper will:

1. Establish a credible technical basis that can be brought forward to the NRC in order to obtain schedule relief from the implementation of plant design modifications.

2. Obtain piping response data (that is, pressure, temperature, and strain as a function of time) that may be used to refine the pressure load estimates assumed in prior utility evaluations.

3. Provide a technical basis for the acceptance of future ASME Section III proposed strain limits.

2

EPRI TEST PROGRAM

2.1 General

The phase 1 test program was designed to examine the long-term operability of isolated piping sections inside containment subject to design basis containment environments. For this initial phase, testing was limited to straight pipe sections. Plant specific data on affected piping systems were used to develop generic models for analysis and testing. Testing was performed on both large bore and small bore piping. The plant survey results were used to ensure that the test specimen sizes and materials would be representative of the effected piping in operating PWR and BWR plants. Uniaxial tensile tests were performed on all test specimen materials. Four thermal expansion tests were completed on three different specimen configurations. In addition, hydrostatic burst tests were conducted on one stainless steel and one carbon steel pipe specimen.

2.2 Plant Survey

In this task, plant specific data on effected piping systems were gathered. The survey involved 12 nuclear utilities: 11 domestic utilities and the Korean Electric Power Company (KEPCO). These 12 utilities represent a total of 58 operating nuclear power plants—39 PWR and 19 BWR plants. A summary of the plant survey participants is shown in Table 2-1. Each utility was asked to provide plant specific information regarding: containment temperature and pressure profiles; containment penetration configurations; material information; and isolation valve types, model, and manufacturer. Examples of the survey results are included in Table 2-2.

Table 2-1
Utility Survey Participants

UTILITY	NUMBER SITES	NUMBER PLANTS	PWR	BWR
Commonwealth Edison	6	12	6	6
Centerior	2	2	1	1
Detroit Edison	1	1	0	1
Duke	3	7	7	0
Entergy	4	5	3	2
Niagra Mohawk	1	2	0	2
PECO	2	4	0	4
PG&E	1	2	2	0
PP&L	1	2	0	2
WPPSS	1	1	0	1
Wisconsin Electric	1	2	2	0
KEPRI/KEPCO	4	18	18[1]	0
TOTAL	**27**	**58**	**39**	**19**

NOTE: 1. Four of the 18 KEPCO plants are PHWR.

Table 2-1
Plant Utility Survey

System	Design Temp °F	Design Press psi	Accident Temp °F	Valve Type	Press Class lbs	Size	Material Spec	Material Type	Seamless	Schedule	Insulation	Length	Fittings
CVCS	200	240	N/A	Gate/Globe	150	3	A-351	A312/TP304 SS	Seamless	10S	Cal/Sil 2"	33.18'	Butt welds, LR elbows, welded tees
CVCS	200	240	N/A	Gate/Globe	150	3	A-351	A312/TP304 SS	Seamless	10S	Cal/Sil 2"	33.18'	Butt welds, LR elbows, welded tees
Sampling System	650	2500	N/A	Globe	1500	3/8	A-351	A312/TP304 SS	N/A	.065 "	No	93'	Socket welds
Sampling System	650	2500	N/A	Globe	1500	3/8	A-351	A312/TP304 SS	N/A	.065 "	No	102'	Socket welds
MS Drain	1250	575	340 max	Gate/Gate	900	3	A234 GR WCB	A106 GR B	N/A	160	2-1/2 Cal/Sil/Mirr or	28'	LR elbow
Drywell Floor Drain Sump Pump Discharge Line	140	150	340 max	Gate/Gate	300	3	A216 GR WCB	A106 GR B	N/A	40 and 160	No	~17'	LR elbow
Drywell Equipt Drain Sump Pump Discharge Line	140	150	340 max	Gate/Gate	300	3	A216 GR WCB	A216 GR WCB	N/A	40 and 160	No	~25'	LR elbow
Recirc Samp Line	575	1500	340 max	Globe/Globe/ Globe	1500	¾	A182 F316	A312/TP316 SS	N/A	80 and 160	No	~30'	Socket welds/tee
Recirc Pump Seal Purge B	150	1750	340 max	Globe/Globe	1500	¾	A182 F316	A312/TP304 SS	N/A	80 and 160	No	~50'	Socket welds

Table 2-2 (Continued)
Plant Utility Survey

System	Design Temp °F	Design Press psi	Accident Temp °F	Valve Type	Press Class lbs	Size	Material Spec	Material Type	Seamless	Schedule	Insulation	Length	Fittings
Recirc Pump Seal Purge A	150	1750	340 max	Globe/Globe	1500	¾	A182 F316	A312/TP304 SS	N/A	80 and 160	No	~62'	Socket welds
Radwaste	300	150	270 water	Ball	150	2/2-1/2	SS	A312/TP304 SS	Seamless	40S	Refl. 1"	10.6'	LR elbow, transition at valve (Sch 10)
Radwaste	300	150	270 water	Ball	150	2/2 1/2	SS	A312/TP304 SS	Seamless	40S	Refl. 1"	13"	LR elbow, transition at valve (Sch 10)
Radwaste	300	150	270 water	Ball	150	2/2 1/2	SS	A312/TP304 SS	Seamless	40S	Refl. 1"	23'	LR elbow, transition at valve (Sch 10)
Radwaste	300	150	270 water	Ball	150	2/2-1/2	SS	A312/TP304 SS	Seamless	40S	Refl. 1"	19'	LR elbow, transition at valve (Sch 10)
Condensate Return	135	25	185	Butterfly	150	10	SA-516 GR 70	SA-106	Seamless	40	No	~12'	None
Fuel Pool Cooling	180	50	185	Butterfly	150	10	SA-351 GR CF 8M	SA-106	Seamless	40	No	Est 15'	Elbows
P-311	150	150	185	Butterfly	150	12	SA-516 GR 70	SA-107	Seamless	Std	N/A		
P50	55	150	185	Butterfly	150	6	SA-516 gr70	SA-106	Seamless	40	N/A		
Post Accident Sampling	575	1410	224	Solenoid	N/A	¾	N/A	SA-312/376 TP304	Seamless	80s	N/A	30+'	
Radwaste Sump	200	100	224	Gate	300	3	SA216 GR WCB	SS 304	Seamless	40	N/A		

Table 2-2 (Continued)
Plant Utility Survey

System	Design Temp °F	Design Press psi	Accident Temp °F	Valve Type	Press Class lbs	Size	Material Spec	Material Type	Seamless	Schedule	Insulation	Length	Fittings
Floor Drain Sump	150	100	224	Gate	300	3	SA216 GR WCB	SA-106 GR B	Seamless	40	N/A		
G50	150	125	224	Gate	300	4	SA-216 GR WCB	SA-106	Seamless	40	N/A		
Reactor Water Level to Condenser	150	1410	224	Gate	1500	4	SA-105	SA-106	Seamless	120	2" Fib Glass		
Chilled Water	60	150	Max: 326 (Air)/247 (Sump)	Gate	150	12	SA-106B	SA-106 GR B	Seamless	40		44'	
Sampling System	225	58	Max: 326 (Air)/247 (Sump)	Globe	58	3/8	SS	SS 304	Seamless	40S			
Pressurizer Sample	670	2500	250	Gate	1500	1	SA182 F316	SA376TP316	Seamless	160	None	535"	SW tees, elbows, reducers
CCW	200	150	250	Butterfly	150	12	SA516 Gr 70	SA-106 GR B	Seamless	40	None	484"	Elbows, reducers, tees
CCW	200	150	250	Butterfly	150	12	SA516 Gr 70	SA-106 GR B	Seamless	Std	None	291"	Elbows, reducers, tees
CTMT Normal Sump	210	40	250	Gate	150	4	SA105	SA-106 GR B	Seamless	40	None	197"	Elbows, tees

These results indicated that effected pipe sizes ranged from as small as ¾" NPS to 12" NPS. All piping was seamless. Some utilities identified pipe segments that included transition welds connecting pipes with the same NPS but different thickness schedules. The pipe schedules varied by pipe sizes as shown below:

- ¾"–1" NPS, Schedule 80/160
- 2"–4" NPS, Schedule 40/120/160
- 6"–12" NPS, Schedule 10/40

All small bore piping material was stainless steel Types 304 or 316; however, the material of most all large bore piping was almost exclusively SA106 Grade B carbon steel. The use of insulation varied for large bore pipes. All small bore piping was not insulated.

Based on these survey results, it was decided that the testing scope should include a stainless steel small bore specimen and a carbon steel large bore specimen. Since some utilities had identified the presence of pipe schedule transitions, an additional small bore specimen—with a transition weld in the center—was also included. It was also felt that the transition specimen would be somewhat representative of the material response in the area of the pipe to valve transition. The following pipe configurations were therefore selected:

- 3" NPS SA312 TP304 Stainless Steel—Schedule 40
- 3" NPS SA312 TP304 Stainless Steel—with Schedule 40/80 Transition Weld
- 8" NPS SA106 Grade B Carbon Steel—Schedule 40

2.3 Test Material Properties

Standard tensile tests in ASTM A370 and E8 standards were performed on all test materials. Testing was performed at the University of North Carolina at Charlotte. All tensile tests were performed on an Instron Model TTD universal testing machine with Instron Model 2630-007 extensometer and Instron Type Gr Model 030-20 load cell. All tensile tests were conducted at room temperature and an extension rate of 0.1 in./min. Pipe tensile test coupons were prepared to the fabrication standards specified in ASTM E8. For each pipe material heat, four tensile specimens were tested. Average values were used to develop engineering stress vs engineering strain curves shown in Figures 2-1, 2-2, and 2-3.

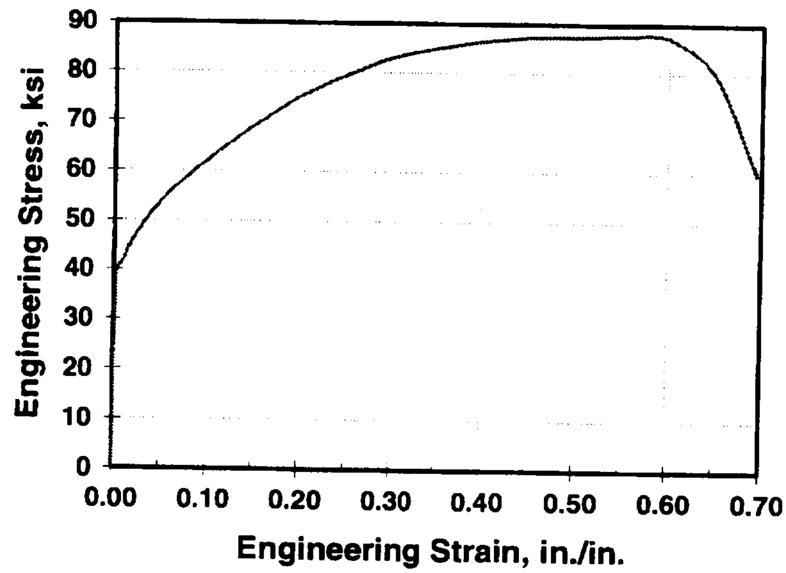

Figure 2-1
3" NPS Schedule 40 SA312 TP304 Stainless Steel

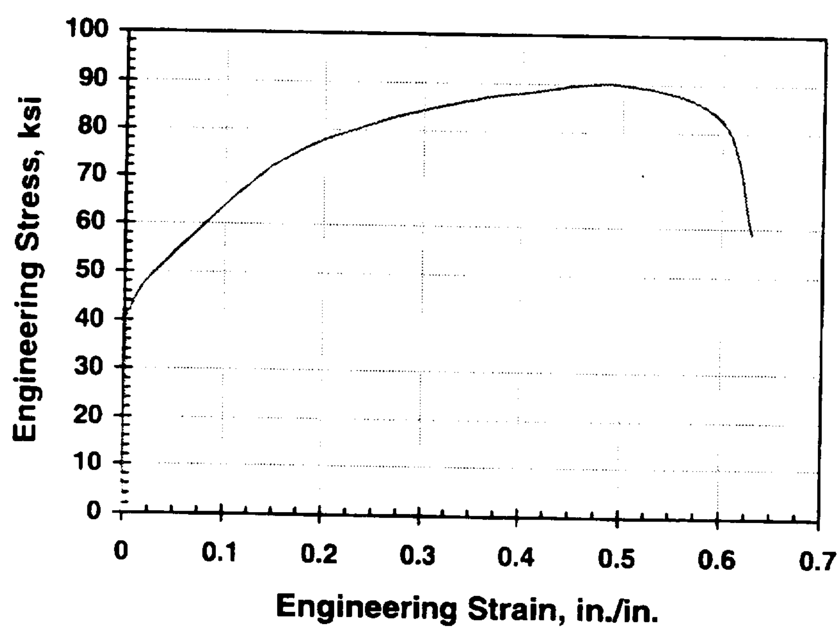

Figure 2-2
3" NPS Schedule 80 SA312 TP304 Stainless Steel

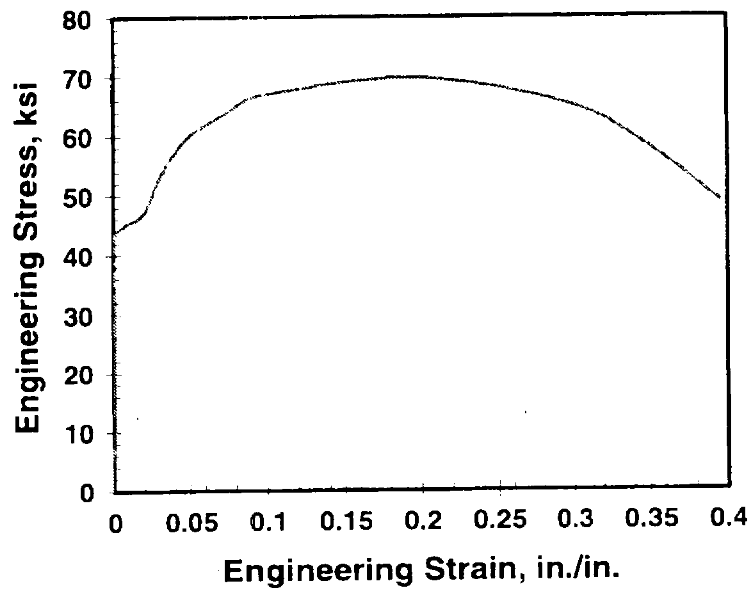

Figure 2-3
8" NPS Schedule 40 SA106 Gr B Carbon Steel

The material properties are summarized in Table 2-3. For stainless steel specimens, the yield strength (S_y) values were determined by the "offset" method and corresponded to the engineering stress at the 0.2% strain offset. As expected, the carbon steel stress-strain results were ragged near the yield point. The average of upper and lower yield strength (engineering stress) values is reported in Table 2-3. The tensile stress (S_u) corresponds to the maximum load sustained by the tensile specimen divided by the original specimen cross-sectional area. Similarly, the fracture strength (S_f) is equal to the load at fracture divided by the original specimen cross-sectional area. Finally, the strain hardening exponent, n, and the strength coefficient, K, in the plastic region was determined in order to support the data analyses performed in Section 3.0 and Section 4.0.

Table 2-2
Tensile Test Material Properties

Pipe Size	Material	Heat #	S_y	S_u	S_f	E	n	K
			psi	psi	psi	psi		psi
3" Sch 40	SS	807038	38,666	87,728	59,956	28.3E6	0.427	191,521
3" Sch 80	SS	SF224	40,239	89,197	58,889	30.6E6		
8" Sch 40	CS	Y46513	42,520	69,656	48,942	28.3E6	0.182	106,000

Unixial engineering strain and true strain values at maximum load (ultimate load) and fracture are shown in Table 2-4 below.

Table 2-3
Uniaxial Tensile Test Ultimate and Fracture Strains

Pipe Size	Material	Heat #	Engineering Strain (in./in.)		True Strain (in./in.)	
			Ultimate	Fracture	Ultimate	Fracture
3" Sch 40	SS	807038	0.533	0.693	0.427	0.527
3" Sch 80	SS	SF224	0.500	0.630	0.405	0.488
8" Sch 40	CS	Y46513	0.200	0.395	0.182	0.332

2.4 Test Specimens

The Phase 1 test specimens for thermal expansion and hydrostatic burst tests were fabricated from seamless A106 Gr B carbon steel or Type 304 stainless steel. All welds in the pipe were prepared and inspected to ASME Boiler and Pressure Vessel Code, Section III standards. In order to ensure that the straight pipe section remained limiting, pressure transducers and thermowells were mounted on the end caps. An example 3" NPS pipe test specimen configuration is shown in Figure 2-4.

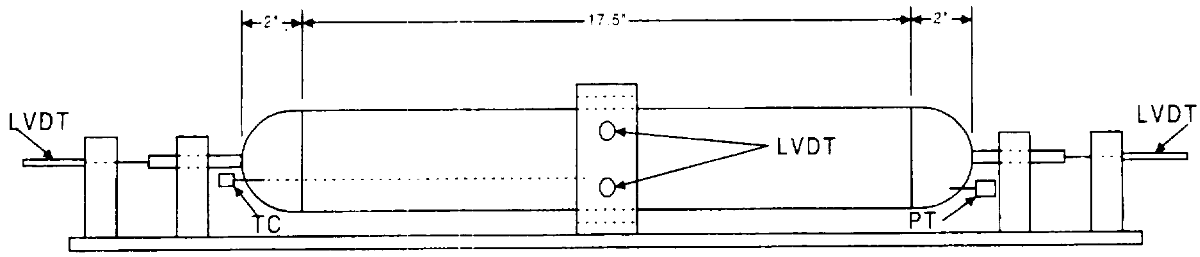

Figure 2-4
3" NPS Test Specimen Configuration

2.4.1 Specimen Fabrication

In order to be sure that all end cap restraint effects are removed, the specimens were at least 5 diameters in length. In the case of the Schedule 40/80 specimen, each straight pipe section was two and a half diameters in length. Finite element analyses were used to confirm that these dimensions were adequate to eliminate end cap effects. The ends of each pipe segment were prepped and cleaned to accommodate access for a full penetration welds. The recommended bevel angle was 37 1/2 degrees.

End cap weld preparation was performed to the same requirements as the pipe section ends. Instrument penetration holes were drilled in end caps to accommodate water inlet, bleed off, thermocouple, and pressure transducer taps. Instrument attachments were welded to the end caps and tested by dye penetrant and radiography. Instrumentation welds were made prior to assembling the end caps to the pipe. Grinding and polishing of the weld metal was performed to ensure a smooth transition of the weld metal to the end cap base metal. A visual inspection of the ID surface was done to verify weld integrity.

When joining of the end caps, the root pass of the weld was made with the gas tungsten arc welding (GTAW) process. The remainder of the weld was completed with shielded metal arc welding (SMAW) electrodes. The filler material types were 70 series weld metal for the SA106 carbon steel specimen and 308 series for the SA312 stainless steel specimens. End cap to pipe attachment welds were inspected via PT and RT afterwards.

The 3" Schedule 40/80 transition was fabricated to ASME Section III Code transition angle requirements on the mating end of the Schedule 80 pipe segment. A taper of 3 to 1 was made on a lathe prior to welding the two segments together. The joining weldment was located in the center of the test specimen. The root pass was made using GTAW and the remainder of the weld was completed with SMAW. A post weld inspection with RT was performed.

2.4.2 Test Instrumentation

The data acquisition instruments used during testing include Type K thermocouples for temperature monitoring, LVDTs for measurement of radial and axial displacement, pressure transducers, and a PC-based acquisition system for high speed data gathering. Four LVDTs were positioned at 90 degree increments around the perimeter and centered about the length of the pipe. Two additional LVDTs were placed at both ends of the specimen to monitor any axial displacement. A thermowell with a Type K thermocouple was located inside the specimen to monitor actual bulk water temperature. Additional thermocouples were mounted on the outside surface of the specimen in order to monitor pipe metal temperature for comparison with water temperatures. A pressure transducer was mounted to the end cap opposite of the thermowell.

2.5 Thermal Expansion Tests

2.5.1 Test Method

After the test specimen was assembled, it was located in a protected area and placed on a raised surface in a to allow for instrument access and insulation clearance. The specimen was filled with water, vented to remove entrained air, wrapped in surface ceramic heaters, and insulated. The specimen surface heaters were connected to a portable controller. All LVDTs and pressure transducers were zeroed just prior to the start of the test.

Data acquisition and the temperature ramp began simultaneously. Thermal loading occurred in incremental temperature steps until the maximum temperature is reached. At each temperature step, the specimen was allowed to reach an equilibrium condition. This ensured a maximum strain at each pressure-temperature state. The results at each equilibrium point were evaluated and compared to finite element model predictions prior to proceeding to the next temperature step. Equilibrium was established when the following conditions were satisfied:

- water and metal temperatures constant and within 3-4°F
- pressure constant
- no radial or axial displacement

A maximum target temperature was established prior to test initiation. This temperature was based on maximum postulated accident temperatures reported in the utility survey. Although survey data indicated that the maximum containment temperature could be as high as 340°F, we were forced to limit test temperature to the maximum rating of the pressure transducers, 325°F. As it turned out, the data was very good and could be extrapolated to the higher temperature, if necessary.

2.5.2 Test Results

In all thermal expansion tests, the radial plastic deformation was limited to the straight pipe section of the specimen. For the uniform thickness specimens (Pretest, Tests 1, and Test 3), the radial dilation was relatively uniform along the majority of the pipe segment length. In the case of the case of the Schedule 40/80 transition specimen (Test 2), essentially all the radial distortion occurred in the thinner Schedule 40 section. The radial distortion in the thicker Schedule 80 section was insignificant. In all cases, no significant radial plastic deformation was observed in the immediate vacinity of the pipe-to-end cap welds or pipe-pipe schedule transition weld. Axial plastic deformation observed at each end cap.

Test data showing pressure and hoop strain as a function of water temperature are shown in Figures 2-5 through 2-10. Final temperature, pressure, and hoop strain are summarized in Table 2-5 below.

Table 2-4
Thermal Expansion Test Results

Test	Pipe Size	Material	Temperature	Pressure	Hoop Strain
			°F	psi	%
Pretest	SA312 TP304	3" Sch 40	305	5400	2.4
Test 1	SA312 TP304	3" Sch 40	323	5700	2.9
Test 2	SA312 TP304	3" Sch 40/80	315	5900	5.4
Test 3	SA106 Gr B	8" Sch 40	265	4800	2.6

Table 2-6 shows the extrapolated the pressure and hoop strain results from Figures 2-5 through 2-10 at a water temperature of 340°F.

Table 2-2
Extrapolated Thermal Expansion Test Results at T = 340°F

Test	Pipe Size	Material	Temperature	Pressure	Hoop Strain
			°F	psi	%
Test 1	SA312 TP304	3" Sch 40	340	5800	3.3
Test 2	SA312 TP304	3" Sch 40/80	340	6200	6.1
Test 3	SA106 Gr B	8" Sch 40	340	5900	4.6

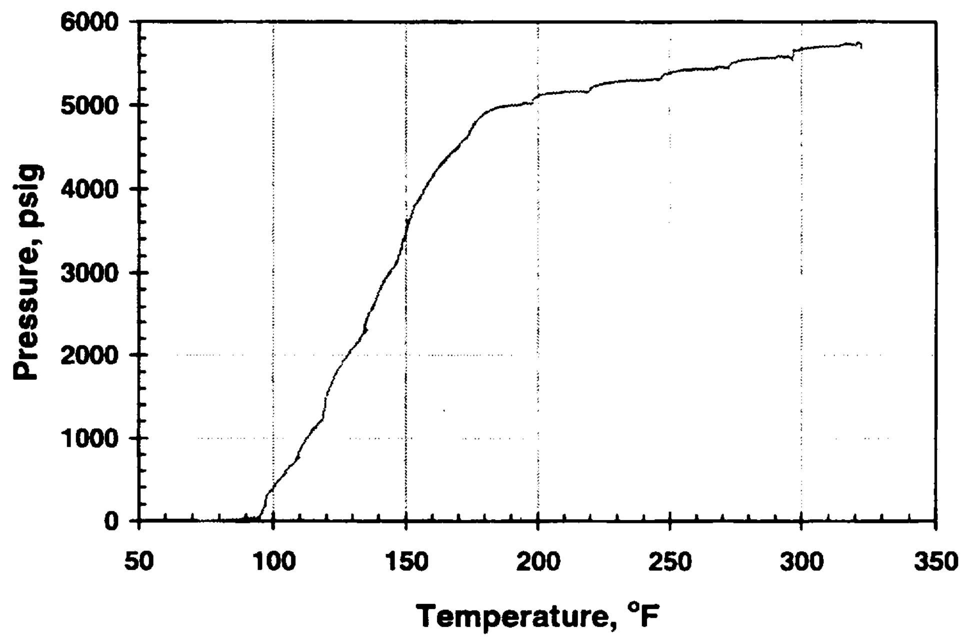

Figure 2-5
Test 1—Pressure vs Temperature

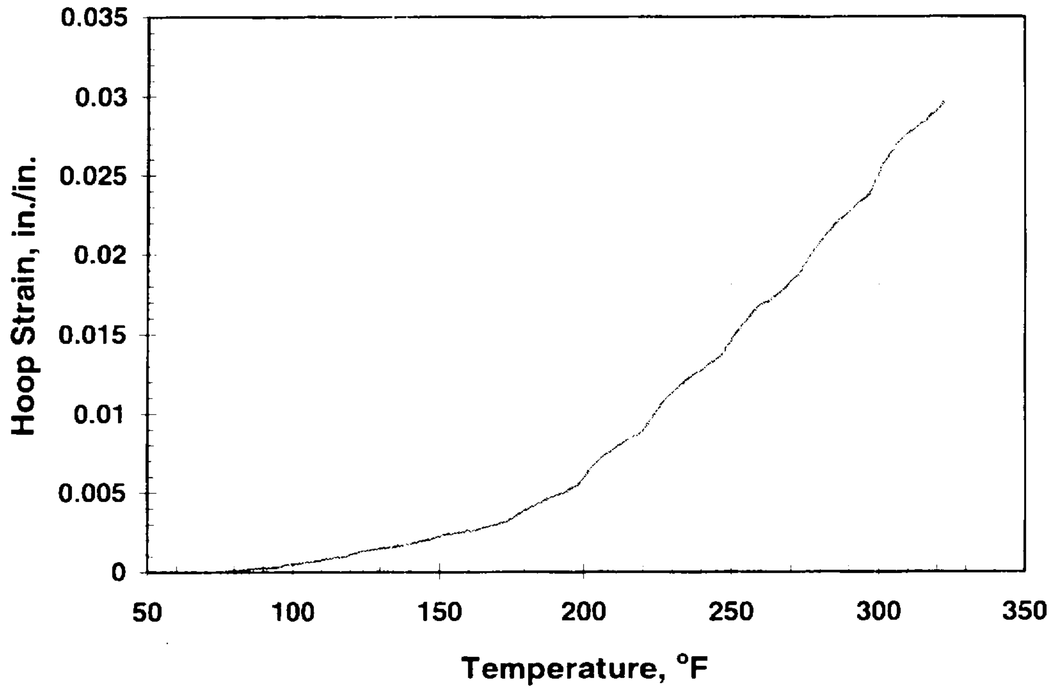

Figure 2-6
Test 1—Hoop Strain vs Temperature

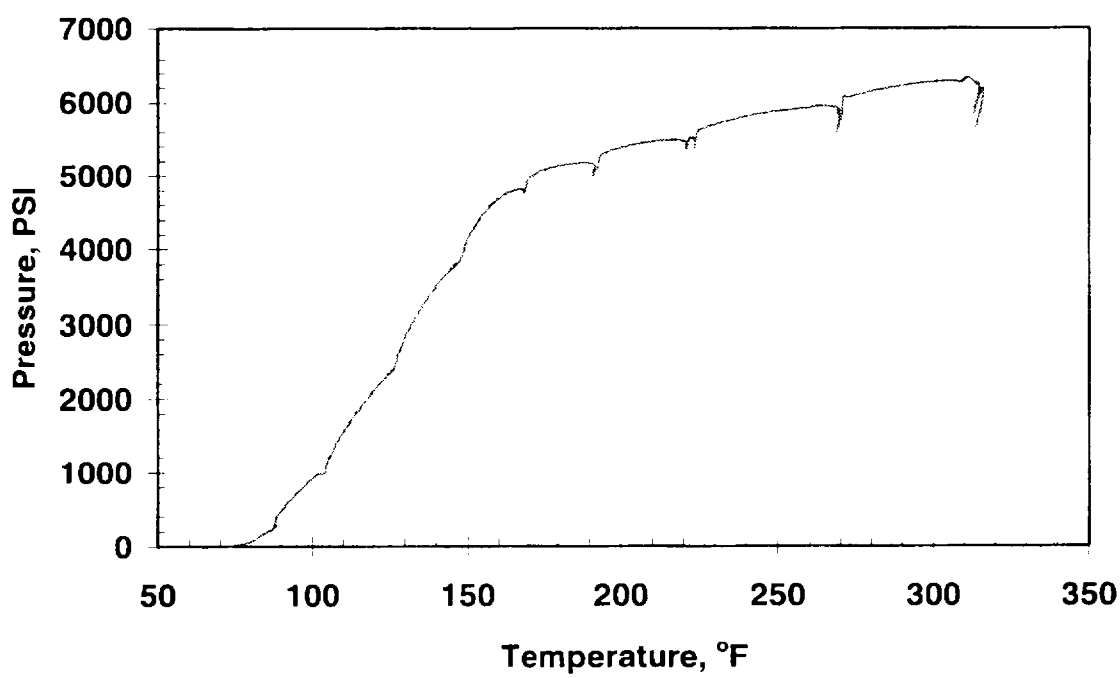

Figure 2-7
Test 2—Pressure vs Temperature

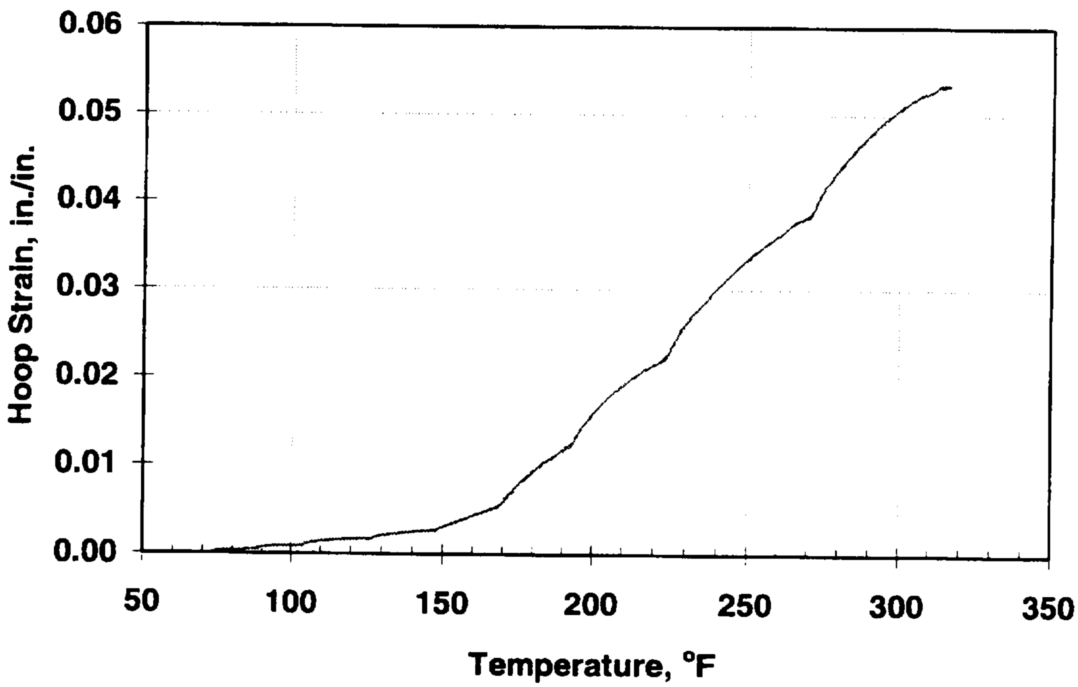

Figure 2-8
Test 2—Hoop Strain vs Temperature

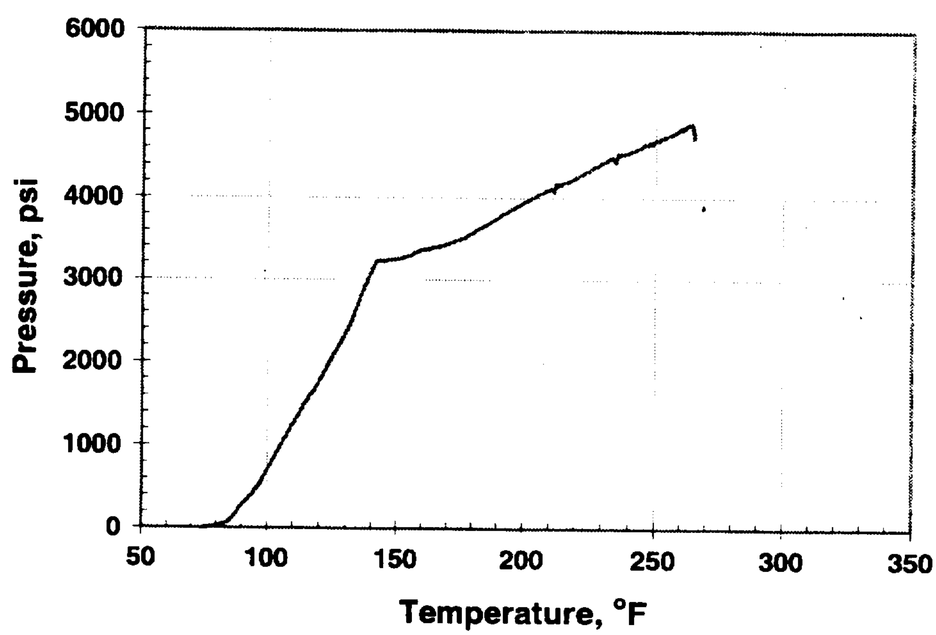

Figure 2-9
Test 3—Pressure vs Temperature

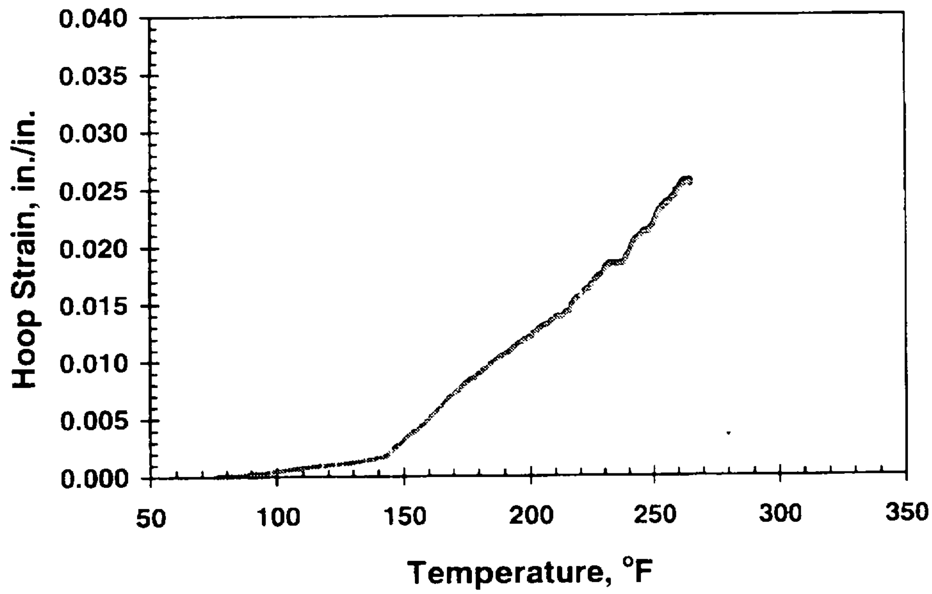

Figure 2-10
Test 3—Hoop Strain vs Temperature

2.6 Hydrostatic Burst Tests

Hydrostatic burst tests were performed on the following specimens:

- SA312 TP304 Stainless Steel, 3" NPS Schedule 40 pipe
- SA106-Gr B Carbon Steel, 8" NPS Schedule 40 pipe

Both burst test specimens were fabricated with the same heat material and dimensions as the corresponding thermal expansion test specimen. All burst tests were conducted at room temperature. The results are shown in Table 2-7 and Figures 2-11 and 2-12.

Table 2-5
Hydrostatic Burst Test Results

		Calculated Burst Pressure			Test	
Pipe Size	**Material**	**Harvey**[1]	**Roark**[2]	**Cooper**[3]	**Burst Pressure**	**Burst Hoop Strain**
3" Sch 40	SA312 TP304	9,637 psi	9,150 psi	10,435 psi	9,220 psi	36.3%
8" Sch 40	SA106 Gr B	5,412 psi	5,293 psi	5,650 psi	6,526 psi	8.7%

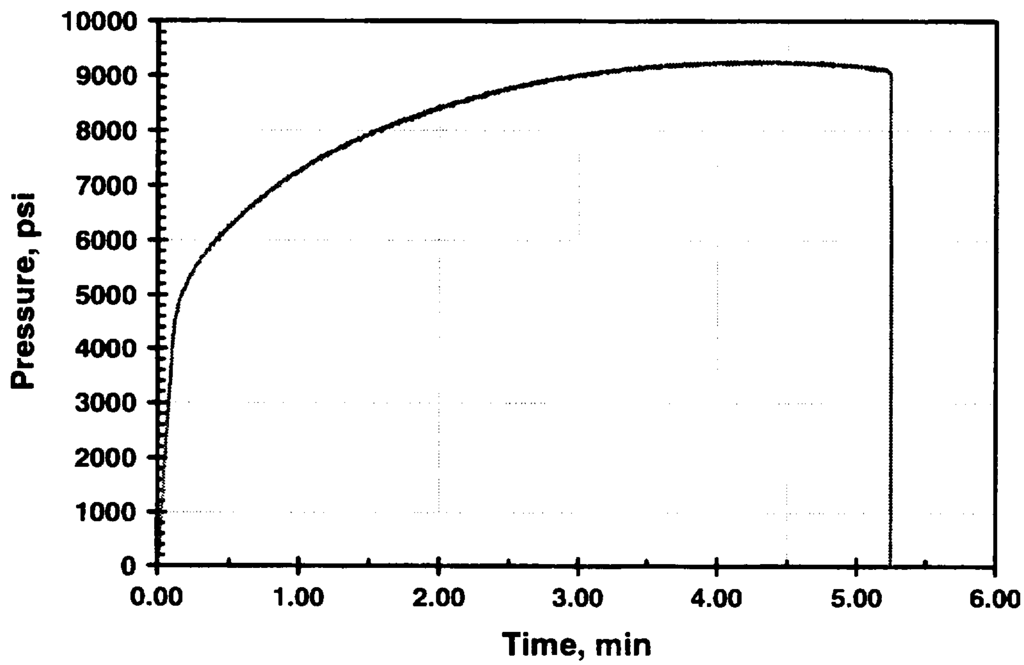

Figure 2-11
Stainless Steel Burst Test

[1] Harvey, "Pressure Component Construction...*design and materials application*", Van Nostrand Reinhold, 1980.

[2] Roark and Young, "Formulars for Stress and Strain", 5th Edition, McGraw Hill, 1975.

[3] Cooper, W. E., "The Significance of the Tensile Test to Pressure Vessel Design", Welding Research Supplement, ASME, January 1957.

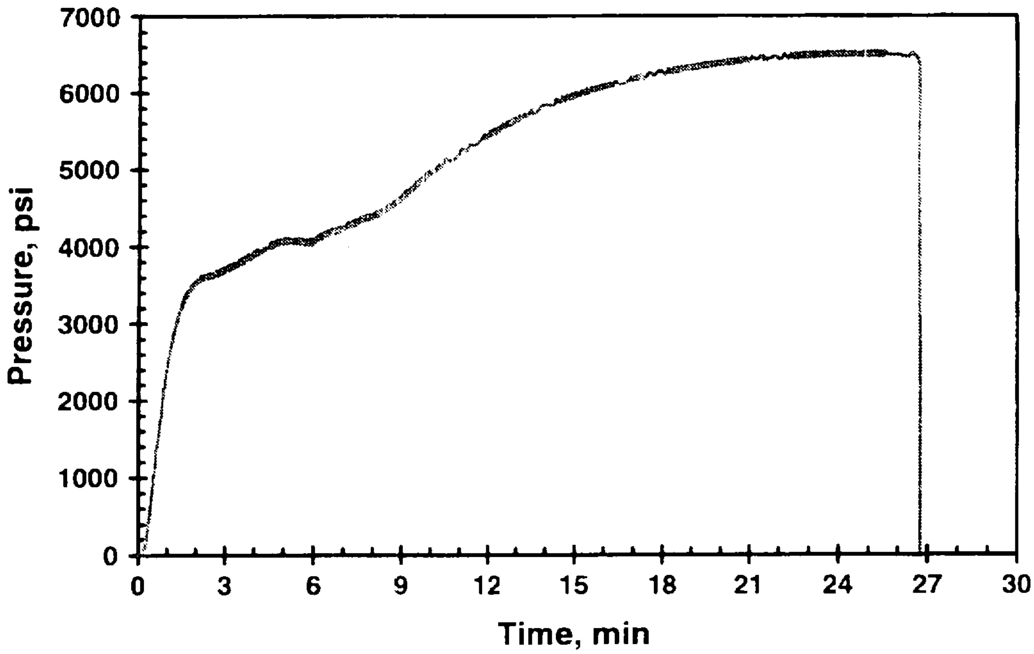

Figure 2-12
Carbon Steel Burst Test

3

DATA ANALYSIS

In any plant specific evaluation, the analyst will need to estimate the pipe internal pressures and strains resulting from the design basis accident containment temperature profile. In doing so, the analyst must be able to relate the thermodynamic response of the water with the structural material response of the pipe. In this section, thermodynamic and structural models are used to examine these aspects. The response predictions for each model are compared with the thermal expansion test results in Section 2.5.2. Plant specific assessments will need to couple both models. The procedures for this are not included in this paper.

3.1 Thermodynamic Analysis

A simple thermodynamic model representing the test configuration is considered to evaluate the test results and thereby provide insights on the thermo-mechanical interaction of the system tested. The simplified model and analysis assume that the water trapped inside the pipe will remain single phase under the temperature range tested, and the system undergoes an infinitesimal process from an initial state of equilibrium to another.

3.1.1 Thermodynamic Model

For a simple thermodynamic system subject to temperature and volume increase, the following equation holds

$$\Delta P = (\beta/\kappa)\,\Delta T - (1/\kappa)\,(\Delta V/V) \qquad \text{(Eq. 1)}$$

where ΔP denotes pressure increase, ΔT denotes temperature increase, ΔV denotes volume increase of the water, β denotes volume expansivity of water, and κ denotes isothermal compressibility of water.[1]

[1] Zemansky, M. W., "Heat and Thermodynamics, *An Intermediate Textbook*", Fifth Edition, McGraw Hill, N.Y., 1966.

The first term on the right hand of the equation is associated with pressure increase due to temperature increase under a fixed volume condition. This means that if the pipe tested is infinitely rigid, thermal expansion of water will result in pressure increase of the quantity $(\beta/\kappa)\ \Delta T$. The second term on the right hand of the equation, $-(1/\kappa)(\Delta V/V)$, is associated with pressure decrease due to volume expansion at a given temperature (an isothermal condition). Thus, one can visualize that the deformability of the pipe during thermal expansion of trapped water inside the pipe will result in a depressurization effect.

It is important to note that Equation 1 is valid only for an energy-controlled condition or temperature driven system. In a load-controlled system, the deformation at a given temperature is governed by structural mechanics consideration without consideration for any thermo-mechanical interaction.

3.1.2 Straight Pipe Uniform Thickness

For a straight pipe of length L and diameter r, the total volume expansion due to delta increase of r, Δr, can be expressed as:

$$\Delta V = \pi\,(r + \Delta r)^2\,L - \pi\,r^2 L \qquad \text{(Eq. 2)}$$

Neglecting second order terms, Equation 2 becomes

$$\Delta V = (2\pi\,r\Delta r)L \qquad \text{(Eq. 3)}$$

Since the hoop strain of the pipe is defined by $\Delta r/r$, from Equation 3, the hoop strain and volume expansion is related by

$$\Delta V/V = 2\varepsilon_h \qquad \text{(Eq. 4)}$$

where $V = \pi r^2 L$ is the original volume and $\varepsilon_h \sim \Delta r/r$

3.1.2.1 Straight Pipe Non-uniform Thickness

For pipe with part of the length of Schedule 40 and part of the length of Schedule 80, assume conservatively that only the thinner schedule portion will deform due to temperature increase. Under this assumption and following the derivation discussed in Section 3.1.2, the hoop strain and volume expansion relationship is as follows:

1. If the thinner section length is equal to 1/2 of total length, then

$\Delta V/V = \Delta r/r = \varepsilon_h$

2. If the thinner section length is equal to 1/4 of total length, then

$\Delta V/V = (1/2)(\Delta r/r) = (1/2)\varepsilon_h$

3.1.3 Test and Analysis Correlation

For temperature range between 68°F to 320°F or 20°C–160°C, the average values of β/κ and κ for Equation 1 are:

β/κ ~ 12.4 atm /°C

κ ~ 0.475×10^{-4} atm^{-1}

Strictly speaking, Equation 1 needs to be integrated or calculated iteratively. For simplicity, average values are used in applying Equation 1 directly to the increment of temperature between 20°C–160°C.

With subscript m denoting measured quantities and c denoting calculated quantities, the following correlation analyses were performed:

3.1.3.1 Pretest: 3" Sch 40 Stainless Steel

$\Delta P_m = 381$ atm, $\Delta T_m = 130$°C

$\varepsilon_{hm} = 0.024$

$(\Delta V/V)_c = (12.4 \times 130 - 381) \times .475 \times 10^{-4} = 0.058 = 2\,\varepsilon_{hc}$

$\varepsilon_{hc} = 0.029$

3.1.3.2 Test 1: 3" Sch 40 Stainless Steel

$\Delta P_m = 388$ atm; $\Delta T_m = 140$ °C

$\varepsilon_{hm} = 0.029$

$(\Delta V/V)_c = (12.4 \times 140 - 388) \times .475 \times 10^{-4} = 0.064 = 2\, \varepsilon_{hc}$

$\varepsilon_{hc} = 0.032$

3.1.3.3 Test 2: 3" Schedule 40/80 Transition

$\Delta P_m = 401$ atm; $\Delta T_m = 136\ ^{\circ}C$

$\varepsilon_{hm} = 0.054$

$(\Delta V/V) = (12.4 \times 136 - 401) \times .475 \times 10^{-4} = 0.061 = \varepsilon_{hc}$

$\varepsilon_{hc} = 0.061$

3.1.3.4 Test 3: 8" Sch 40 Carbon Steel

$\Delta P_m = 326$ atm; $\Delta T_m = 108^{\circ}C$

$\varepsilon_{hm} = 0.026$

$(\Delta V/V)_c = (12.4 \times 108 - 326) \times .475 \times 10^{-4} = 0.048 = 2\, \varepsilon_{hc}$

$\varepsilon_{hc} = 0.024$

Comparing measured and calculated hoop strains, all cases show excellent test and analysis correlation.

3.1.4 Bounding Analyses

As discussed previously, the pressure change resulting from the water temperature increase in a confined system, can be compensated by the volume expansion of the confinement structure—pipe. The extent of structural expansion will be dependent on the pipe's material properties. This will be examined in Section 3.2. Theoretically, the maximum structural expansion would occur when the confined water is allowed to expand freely with no resulting increase in pressure. To visualize this limiting condition, we assume that $\Delta P = (\beta/\kappa)\Delta T - (1/\kappa)(\Delta V/V) = 0$, or $\beta\Delta T = \Delta V/V$. Therefore, for $\Delta T = 140^{\circ}C$, substituting the β values defined above, one can calculate that the limiting condition leading to total depressurization for the uniform schedule straight pipe is

$\Delta V/V = 0.082 = 2\varepsilon_h$

$\varepsilon_h = 0.041$

If half of the pipe is much thicker that the other half, then

$\Delta V/V = 0.082 = \varepsilon_h$

$\varepsilon_h = 0.082$

The physical meaning of this limiting condition is that if the material mechanical property of the pipe is such that the themo-mechanical interaction associated with temperature-pressure increase from 20°C–160°C results in 4.1% hoop strain for the uniform thickness pipe, the delta increase of pressurize will be zero, totally compensated by pipe volume expansion. If half of the pipe does not experience any deformation, then the limiting hoop strain will be 8.2%. Since stainless steel and carbon steel do not have the mechanical property to reach the limiting state, the final equilibrium state observed in the tests is such that there exists a finite amount of pressure and the hoop strain is smaller than the limiting bonding hoop strain calculated here (2-3% versus 4%).

3.2 Structural Non-Linear Analysis

3.2.1 Structural Model

3.2.1.1 Uniform Pipe Thickness

The relationship between stress and strain for an ideal plastic solid, where elastic strains are negligible, can be represented by the Levy-Mises equations:[2]

$$d\varepsilon_1 = \frac{d\bar{\varepsilon}}{\bar{\sigma}}\left[\sigma_1 - \frac{1}{2}(\sigma_2 + \sigma_3)\right] \qquad \text{(Eq. 5a)}$$

[2] Dieter, "Mechanical Metallurgy", Third Edition, McGraw Hill, 1986.

$$d\varepsilon_2 = \frac{d\bar{\varepsilon}}{\bar{\sigma}}\left[\sigma_2 - \frac{1}{2}(\sigma_3 + \sigma_1)\right] \qquad \text{(Eq. 5b)}$$

$$d\varepsilon_3 = \frac{d\bar{\varepsilon}}{\bar{\sigma}}\left[\sigma_3 - \frac{1}{2}(\sigma_2 + \sigma_1)\right] \qquad \text{(Eq. 5c)}$$

where:

$$d\varepsilon_1 + d\varepsilon_2 + d\varepsilon_3 = 0 \qquad \text{(Eq. 6)}$$

From strength of materials for a pressurized thin wall cylinder,

$$\sigma_1 = \frac{Pr}{t} \qquad \text{(Eq. 7a)}$$

$$\sigma_2 = \frac{Pr}{2t} = \frac{\sigma_1}{2} \qquad \text{(Eq. 7b)}$$

$$\sigma_3 = 0 \qquad \text{(Eq. 7c)}$$

Combining Equations 5, 6, and 7, we can show that $d\varepsilon_1 = -d\varepsilon_3$ and $d\varepsilon_2 = 0$. From Von-Mises effective strain,

$$d\bar{\varepsilon} = \frac{\sqrt{2}}{3}\left[(d\varepsilon_1 - d\varepsilon_2)^2 + (d\varepsilon_2 - d\varepsilon_3)^2 + (d\varepsilon_3 - d\varepsilon_1)^2\right]^{\frac{1}{2}}$$

$$d\bar{\varepsilon} = \frac{\sqrt{2}}{3}\left[d\varepsilon_1{}^2 + d\varepsilon_1{}^2 + 4d\varepsilon_1{}^2\right]^{\frac{1}{2}}$$

$$d\bar{\varepsilon} = \frac{2}{\sqrt{3}}d\varepsilon_1$$

integrating,

$$\bar{\varepsilon} = \frac{2}{\sqrt{3}}\varepsilon_1 \qquad \text{(Eq. 8)}$$

Similarly we can show for σ_1, σ_2, and σ_3 that

$$\bar{\sigma} = \frac{\sqrt{3}}{2}\sigma_1 \qquad \text{(Eq 9)}$$

where Von-Mises effective stress, $\bar{\sigma}$ is

$$\bar{\sigma} = \frac{1}{\sqrt{2}}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{\frac{1}{2}}$$

The flow curve in the plastic region can be expressed by the simple power curve relation

$$\bar{\sigma} = K\,\bar{\varepsilon}^n \qquad \text{(Eq. 10)}$$

where **n** is the strain hardening exponent and K is the strength coefficient.

Rewriting Equation 10 and substituting Equations 7, 8, and 9

$$\varepsilon_1 = .866\left(\frac{.866\,\mathrm{Pr}}{\mathrm{Kt}}\right)^{\frac{1}{n}} \qquad \text{(Eq. 11)}$$

For our loading condition hoop strain, $\varepsilon_{hoop} = \varepsilon_1 + \alpha\,\Delta T$. Therefore the hoop membrane strain is equal to

$$\varepsilon_{hoop} = .866\left(\frac{.866\,\mathrm{Pr}}{\mathrm{Kt}}\right)^{\frac{1}{n}} + \alpha\Delta T \qquad \text{(Eq. 12)}$$

3.2.1.2 Non-Uniform Pipe Thickness

In this case we assume that the entire volume change occurs in the thin section, see Figure 3-1.

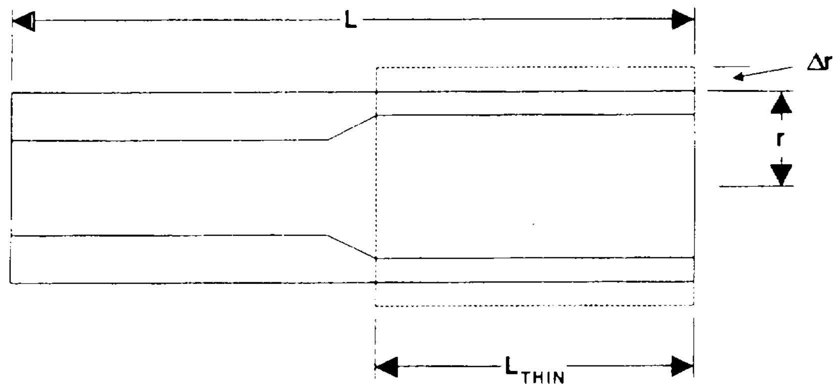

Figure 3-1
Non-uniform Pipe Thickness Model

Therefore the change in volume is equal to

$$\Delta V = [\ \pi\ (r + \Delta r\ )^2 - \pi r^2]L_{THIN}.$$

Expanding and ignoring higher order terms for Δr, then

$$\Delta V = 2\pi r \Delta r L_{THIN} \qquad \text{(Eq.13)}$$

Since the original volume $V = \pi r^2 L$ and letting $L_{THIN}/L = \xi$ then

$$(\Delta V/V)_\xi = 2\ (\Delta r/r)\xi$$

Since $\Delta r/r = \varepsilon_{hoop}$ then

$$(\Delta V/V)_\xi = 2\ \xi\ (\varepsilon_{hoop}\ )_\xi \qquad \text{(Eq. 14)}$$

Similarly for a uniform thickness pipe, $\xi = 1$ and

$$(\Delta V/V)_u = 2\ (\varepsilon_{hoop}\ )_u \qquad \text{(Eq. 15)}$$

Equating the volumetric strains for the non-uniform thickness case Equation 14, and the uniform thickness case Equation 15, and substituting Equation 12 in Section 3.2.1.1 for uniform hoop strain, the general form for hoop strain can therefore be expressed as:

$$\varepsilon_{hoop} = \left[.866 \left(\frac{.866\,\mathrm{Pr}}{\mathrm{Kt}} \right)^{\frac{1}{n}} + \alpha \Delta T \right] \cdot \frac{1}{\xi} \qquad \text{(Eq. 16)}$$

3.2.2 Test Data and Analysis Comparison

Equation 16 was used to estimate the final hoop strains for the thermal expansion test specimens. The hoop strains predicted are consistent with measured hoop strains. The results of this comparison are shown in Table 3-1.

Table 3-1
Test Data and Analysis Comparison

Test	Pipe Size	Material	Pressure	ΔT	$\varepsilon_{measured}$	$\varepsilon_{calculated}$
			psi	°F	%	%
Pretest	3" Sch 40	SS	5,400	230	2.4	2.2
Test 1	3" Sch 40	SS	5,700	253	2.9	2.5
Test 2	3" Sch 40/80	SS	5,900	243	5.4	5.4
Test 3	8" Sch 40	CS	4,800	190	2.6	2.2

4

STRAIN LIMIT CRITERIA

4.1 Basic Considerations

In general, the design process is limited to the use of elastic stress analyses and the application of criteria that presumes important loading are load controlled, rather than energy controlled. The behavior of structural materials undergoing plastic deformation is dependent upon the true stress-true strain properties of the material. The maximum loads that a structure can withstand will be limited by the onset of plastic instability or initiation of ductile tearing.

Plastic instability is expected to occur when the applied strain is equal to the effective strain[3] at maximum load. At this point, the true stress in the material increases faster than the material strain hardening can accommodate. The initiation of ductile tearing is equated with the effective strain at fracture. Both plastic instability and ductile tearing initiation represent a measure of the usable ductility of the material.

Avoidance of the onset of plastic instability and the initiation of ductile tearing is the object of ASME Section III, Appendix F; however, these rules presume load controlled conditions. Since the loading described in Generic Letter 96-06 is an energy controlled condition, it is necessary to consider alternative yet equivalent acceptance criteria.

4.2 Energy Controlled Strain Limits

In EPRI technical report NP-1921, W. E. Cooper of Teledyne Engineering Services pointed out that, for energy controlled conditions, the structural acceptance criteria should be related to the energy absorption capability of the structure.[4] Accordingly, the

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[3] In its simplest form, the effective strain, $\bar{\varepsilon}$, in a relatively homgeneous and isotropic material, is related to the true tensile test strain, ε, by: $\bar{\varepsilon} = \frac{\varepsilon}{TF}$, where the triaxiallity factor (TF) is defined as

$$TF = \frac{\sigma_1 + \sigma_2 + \sigma_3}{\bar{\sigma}}$$

[4] Cooper, W. E., "Rationale for a Standard on the Requalification of Nuclear Class 1 Pressure-Boundary Components", EPRI NP-1921, Electric Power Research Institute, Palo Alto, CA, October 1981.

only way to accomplish this objective is to present the criteria in terms of strain limits that are proportional to the usable ductility of the material. Plastic instability strain can provide a basic approach for doing this.

Since Appendix F permits loads as high as 70% of the maximum load carrying capability of the material, Cooper recommended that plastic instability be prevented by limiting energy controlled event strains to 70% of the effective strain at maximum load. In doing so, the safety margins would be consistent with those applied to load controlled conditions in Appendix F. Cooper went on to caution that if one were to permit energy absorption approaching the capability of the structure, then it may be necessary to also place a limit on peak strain in order to prevent local ductile tearing initiation. He suggested that this limit be 70% of the effective strain at fracture.

The two criteria become:

1. $\boldsymbol{\varepsilon < 0.7\, Z\, n}$ for membrane strain, and

2. $\varepsilon \le 0.7\left\{\dfrac{\sinh\left[\dfrac{\sqrt{3}}{3}\right](1-n)}{\sinh\left[\dfrac{\sqrt{3}}{3}\right](1-n)\cdot TF}\right\}\cdot \varepsilon_f$ for local peak strain

where: Z = Ratio of effective strain @ maximum load, $\bar{\varepsilon}_{max}$, to strain hardening exponent, n

ε_f = Fracture Strain

n = Strain Hardening Exponent

TF = Triaxiality Factor

In Table 4-1 the Cooper membrane strain limit was applied to the materials tested in Section 2.3. The membrane strain limits were calculated for both effective strain, $\bar{\varepsilon}$, and hoop strain, ε_{hoop}. Since the effective strain at maximum load, $\bar{\varepsilon}_{max}$, represents the onset of plastic instability, the strain limit safety margin to plastic instability $FS = \dfrac{\bar{\varepsilon}_{max}}{\bar{\varepsilon}}$.

Table 4-1
Energy Controlled Membrane Strain Limits

Pipe Size	Material	Z	n	$\bar{\varepsilon}_{max}$	$\bar{\varepsilon}$	ε_{hoop}	FS
				%	%	%	
3" Sch 40	SS	0.577	0.43	24.9	17.4	15.0	1.43
8" Sch 40	CS	0.577	.018	10.4	7.3	6.3	1.43

4.3 ASME Code Case Strain Limits

As proposed, the ASME code case limits hoop membrane strain to 5% for both carbon and stainless steels. Since the margins of safety shown in Table 4-1 are consistent with the safety factors applied to load controlled conditions in Appendix F, it would appear that, in the case of stainless steel, this hoop strain limit may be overly restrictive. In fact, the measured hoop strain for the stainless steel transition specimen 5.4% (see Test 2 results in Table 2-5) exceeds this limit. Note that the measured burst hoop strain for the 3″ Schedule 40 stainless steel pipe was 36.3%. We can see from Table 4-2 that the 5% strain limit will result in a factor of safety to plastic instability of 4.3 for stainless steel and 1.8 for carbon steel. Increasing the strain limit for stainless steel to 10% would result in a safety factor on plastic instability of 2.2.

Table 4-2
Safety Factor to Plastic Instability

Pipe Size	Material	Hoop Strain @ Max Load	Current Code Case Strain Limit	Current FS	Revised Code Case Strain Limit	Revised FS
		%	%		%	
3" Sch 40	SS	21.5	5	4.3	10	2.2
8" Sch 40	CS	9.0	5	1.8	5	1.8

Safety factors to ductile tearing (that is, fracture) for the current code case strain limits and the proposed change to the stainless steel limit are shown in Table 4-3.

Table 4-3
Safety Factor to Ductile Tearing Initiation

Pipe Size	Material	Hoop Strain @ Fracture	Current Code Case Strain Limit	Current FS	Revised Code Case Strain Limit	Revised FS
		%	%		%	
3" Sch 40	SS	26.4	5	5.3	10	2.6
8" Sch 40	CS	16.7	5	3.3	5	3.3

We can see from Tables 4-2 and 4-3 that a hoop membrane strain limit of 5% for carbon steel and 10% for stainless steel accounts for the difference in usable ductility of the two materials and provides for a nominal factor of safety of 2 on plastic instability and 3 on fracture.

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