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Containment Penetration System (CPS) Tests Under Accident Loads

Prepared by H.S. Crapo, R. Steele, Jr

Idaho National Engineering Laboratory
EG&G Idaho, Inc.

Prepared for
U.S. Nuclear Regulatory
Commission

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ABSTRACT

This report provides the results of accident simulation tests of three typical light water reactor containment penetration systems to provide a technical basis for the support and development of equipment qualification procedures at design basis load levels and to determine safety margins at severe accident load levels. The three systems tested were (a) an 8-in. gate valve system modeling a containment spray system; (b) an 8-in. butterfly valve system modeling a purge and vent system; and (c) a 2-in. globe valve system modeling the numerous small-bore piping systems. The valve types, valve sizes, piping configurations, penetrations, and supports used for the tests are typical of those found in commercial U.S. nuclear power plants for containment isolation applications. The three systems tested were mounted in a fixture and exposed to simulated severe accident mechanical loads by displacing the penetrations relative to the piping. Thermal and pressure loads were also applied. The test results indicate that valve, penetration, or piping system failure during hypothesized accident events is unlikely due to accident-induced loads.

FIN No. A6322—Environmental Qualification of Mechanical and Dynamic (Including Seismic)
Qualification of Mechanical and Electrical Equipment Program (EDQP)

EXECUTIVE SUMMARY

This report presents the test results of the mechanical displacements and thermal loads applied to penetration systems as part of the Containment Penetration Systems Testing Task. The test program was performed by the Idaho National Engineering Laboratory for the United States Nuclear Regulatory Commission (USNRC), Office of Nuclear Regulatory Research.

The purpose of the Containment Penetration Systems Testing Task was to provide an experimental basis for support and development of equipment qualification procedures with loadings up to the design basis level and to understand the margin of safety of equipment during severe accident loadings. Specifically, the test program addressed the operability and integrity of representative pressurized water reactor (PWR) containment penetration systems (CPS) when subjected to thermal and mechanical loads characteristic of design basis accident and severe accident events. Loads included displacement of penetrations relative to anchored piping, heating of valve bodies to elevated temperatures, and increased pressures in the penetration piping. The valve operator inside containment was not subjected to high temperature steam or radiation because that testing is more effectively performed in separate effects testing. Containment penetration systems include the piping, penetrations, isolation valves, and supports associated with piping systems that penetrate light water reactor containments.

The two main criteria used to select systems to be tested in the CPS test program were (a) systems with a relatively high potential for leaking from the containment environment to the outside atmosphere and (b) systems that would be required to mitigate the results of an advanced severe accident. The three PWR CPS systems identified and tested were (a) an 8-in. gate valve system modeling a containment spray system (important to containment integrity as it is the final heat removal system), (b) an 8-in. butterfly valve system modeling a purge and vent system (critical to containment integrity because of the direct path to the outside environment), and (c) a 2-in. globe valve system modeling the numerous small-bore piping systems.

The 8-in. piping systems were configured to be typical of nuclear industry piping designs so that the results would be directly applicable to existing plants. Numerous PWR CPS piping configurations were reviewed to establish the test piping layouts. Important piping characteristics included pipe lengths from containment wall to valves, lengths to first elbow, and direction of first bend. In order to maintain test models that were as representative as possible, only nuclear-grade equipment and fabrication processes were used in the assembly of the three piping systems. Full-scale, complete systems (valve, penetrations, piping and supports) were tested to avoid the uncertainties inherent in analytical extrapolation of small-scale test results.

The 2-in. piping system was configured so that extreme loads could be applied to the piping and valve to look for failure thresholds without being limited by a simulated CPS geometry. As in the 8-in. tests, full-size nuclear-grade equipment was used.

The test apparatus consisted of a large welded test frame, constructed from 14-in. square tubing. Each piping system was individually supported in the test frame using nuclear-grade supports including rigid struts, spring hangers, and box beam supports. The support sizing and placement were based on typical ASME Section 3 Class II deadweight and seismic analyses. The 8-in. penetrations were mounted on guided rollers and displaced by a hydraulic ram to simulate containment wall expansion due to the effects of accident pressures and temperatures inside containment. The 2-in. penetration was mounted solidly to the test frame, and the piping was displaced. Valve bodies and selected portions of piping were heated with flexible electric resistance heaters. Piping systems were pressurized with air or nitrogen (depending on system) for evaluation of valve operability and leakage. Piping systems and pipe supports were instrumented with strain gauges, thermocouples, and pressure transducers to measure the various physical phenomena of interest.

After checkout of the valves and instrumentation, each piping system was subjected to thermal, mechanical, and pressure loads simulating design basis and severe accident events. Containment wall displacements as large as 18 in. and temperatures to 350°F were achieved in incremental steps. Load levels were developed from a review of other USNRC-sponsored projects and information obtained in plant final safety analysis reports. The primary areas of interest during testing were CPS valve operability and piping system pressure boundary integrity.

The review of the test results was based on examination of measured parameters such as piping strains, valve stroke times, operator currents, and leak rates as well as visual observations during and after the tests. Based on the parameters studied, the following conclusions concerning the operability, leakage, and structural integrity of CPS valves, piping, penetrations, and supports were deduced.

All valves maintained as-installed leak integrity through the design basis accident simulation. Only the most highly loaded gate valve (inside containment) showed increased leakage during the severe accident test and after load release. The heated inside butterfly valve leaked on cooldown. Although leakage occurred through the inner valves, the outer valves did not leak; thus, the dual-valve systems maintained leak integrity of the overall penetration for all test conditions in all systems. None of the valves experienced any difficulty cycling during or after any of the tests. In terms of operability, all valves performed well and were unaffected, either during or after mechanical loading. No observable structural damage occurred to any of the valves or penetrations. Some piping components experienced significant strain (~5%) but showed no signs of buckling or failure of the pressure boundary. Some spiral-wound gaskets leaked due to bending moments at flanged joints during severe accident tests. Most of the pipe supports were not damaged or deformed. Two exceptions were a support strut near the penetration that failed in tension and another support strut that failed in compression (buckled) during the 8-in. butterfly valve test.

Although the three containment penetration systems were not tested to failure, system integrity was maintained through simulated containment displacements well beyond design basis accident values and through hypothesized severe accident loads. Valve operator performance parameters remained constant throughout the test indicating that valve operability should not be a concern at design basis accident or severe accident loading levels. In summary, the loads applied during mechanical testing did not:

- Increase the required operator torque for CPS valves,
- Induce leaks through containment penetration systems, or
- Cause structural failures in CPS piping, valves, or penetrations.

However, it was verified that water trapped between valves can experience significant pressure buildup during design basis accident conditions.

ACKNOWLEDGMENTS

The efforts of many people were required to successfully conduct the containment penetration system accident simulation tests. The author wishes to thank personnel from the Idaho National Engineering Laboratory (INEL) Test and Evaluation Laboratory and the following INEL staff for their technical assistance: R. A. Larson who provided on-site supervision for the initial test set-up; K. G. DeWall, D. K. Morton, and R. Steele, Jr. who wrote the document which defined the tests and provided consultation throughout the project; and to R. C. Hill who supervised the project. The author also would like to acknowledge the important and helpful support of Dr. G. H. Weidenhamer, the NRC project manager for this task.

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CONTAINMENT PENETRATION SYSTEM (CPS) TESTS UNDER ACCIDENT LOADS

1. INTRODUCTION

A number of light water reactor systems are critical to plant recovery and protecting the public from the possible release of radiation during an accident. Such systems are designated *safety-related*. One of the important considerations in evaluating the safety of nuclear power plants is to ensure that safety-related systems will indeed function during and after accidents. Safety-related systems are typically evaluated based on analysis, qualification testing of major components, and code-certified construction. The U.S. Nuclear Regulatory Commission (USNRC) is sponsoring research to further develop the technical basis for the current equipment qualification portion of the system qualification process.

One important group of safety-related systems is the hardware which allows the reactor coolant piping to penetrate the containment walls. A containment penetration system (CPS) includes the piping, penetration, isolation valves, and supports associated with a piping system that penetrates the containment. In conjunction with the containment structure and electrical penetrations, CPSs provide the last barrier to fission product release. The USNRC is especially concerned with the uncertainties involved in determining whether containments will leak during an accident.[1] Because of the large number of piping penetrations (100-200 per plant of U.S. design), CPS valves are among the prime potential sources of localized leakage. This issue is being addressed in the USNRC-sponsored Equipment Qualification Research Program at the Idaho National Engineering Laboratory (INEL), under the task of Containment Penetration Systems Testing. The CPS Testing Task was established to evaluate the operability and leak integrity of safety-related equipment when subjected to conditions typical of design basis and severe accident events. The first phase of this work consisted of design basis and safe shutdown earthquake load tests of three full-scale nuclear-grade CPS configurations. The results of those tests are presented in Reference 2 and indicate that light water reactor CPSs will continue to properly operate and not leak during and after worst case seismic events. This report presents the response of typical pressurized water reactor CPSs when subjected to quasi-static thermal and mechanical loads resulting from containment wall displacements and elevated temperatures representative of design basis accident and severe accident conditions in a light water reactor containment.

The CPS tests were not intended to be component qualification tests but rather a series of accident simulations which would provide in-situ performance data under combined thermal and mechanical loads applied to both the system and individual components. The systems approach was taken to eliminate the uncertainties involved in calculating the combined loads on each individual component and to account for the redundant capacity caused by system responses which redistribute the loads. Exhaustive testing of all valve types and sizes in many different piping configurations was neither practical nor necessary in light of the test objectives. A testing scheme was sought which included systems, piping configurations, and loads representative of the majority of U.S. plants. Systems were chosen which represent both (a) systems with the potential for radioactive release during a severe accident and (b) systems in which valve operation is required to mitigate the effects of an accident. A system was also selected to represent the numerous small-diameter penetrations in a typical containment.

It should be noted that the effects of high temperatures, radiation, steam, and chemical spray on the performance of the CPS inside valve operators and their associated cables and connectors were not investigated in this project. Motor-operated valve operator performance during design basis accidents is demonstrated by the normal valve qualification process. The need to address these effects for severe accidents is the subject of other USNRC research. Penetration and piping performance is not affected by radiation, steam, or chemical spray (no susceptible materials). The ability of purge and vent valves to close against a rising flow has been investigated in a companion USNRC-sponsored project and reported by Watkins[3] and discussed in Section 1.1.

The design basis and severe accident loadings initially were developed from other NRC research including:

NUREG/CR-3234, *Loads From Severe Accident Studies on Generic Containments (Appendix B)* (Zion, Bellefonte, Watts Bar, and Browns Ferry-1)[4]

NUREG/CR-2228, *Containment Response During Degraded Core Accidents Initiated by Transients and Small Break LOCA in the Zion/Indian Point Reactor Plants*[5]

NUREG/CR-3278, *Hydrogen Burn Analyses of Ice Condenser Containments* (Sequoyah, McGuire)[6]

NUREG/CR-1891, *Reliability Analysis of Containment Strength* (Sequoyah, McGuire)[7]

NUREG/CR-1967, *Failure Evaluation of Reinforced Concrete Mark III Containment Structure Under Uniform Pressure* (Grand Gulf)[8]

NUREG/CR-4913, SAND 87-0891, *Round-Robin Pretest Analysis of a 1:6 Scale Reinforced Concrete Containment Model Subject to Static Internal Pressurization.*[9]

From these NUREGs and others, Table 1 was developed.

The last document contains predicted containment growths due to pressurization significantly greater than any of the early work. Radial growths of up to 18 in. in full-size containments are predicted.

Although severe accident containment temperatures have been reported, the available literature did not contain containment thermal growth responses. Therefore, a study was performed at the INEL to develop a generic thermal growth response. It was found that the radial thermal response was about equal to the radial growth from pressure. However, the thermal response study also revealed a relatively strong vertical response. The amount of vertical growth due to thermal expansion that could be expected depended on how high in containment a piping penetration was located. For the purposes of conservatism, 2/3 of typical containment height was chosen for the vertical growth test requirements.

A one-to-six-scale reinforced concrete containment model was recently tested to failure (caused by static internal pressurization) at the Sandia National Laboratory. The containment liner tore at an equivalent radial growth of about 12 in. and depressurized the containment before total concrete failure. The INEL tests reported here were conducted at equivalent displacements of 13.2 to 18.0 in. and can be considered conservative.

1.1 Related Research

The primary purpose of the work presented in this report was to assess the response of representative containment piping penetration systems to the mechanical loads caused by the radial and vertical movement of a containment structure during design basis accident and severe accident transients. However, there are other important CPS equipment loadings during design basis accident and severe accident transients that can affect control and recovery of the plant. The INEL has performed NRC-sponsored research which involved testing of three of these loadings.

The first work dealt with requirements for containment purge and vent valve closure when exposed to the internal containment pressures of a design basis loss of coolant accident. This work was also part of the TMI Action Plan, NUREG-0660, Item II.E.4.2.[10] Elastomerically sealed butterfly valves are generally used on light water reactor containment purge and vent lines. Butterfly valves are unique when determining closing torque requirements in a compressible flow environment. The butterfly disc acts much like a wing of an airplane where the peak force occurs just before the wing stalls. Unlike a gate valve where the maximum closing forces are in the last 10% of closure, the butterfly valve peak torque occurs at 70 ± 10% open. The utility responses to the TMI action plan indicated that very little research had been accomplished on butterfly valve closure requirements in a compressible fluid environment. The NRC determined that it required a better technical basis on which to judge the analytical responses it was receiving from the utilities. A test program was devised wherein two 8-in. butterfly valves from different manufacturers and a 24-in. butterfly valve were tested at inlet pressures up to 60 psi with the downstream vented to atmosphere to establish worse case conditions.

The two 8-in. valves of different manufacture established a baseline, and the 24-in. valve results provided data for validating the extrapolation of small valve results, which is industry's normal practice. The inlet pressures, valve installation geometry, and piping inlet conditions were varied to match most of the possible field applications. The work also included single effects leak testing at design basis accident and severe accident temperature and pressure conditions. The results of the work did cause a change in the American Society of Mechanical Engineers (ASME) Standard

Table 1. Containment design and ultimate capacity predictions

Plant	Design		Predicted Ultimate Capacity	
	Pressure (psi)	Temperature (°F)	Pressure (psi)	Temperature (°F)
BWR-Mark I	62	281		
Dresden 2	62/35	175/281		
Oyster Creek	62	281		
Millstone	62	281		
Arnold	56	281		
E. Fermi 2	56	281		
Browns Ferry	56	281	117	375
BWR-Mark II		Drywell Sup.Cham.		
Zimmer	45	340/275		
LaSalle	45	340/275		
WPPSS 2			133	
BWR-Mark III				
Perry 1			100	
Grand Gulf			52	
MK III Standard	15		56	
PWR-Ice Condenser				
Sequoyah	10.8	220	60	250
McGuire	15	190	84	250
Watts Bar	13.5	220	120	350
PWR-Subatmosphere				
North Anna	45	280		
PWR-Large Dry				
Palisades	55	283		
Diablo Canyon	47	246		
St. Lucie	39.6	274	95	
Midland	70	120		
Rancho Seco	59	286		
Zion	47	271	125	325
J. M. Farley	54	220		
SONGS 2&3	60	300		
ANO 2	54	300		
Summer	57	283		
Comanche Peak	50	280		
Cherokee			116	
Indian Point			118	350
Bellefonte			130	350
Maine Yankee			96	
Byron/Braidwood			99	

QV-4, *Functional Qualification Requirements for Power Operated Active Valve Assemblies for Nuclear Power Plants*[11], which is the ASME replacement standard for the currently released ANSI B16.41 standard of the same title.[12] The complete results of this work can be found in Reference 3.

The second containment isolation valve flow interruption project involved research to assist in the resolution of the NRC's Generic Issue 87, "Failure to HPCI Steam Line Without Isolation." This issue includes concerns about uncertainties in gate valve operator sizing and torque switch settings for high pressure coolant injection, reactor core isolation cooling, and reactor water cleanup system isolation valves. The test program is currently in progress. The valves are full-scale 6-in. gate valves typical of those installed in BWRs. The test conditions are typical blowdown conditions with BWR primary conditions at the valve inlet and the valve outlet vented to atmosphere. The first part of the test program is being conducted with subcooled water at the valve inlet. The second phase is scheduled to be performed with steam. A report on the water portion of the test program will be published in FY-89.

The third loading to which containment penetration and isolation valves have been subjected is seismic. Prior to performing the testing documented in this report, portions of the piping, valves, and penetrations mounted on a tubular steel frame were subjected to simultaneous triaxial acceleration at levels up to and equivalent to west coast safe shutdown earthquakes. The results of this work indicate that adverse valve, penetration, or piping system behavior during typical seismic events is very unlikely. The complete results of this work are documented in Reference 2.

Design basis and severe accident environments can be very harsh. Radiation, temperature, and steam must be considered in the qualification of valve operators. IEEE Standard 382, "Standard for Qualification of Safety-Related Valve Actuators" is one of the most complete standards currently issued for environmental qualification. Considerable work in the environmental qualification of valve actuators has been completed by industry. In addition, the Central Electricity Generating Board (CEGB) of the United Kingdom (UK) is about to undertake a large effort for Sizewell B. Sizewell B is a standard design Westinghouse PWR being built in the UK. The CEGB has invited valve and valve operator manufacturers to cooperate in a complete qualification program before valves can be approved for installation in Sizewell. This includes valve life testing, motor operator environmental qualification, valve qualification, and, when required, flow interruption testing. Sizewell is being built to the ASME Code, and US qualification standards are being used for equipment qualification. This is probably the most complete checkout of nuclear equipment and qualification standards ever performed, as most of the current qualification standards were issued after the peak plant building activity in the US. It is hoped that the Sizewell harsh environment qualification of valve operators will provide insights into the adequacy of the current qualification of operators for harsh environments.

2. OBJECTIVES

The following objectives were established for the physical loading tests of the CPS Testing Project:

- Characterize the response of typical safety-related CPS installations exposed to simultaneously applied pressure, temperature, and displacement loads at design basis event levels;
- Improve the understanding of valve operability and leak integrity in response to design basis loads;
- Determine whether valves with hardened metal seats can seal tightly enough to seal a heatup-driven water expansion pressure transient;
- Improve the ability to analytically predict system response to design basis loads;
- Characterize the response of typical safety-related CPS installations exposed to simultaneously applied pressure, temperature, and displacement loads at severe accident event levels; and
- Provide experimental results to support improvements to the equipment qualification standards and regulatory guides listed in Table 2.

A potential benefit of the accomplishment of these objectives is to determine if the effects of physical loads on CPSs are acceptable. If so, this would significantly reduce the safety concerns associated with one of the major potential sources of localized containment leakage.

Table 2. Equipment qualification standards and regulatory guides potentially affected by CPS testing results

— ANSI/ASME B16.41, Functional Qualification Requirements of Power-Operated Active Valve Assemblies for Nuclear Power Plants (currently being revised as ASME QV-4)

— ANSI/ASME N278.1-1975, Self-Operated and Power-Operated Safety-Related Valves Safety Specification Standard

— IEEE Standard 382-1980, Qualification of Safety-Related Valve Actuators

— IEEE Standard 627-1980, Design Qualification for Safety Systems Equipment Used in Nuclear Power Generating Stations

— Regulatory Guide 1.148, Functional Specification of Active Valve Assemblies in Systems Important to Safety in Nuclear Power Plants

— Regulatory Guide 1.73, Qualification Tests of Electric Valve Operators Installed Inside the Containment of Nuclear Power Plants

3. TEST DESIGN

The objective of the CPS tests was to determine the response of typical containment penetration systems to accident conditions. The considerations involved in the design of the physical load tests of containment penetration systems included the following:

1. Selecting representative systems for testing,
2. Determining the important thermal and mechanical loads and load combinations that should be included,
3. Selecting appropriate hardware for the tests, and
4. Determining which parameters would best characterize the response to the physical loads.

Table 3 gives the nomenclature used for this series of CPS tests. The following sections provide discussion of each of the considerations.

3.1 Selection of Representative Systems

The criteria for selecting which CPS systems to test were (a) choose systems with a potential for leaking the containment environment directly to the outside atmosphere and (b) choose systems that would be required to mitigate an advanced severe accident. The most likely systems to be involved in a release to the outside containment atmosphere are systems that open to both the containment environment and the outside environment. The leading candidates fitting that description are the containment ventilating and vacuum release systems. The systems needed to mitigate severe accidents are most likely the containment spray and sump recirculating and cooling systems.

Therefore, it was decided to create three typical CPSs that represent a large number of low-to-medium pressure systems, which in turn would provide generally applicable results from the testing. An 8-in. gate valve system (Sch. 40 piping) modeling a containment spray system was chosen because this latter system is important to containment integrity as the final heat removal system. The characteristics important for containment spray systems are leak integrity and valve operability. Containment spray systems are closed-loop, liquid-filled.

Another system that was chosen was an 8-in. butterfly valve system (Sch. 40 piping) modeling a purge and vent system. A purge and vent system is critical to containment integrity because of risk of leakage to the outside environment. Purge and vent systems are gas-filled, open-loop systems using elastomerically sealed valves, requiring leak integrity and valve operability for prevention of leaks of radioactive materials to the outside environment.

Table 3. Nomenclature

The following terms are used for describing hardware and instrument locations:

Inside - equipment located inside the simulated containment building wall.

Outside - equipment located outside the simulated containment building wall.

Upstream - toward source of flow, assuming flow from inside to outside of containment.

Downstream - opposite of upstream.

X - direction parallel to axis of penetration pipe; positive from inside to outside.

Z - direction perpendicular to axis of penetration, positive from left to right when facing along the axis of the penetration from inside to outside. (X,Y, Z form a right-handed coordinate system, with Y vertical, positive up).

Axial - parallel to centerline of pipe.

The third system selected was a 2-in. globe valve system (Sch. 160 piping) modeling the many small-bore piping systems that make up a large fraction of containment penetration systems. Piping systems of this size show a large ratio of valve stiffness to pipe stiffness, when compared to larger piping systems.

To establish the system configuration, information was obtained from Reference 13 which reviewed five containments considered to be representative of most types of US containments. This task analytically studied containment piping penetration stresses in an accident environment. Review of the piping penetrations and piping geometry established that most PWR CPS installations are similar on the inside of the containment. The pipe comes out the penetration and within 15 ft makes a 90° bend. In some systems, the valve is in the straight run and in others it is after the bend. For the loadings being considered in this research, it was determined the most conservative results could be obtained with the valve in the straight run before the bend. The piping geometry finally arrived at for the CPS test is considered generic; however, it is modeled very closely after one of the containments identified in the containment leak rate estimate task mentioned above.

The 8-in. test systems modeled piping inside and outside the containment. The 2-in. test system modeled only piping inside the containment. The flexibility of the 2-in. pipe compared to the 2-in. globe valve is such that no effect on valve performance would be expected for severe accident loads applied in the manner used for the 8-in. tests. Simplifying the system allowed testing at higher loads in an attempt to investigate failure modes and thresholds. Typical of systems that operate at ambient temperature, the three configurations tested did not include pipe snubbers. Ambient temperature systems are considered to be the systems most susceptible to anchor movements.

3.2 Hardware Considerations

The systems used for the tests were designed to be representative of systems found in actual plants; this applied to design and installation as well as hardware. All tests were performed with full-size components. The piping systems were designed in accordance with ASME Section III Class 2.[14] The N-stamped Class 2 valves were acquired from the cancelled Hope Creek Nuclear Power Station Unit 2 and the Washington Public Power Supply System Unit 4 (WPPSS-4). The Class 2 penetrations also came from the WPPSS-4 plant, and the piping and piping supports were purchased from nuclear power plant suppliers. Typical containment wall rigidity was simulated using heavy steel members. Figure 1 shows a typical containment penetration installation for a west coast plant. Figure 2 shows the fixture developed for mounting the penetrations in the CPS test program. A flued head design was use for the 2-in. assembly and a flanged piping penetration design was used for the 8-in. assembly. Fabrication of the systems was performed to the ASME Code without third party inspection.

The 8-in. containment spray and 8-in. purge and vent test systems were similar in design and used much of the same hardware. As mentioned above, piping configurations were based on studies of numerous nuclear plants and are typical of the piping located near the containment penetrations of the respective systems. However, the layout used is more typical of containment spray systems than purge and vent systems but provided a convenient test bed for the butterfly valves; the additional upstream piping created conservative piping loads and valve reactions. It is estimated that enough of the piping was included in each test configuration to develop essentially all of the mechanical loads typical of valves and penetration assemblies in an actual nuclear plant system with comparable wall motion. Both 8-in. systems modeled piping both inside and outside the containment wall with two isolation valves. An isometric diagram of the 8-in. systems is presented in Figure 3. Photographs of the gate valve assembly installation are presented as Figures 4 and 5. The 8-in. gate valves were 150-lb class Anchor/Darling butt weld gate valves with Limitorque SMB motor operators. Figure 6 shows a cross section of the valve. The butterfly valves were 150-lb class elastomerically sealed units built by Allis Chalmers. The inside valve was operated by a Limitorque SMB motor operator. The outside valve utilized a hydraulic valve operator. Figure 7 shows a typical butterfly valve cross section. Both 8-in. test systems used the same rigid structure and floor-mounted piping supports and restraints. The plan and elevation views of the 8-in. systems are shown in Figures 8 and 9. The penetration assembly was mounted with rollers on rails to permit a controlled displacement. A hydraulic ram was used to incrementally move the penetration, simulating expansion of the containment during an accident (see Figures 10 and 11).

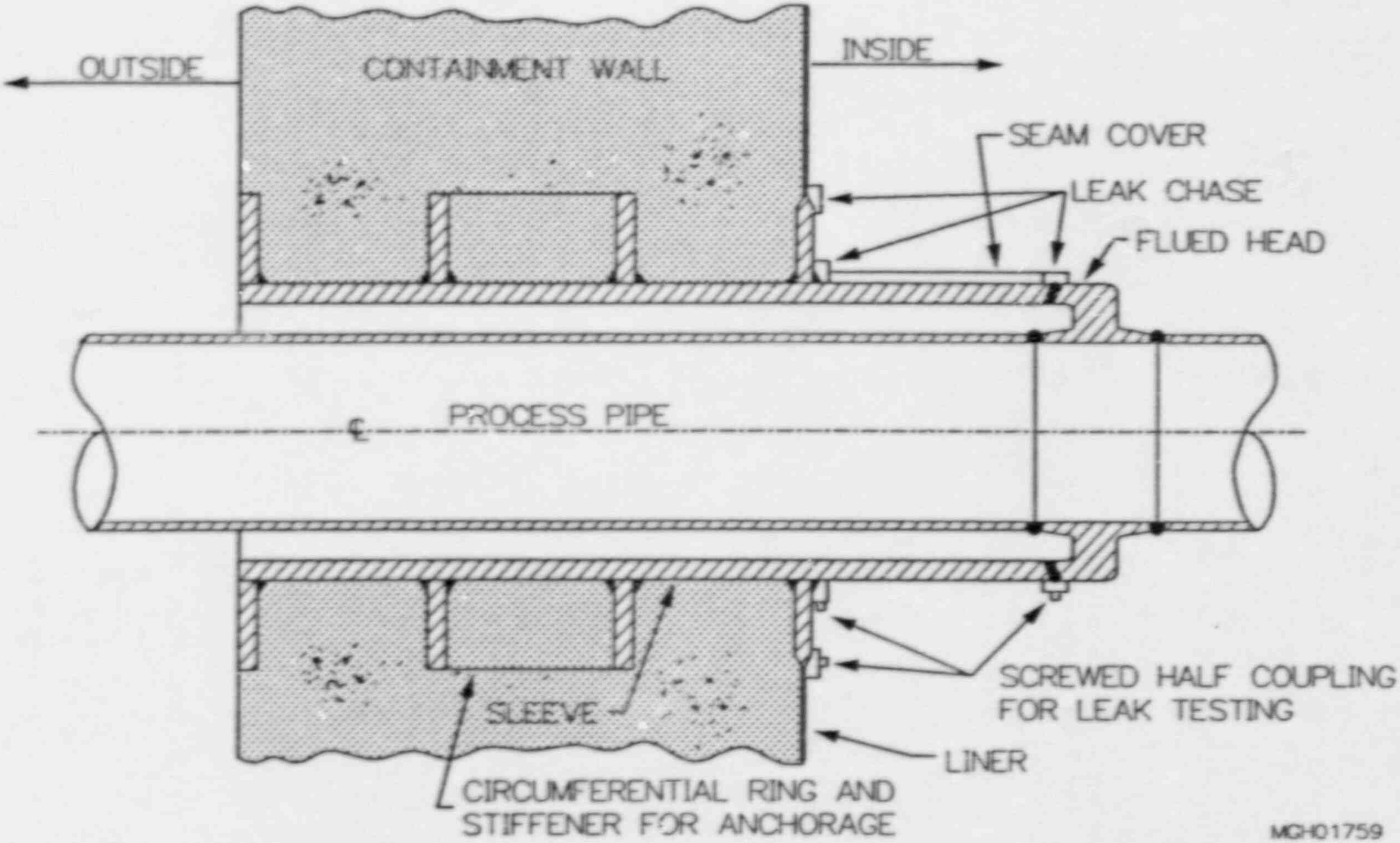

Figure 1. Typical containment penetration installation.

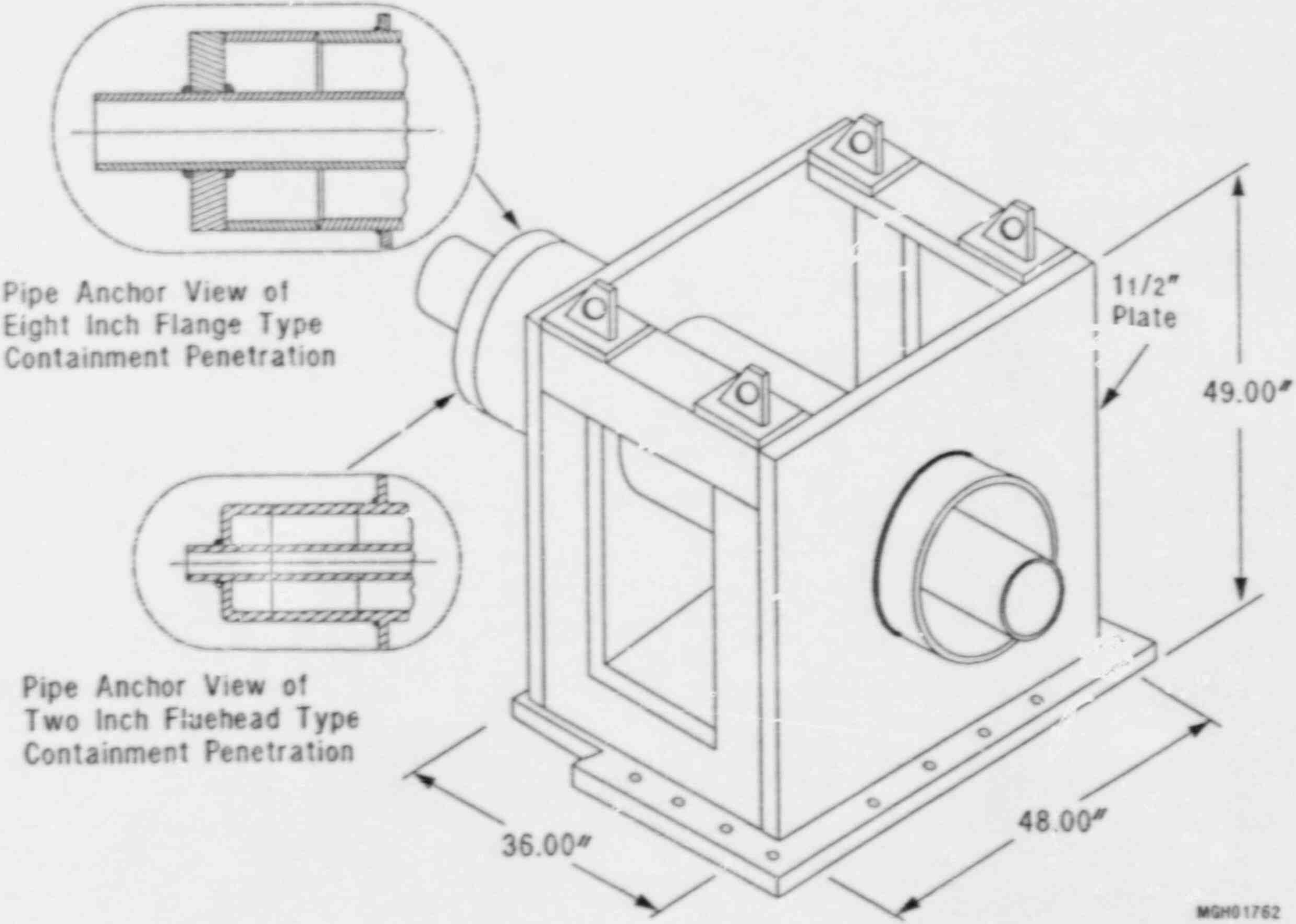

Figure 2. Containment penetration test assemblies.

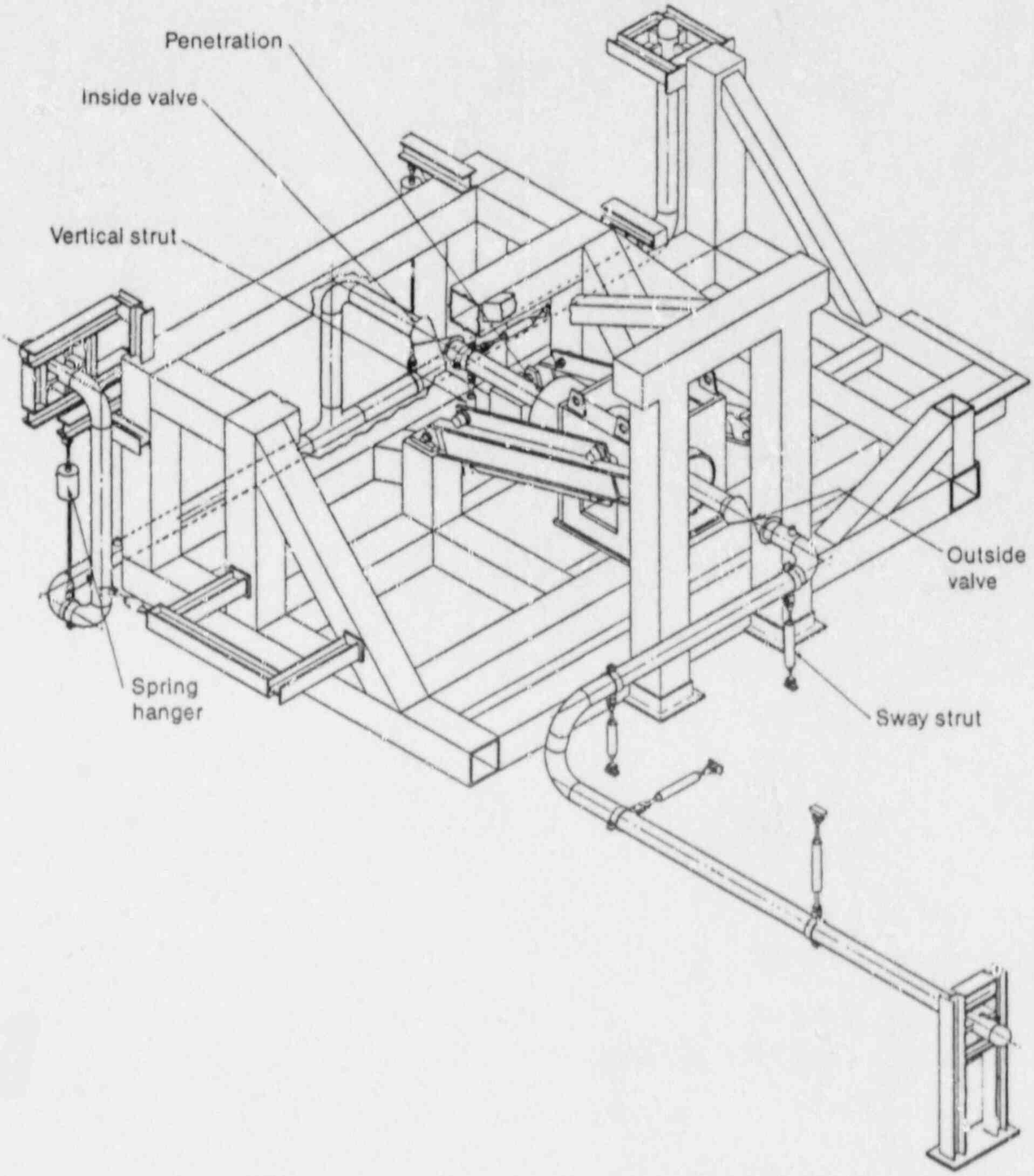

Figure 3. Isometric of 8-in. CPS piping arrangement.

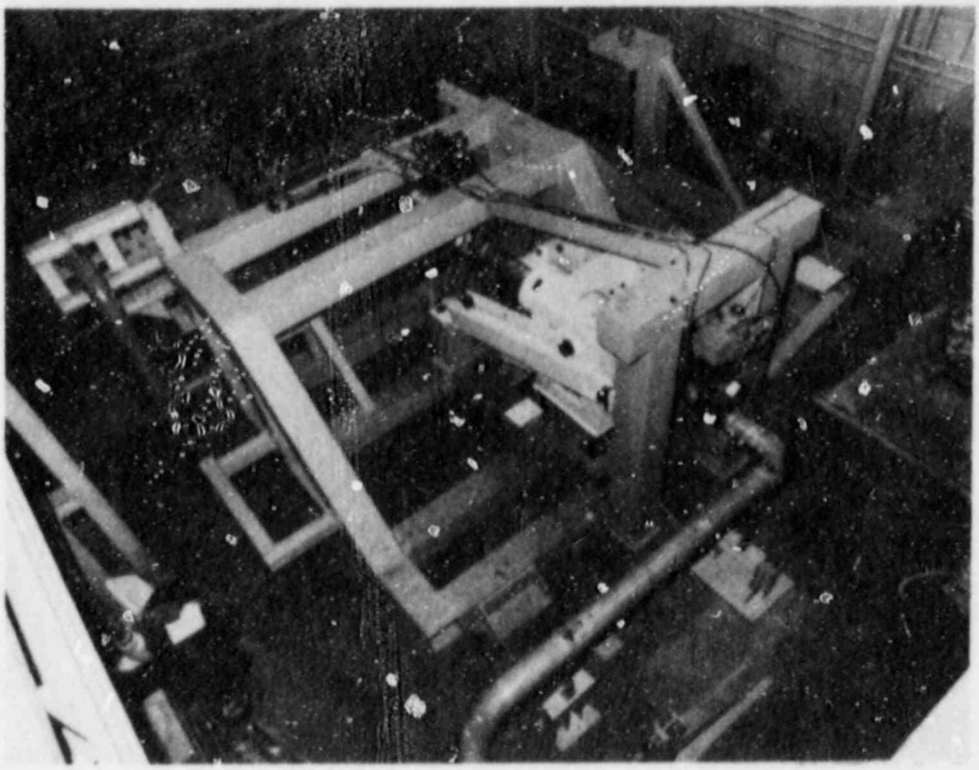

Figure 4. Overhead view of test fixture, penetration, and most piping of the 8-in. gate valve assembly.

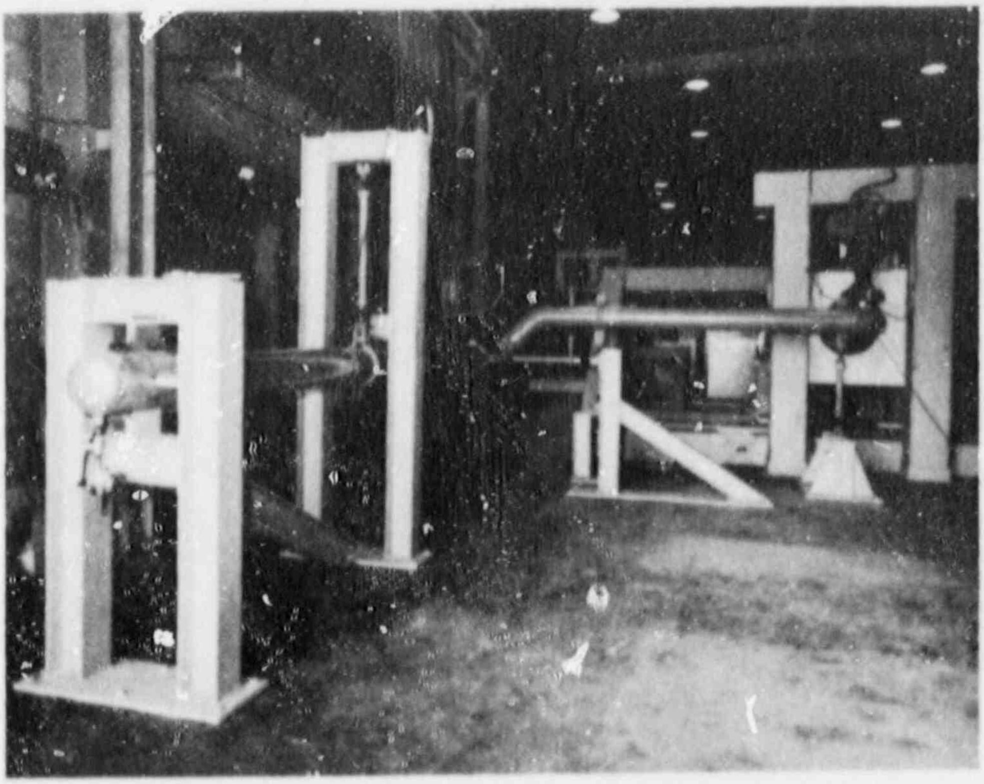

Figure 5. Outside piping with typical box beam support and pipe struts of the 8-in. gate valve assembly.

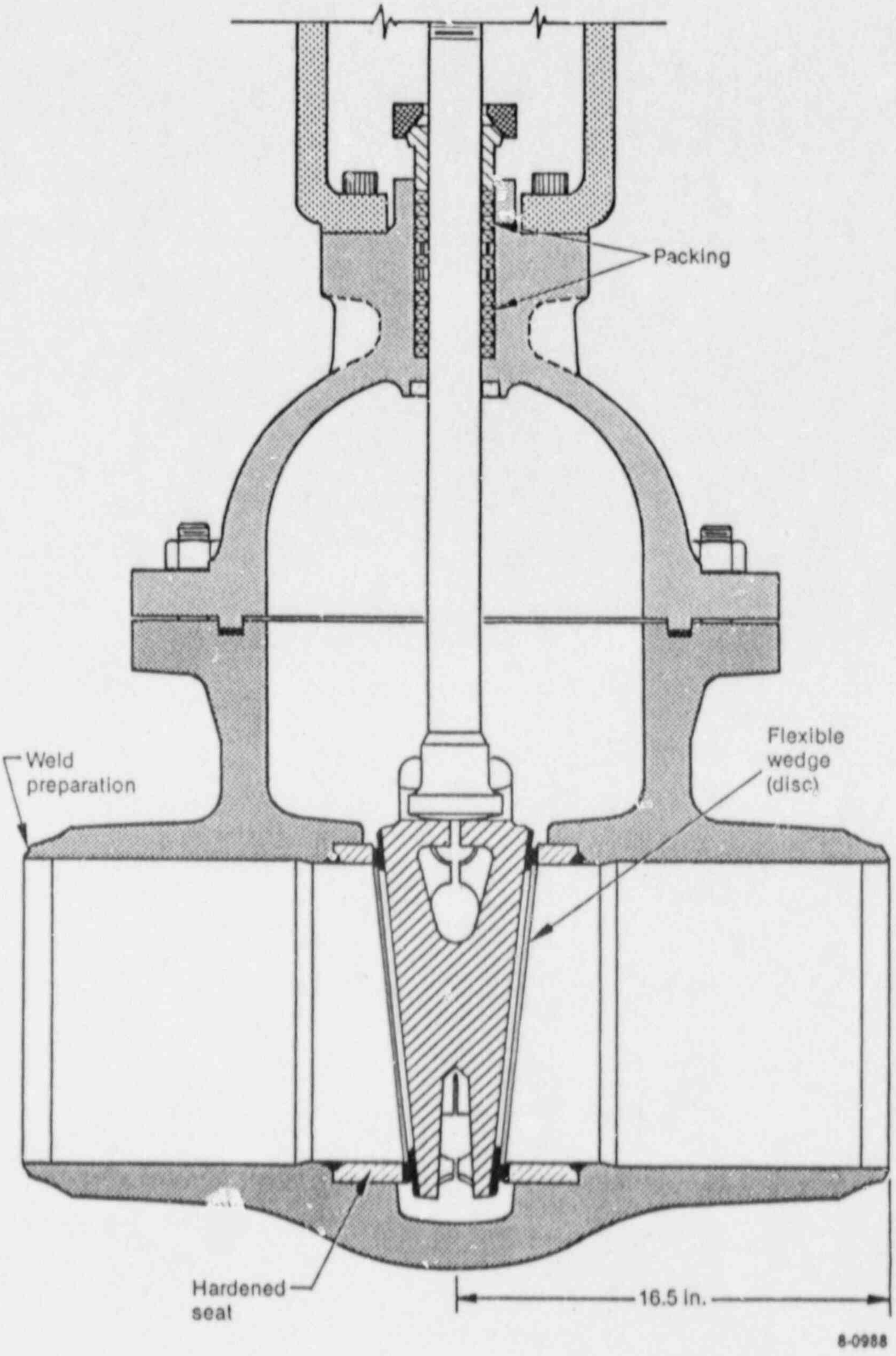

Figure 6. Cross section of the 8-in. gate valve.

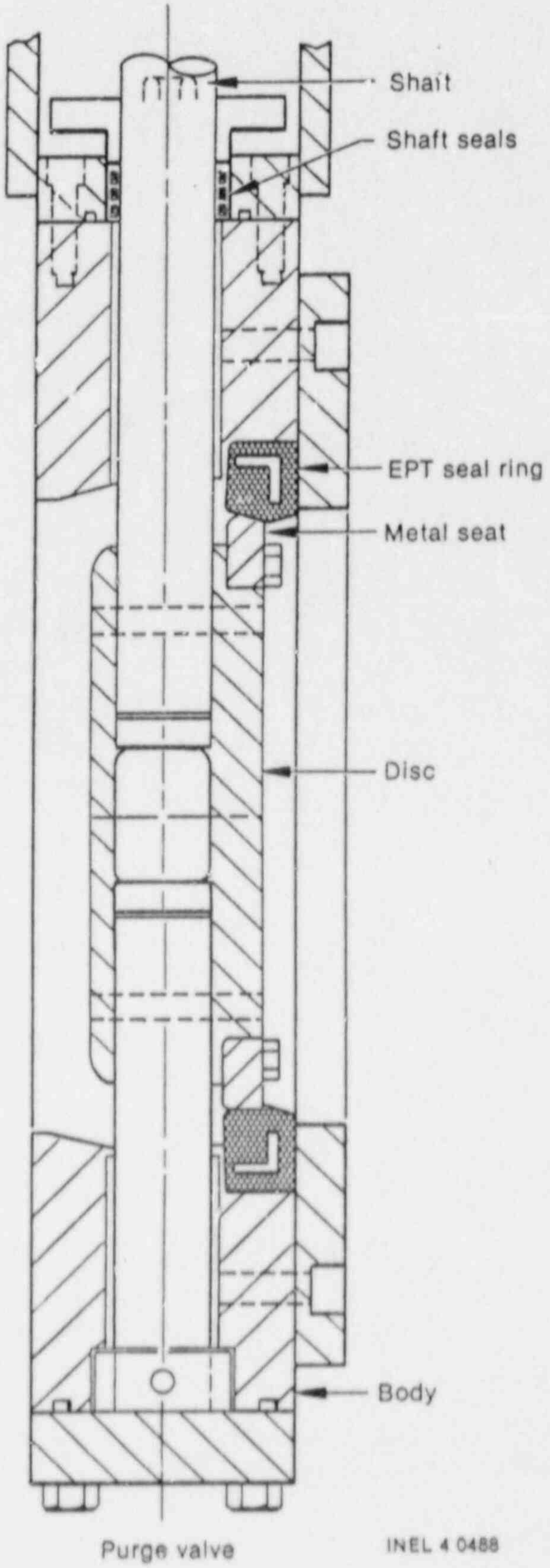

Figure 7. Cross section of the 8-in. butterfly valve.

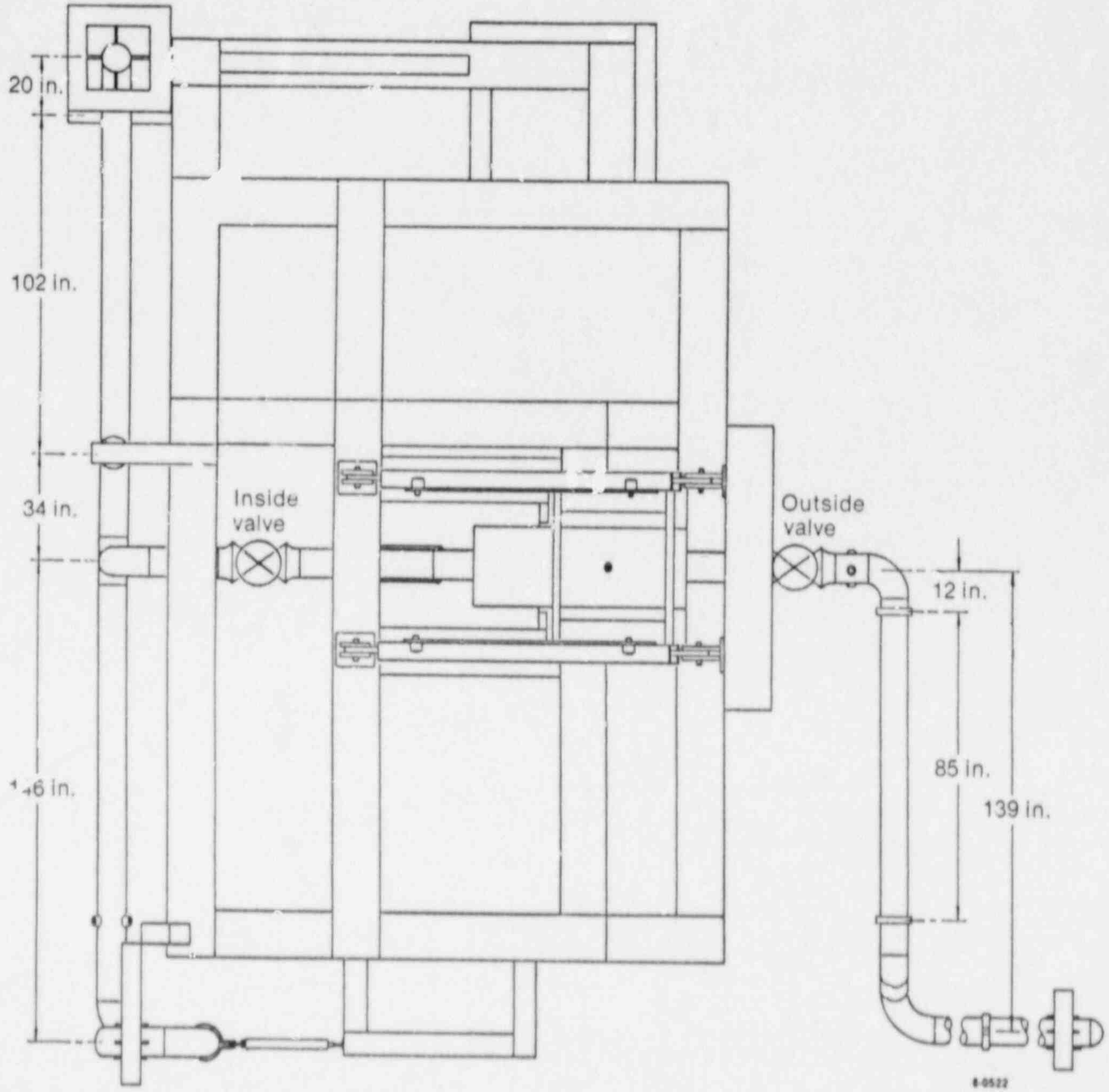

Figure 8. Plan view of 8-in. piping.

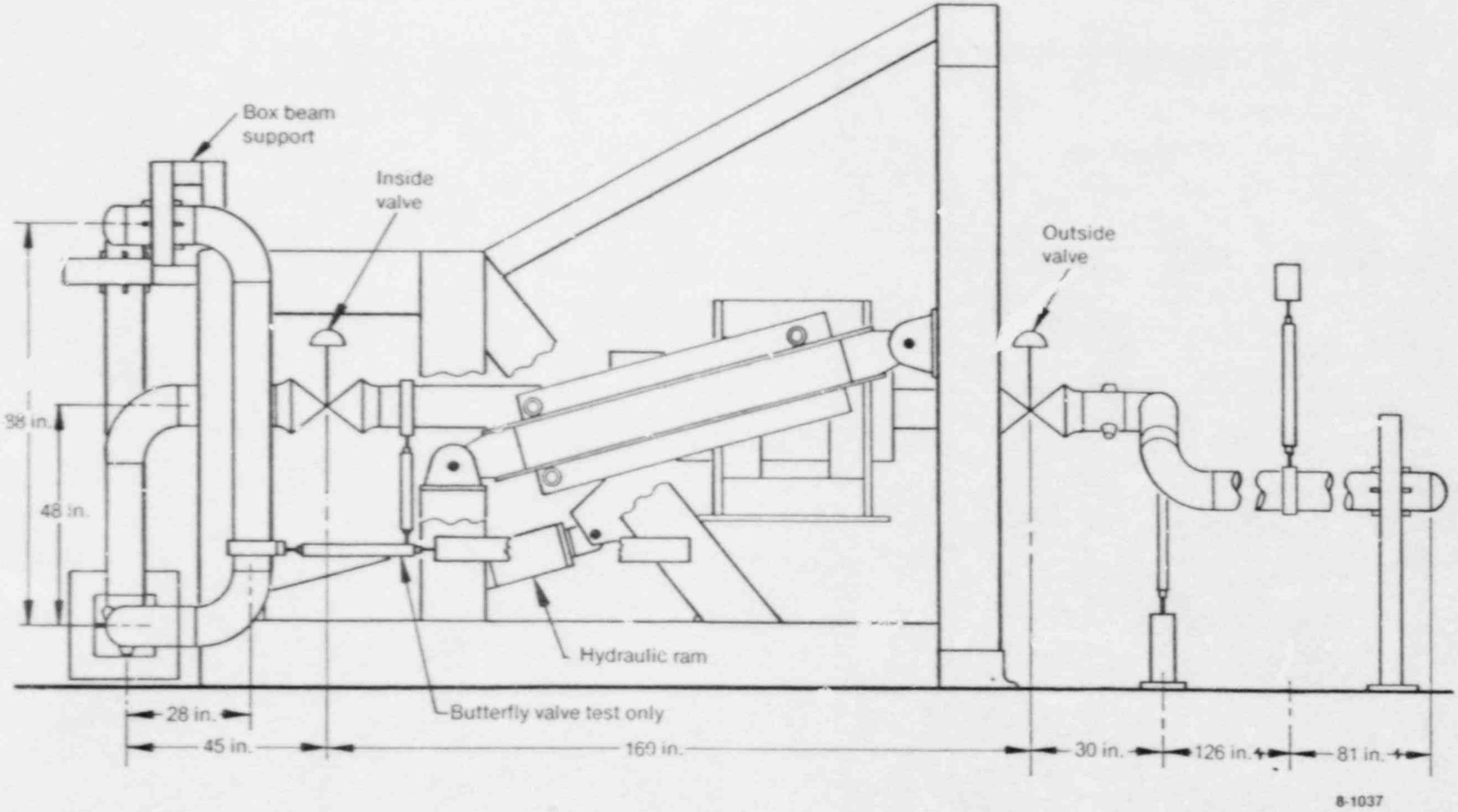

Figure 9. Elevation of 8-in. piping.

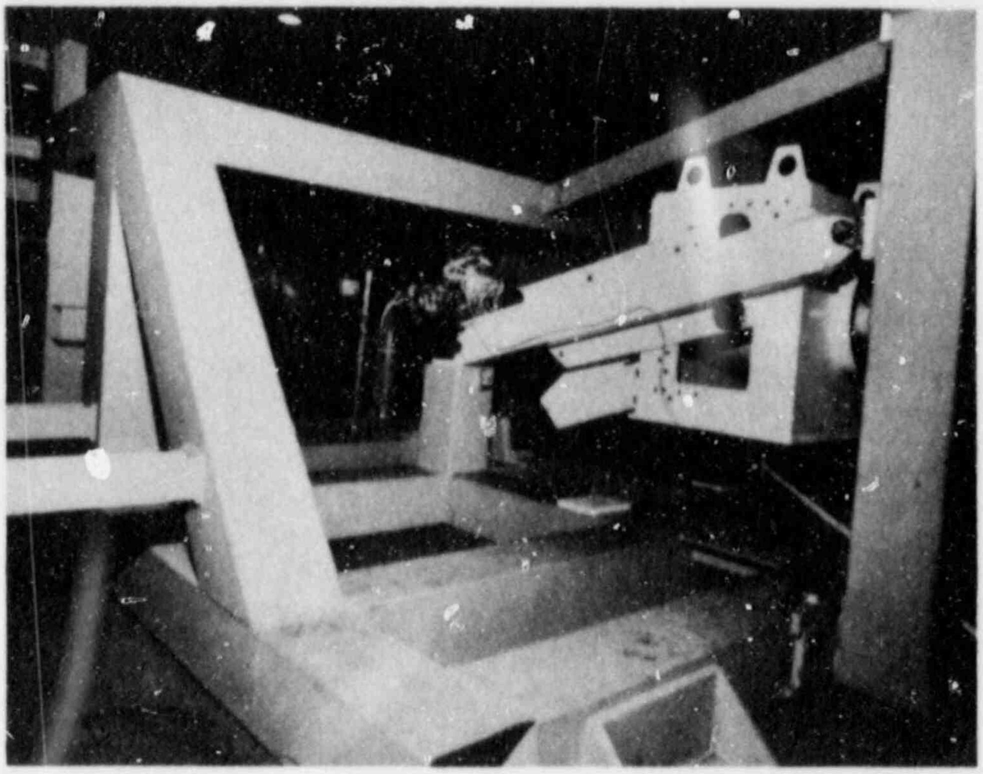

Figure 10. Penetration assembly mounted on rails.

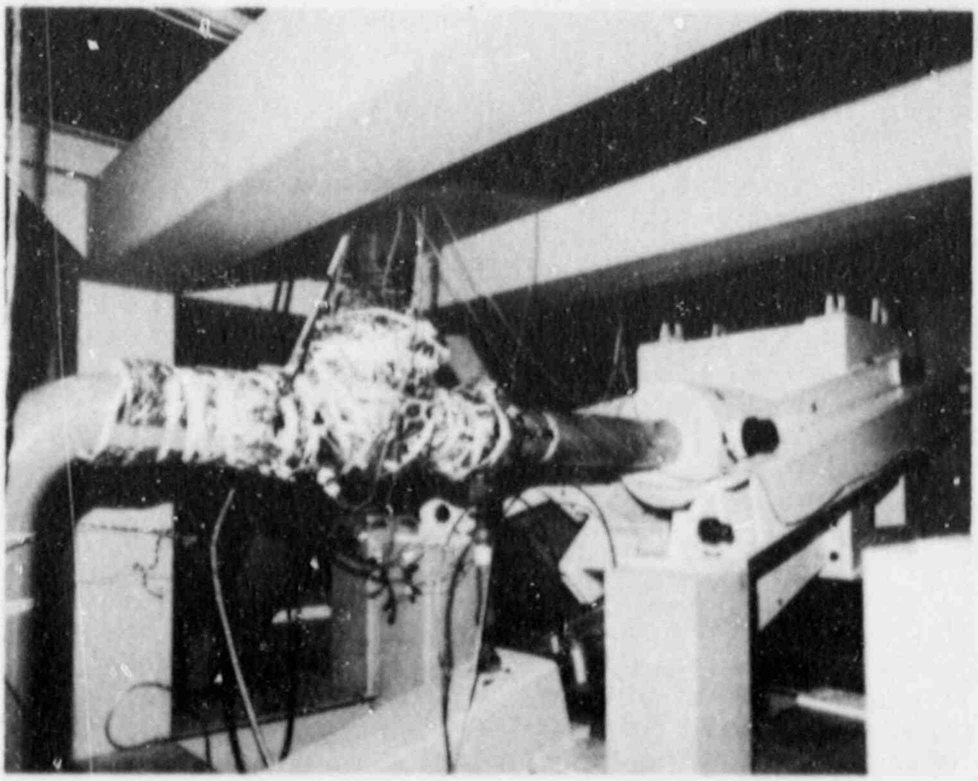

Figure 11. Penetration assembly, hydraulic cylinder, inside valve, inside vertical strut.

The 2-in. test system was not based on any particular piping system geometry, but rather was designed to allow the valve and piping to be tested with measured loads (shear and moment) in an effort to define failure thresholds without being constrained by predetermined displacement limits. An isometric sketch of the 2-in. system is shown in Figure 12. The one valve was a socket-weld 1500-lb carbon steel Y-pattern globe valve. A cross section of the valve is shown in Figure 13. The pipe was 304 Sch. 160 stainless steel. The penetration consisted of a 2-in.-by-12-in. stainless steel flued head welded to a 12-in. carbon steel pipe. All welds were socket welds except the attachment to the flued head penetration which was a butt weld.

3.3 Load Considerations

The CPS tests were designed to test the mechanical integrity and operability of penetration system valves and piping in response to mechanical, thermal, and pressure loads. Mechanical loads were applied by displacing the penetration relative to the piping which was anchored in a solid framework. The framework was constructed so that there would be no interference with valve operators during piping displacements. Thermal loads were applied to the valve bodies and selected portions of piping. Valve motor operators were not heated. Pressure (air or nitrogen) was applied to check for leakage across valve seats and to provide additional loading during valve operability tests (opening cycle). Sustained flow was not used. Mechanical loads on the containment systems were formulated and applied in terms of penetration movement (displacement). Radial displacement of the containment for design basis accidents was taken from published design data, which was reviewed and documented in the original test description and used for the 8-in. piping systems.

As mentioned in the introduction to this report, the severe accident loads applied to the two 8-in. CPSs were based on the pretest predictions and test results of a 1/6-scale model concrete containment experiment recently conducted at the Sandia National Laboratory.[9] Radial deflections of up to 18 in. were calculated for containment pressures up to 160 psig. The 1/6-scale model reinforced concrete containment liner tore at an equivalent radial growth of about 12 in. during the experiment. Therefore, 18 in. of radial deflection was used for the purge and vent system (butterfly valve) test and 13.2 in. of radial deflection was used for the containment spray (gate valve) test. A lower, but still conservative, value was used for the gate valve test because of facility limitations. Both tests used the 0.27 (15-degree) vertical-to-horizontal rise ratio typical of predictions for relative growth ratios for moderate elevations in the containment. Loads were applied in increments to produce the desired deflection. Measurements of valve operability and leakage were made at the incremental positions.

Mechanical load on the 2-in. globe valve test was based on a computer analysis of the test assembly which predicted the displacement and load necessary to achieve Section III, Class 1, Level D stress. This stress level was defined as the stress at the end of a design basis accident. Displacement at the end of a severe accident was initially defined as four times the design basis accident displacement. Since displacement was not limited by the 2-in. assembly test setup, displacement was eventually continued to 24 times the design basis value in search of a failure threshold.

The pressure loads (for 8-in. tests) chosen were those that would test the leak integrity and operability of each valve type under typical load conditions. For example, the differential pressure across the butterfly valve was set at 60 psig for the design basis accident part of the test and 120 psig for the severe accident part of the test. These were near the maximum values expected for valve operation under the stated conditions. The differential pressure across the gate valve was set at 100 psig. For the gate valve leak checks and valve function tests, pressure was applied to the piping section between the valves. For the butterfly valve test, pressure was applied to the piping upstream of the valve being tested. The test fluid for the 8-in. tests was air.

The differential pressure across the seat of the 2-in. globe valve was set at 1500 psig. The test fluid was nitrogen gas. Leak checks and valve function tests on the 2-in. valve were done with pressure applied alternately in both directions across the seat. The design basis accident portion of the 2-in. globe valve test also included a pressurization transient resulting from thermal expansion of water in the downstream piping.

The maximum temperature for the design basis accident portion of the tests was 280°F. Temperature loading on all systems varied with mechanical loading up to a maximum of 350°F for the severe accident portion of the tests. Only the inside valve was heated during the 8-in. gate valve test. Both the inside valve and the penetration piping were heated during the 8-in. butterfly valve test. Both the valve

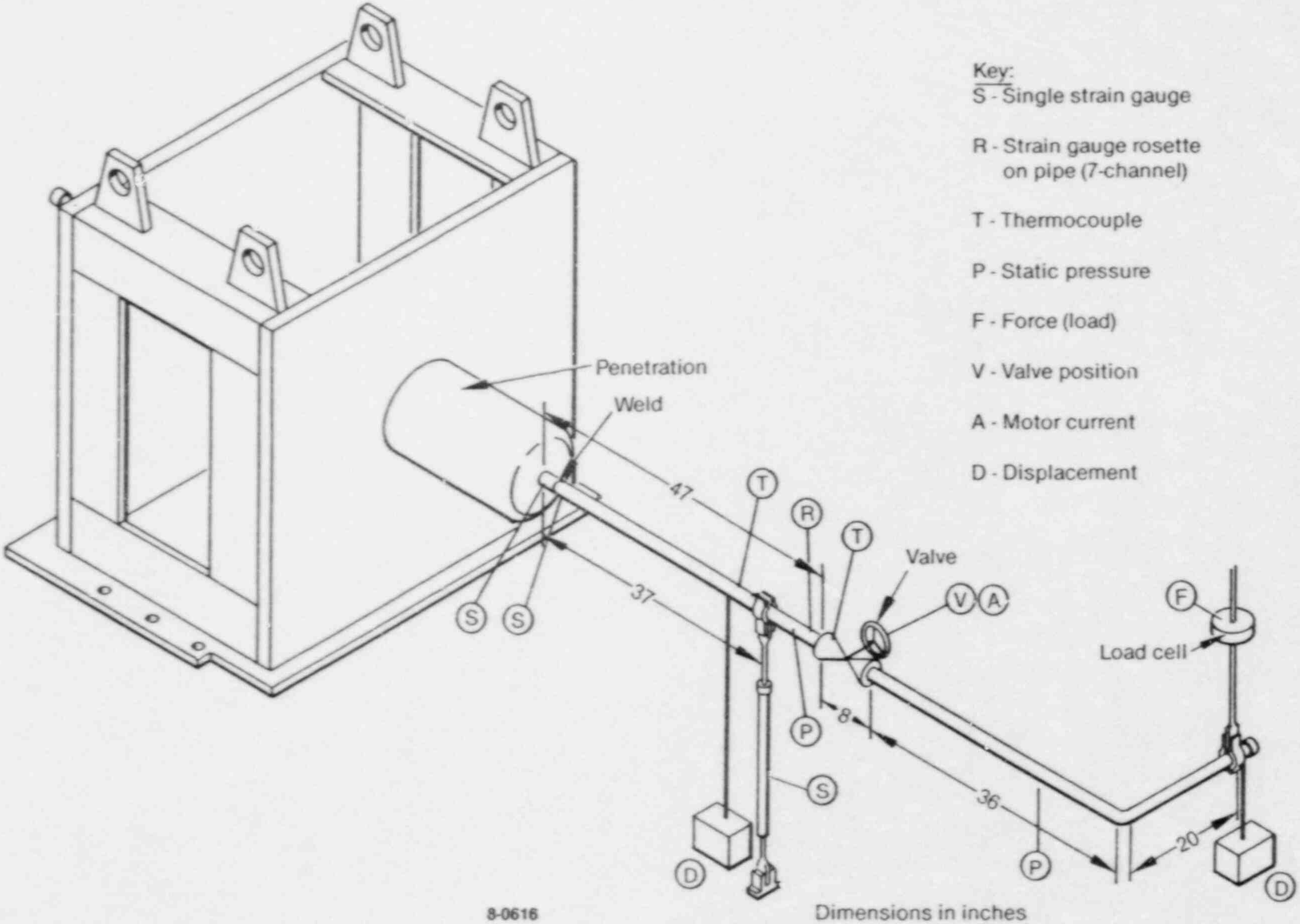

Figure 12. Isometric of 2-in. test system with instrumentation.

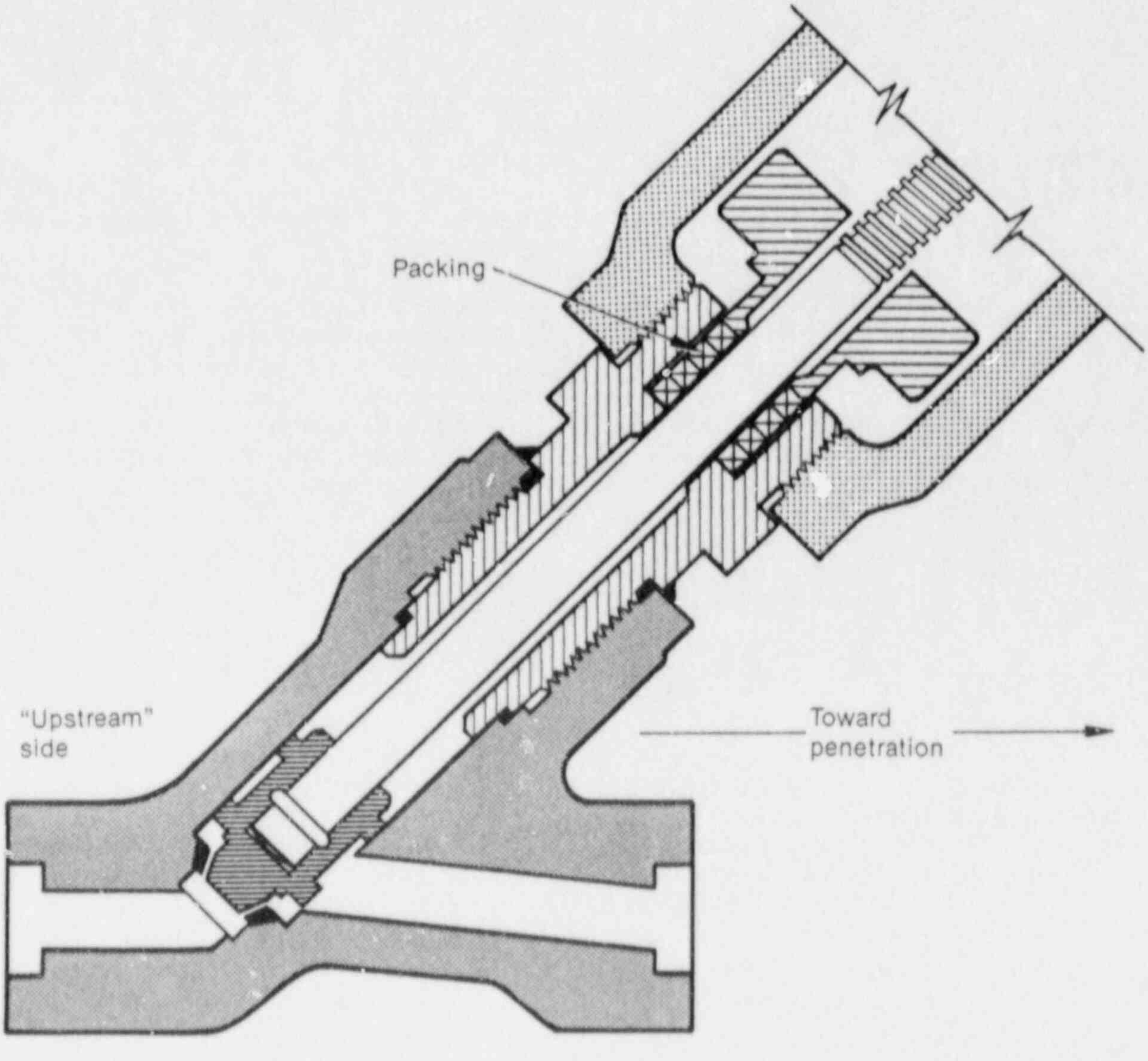

Figure 13. Cross section of the 2-in. globe valve.

and piping to the penetration were heated during the 2-in. globe valve test.

3.4 Instruments

The systems were instrumented to measure leak rates, pressures, temperatures, valve motor operator current, valve stroke times, and strains on the valves and piping. Isometric drawings showing instrument locations for the gate valve and butterfly valve tests are presented as Figure 14. A typical strain gauge installation on the piping consisted of six strain gauges mounted at each axial location. Four gauges were axial and mounted 90° apart around the pipe circumference. The other two formed a standard rosette configuration with one of the axial gauges (for torsion measurements). The instrumentation on the 2-in. globe valve test system is shown in Figure 12. Lists of the measured parameters r all three tests are presented in Appendixes A, B, and C. Valve seat leak measurements were taken with calibrated variable-area flow meters (0.0003 - 0.8 scfm). Flows exceeding the meter range were calculated from pressure decay.

3.5 General Testing Sequence

Each of the three systems was separately subjected to a testing sequence simulating design basis and severe accident conditions. The basic testing sequence consisted of (a) performing operational baseline tests on the system and (b) heating the inside valve and displacing the penetration (or pipe) in a stepwise fashion until reaching the desired conditions, while monitoring valve function, valve seat leakage, and strains on the piping. The testing sequences for the 8-in. and 2-in. systems are summarized in Table 4. Baseline and valve function data included leakage measurements through the valve, valve stroke time from open-to-close and close-to-open, and valve actuator current measurements when opening and closing. Opening current was measured both with the system at atmospheric pressure and with the system at increased pressure (on one side of the valve at a time) for the initial unseating of the valve. In all cases, the valve function and leakage tests were repeated regularly throughout the test to detect any changes in leakage or actuator demands.

While the 2-in. piping system was mechanically the simplest of the three systems tested, the operational sequence involved a greater variety of conditions. The design basis accident simulation portion of the 2-in. test included a heatup of the water-filled penetration pipe to 280°F with the valve closed to check for overpressurization due to thermal expansion of the water. The severe accident simulation portion of the 2-in. test included valve function and leakage tests with increased displacement and temperature. Valve testing was done with 1500-psig nitrogen pressure applied alternately upstream and downstream from the valve. After the severe accident simulation testing sequence, the vertical support strut was disconnected to allow more direct loading of the penetration assembly. Valve function and leakage data were not taken during this portion of the test. After attempting to induce damage in the penetration assembly, the vertical strut was reconnected to maximize moment loading on the valve. Vertical displacement was continued (with valve function and leakage tests) until the pipe was sufficiently bent to the point that additional displacement would have caused the valve operator to contact the pipe.

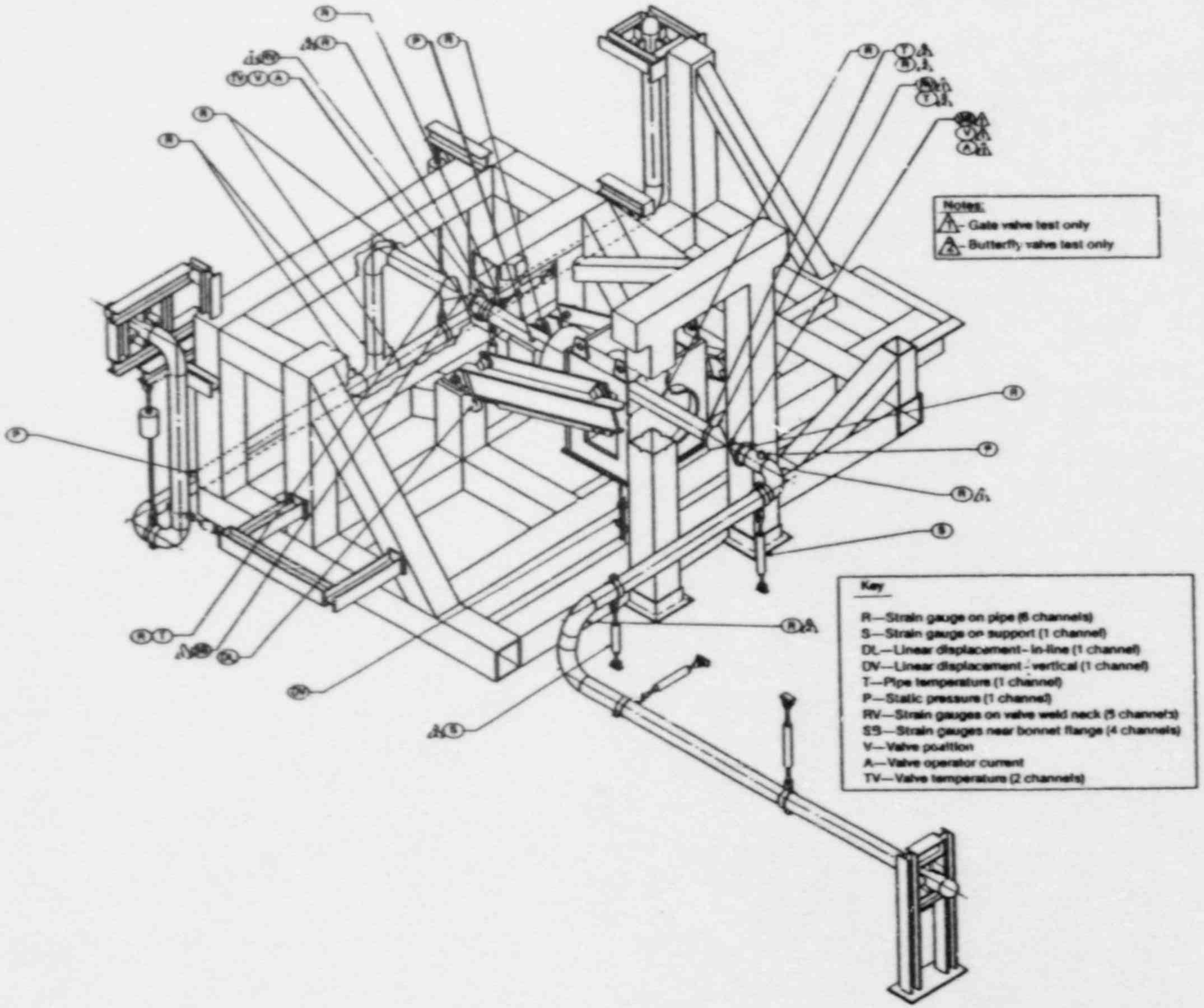

Figure 14. Isometric of 8-in. test system with instrumentation.

Table 4. Summary of testing sequence

System Integrity and Pretest	Design Basis Accident Simulation	Severe Accident Simulation	After Severe Accident Simulation
8-in. Systems:			
Radiography of Piping Welds 300 psi Pneumatic Test 100 psi Bubble Test (Butterfly Valves Only) Baseline Valve Function	Heat valve to 280°F while displacing penetration 1.04 in. (horizontal) Regularly monitor leakage and valve function	Heat valve to 350°F while displacing penetration to 13.2 in. (gate valve) and 18 in. (butterfly valve) Regularly monitor leakage and valve function	Release load Check for leakage and valve function
2-in. System:			
4750 psi Hydrotest Dye-Penetrant Exam Baseline Valve Function	Fill pipe with water downstream from valve Heat valve and pipe to 280°F while displacing pipe 2.0 in. (vertical) Monitor pipe for pressure buildup	Drain water from pipe Heat valve to 350°F while displacing pipe 8 in. (vertical) Regularly monitor for leakage and valve function	Apply load to flued head Displace to disfunction or failure Valve function 4750 psi hydrotest Dye-penetrant exam

4. TEST RESULTS

This review of test results is directed at providing information to answer three questions:

Are qualification testing loads conservative compared to measured DBA loads?

What effect did the thermal, pressure, and mechanical loads have on CPS valve operability?

What effect did the thermal and mechanical loads have on containment penetration system integrity?

The first question addresses the issue of conservatism in qualification testing methods. The last two questions address the issue of whether typical containment penetration systems can perform their intended safety function during and following a design basis or severe accident event. This section of the report presents results from the tests and interprets the results to answer these questions.

A separate section is presented for each of the three systems tested. Each section includes a description of the test as conducted and an evaluation of the performance of individual system components.

4.1 Containment Spray: 8-In. Gate Valve Testing and Results

The purpose of this part of the test program was to evaluate the ability of a containment spray CPS installation with gate valves to remain leak tight and maintain valve operability when exposed to design basis and severe accident temperatures, pressures, and mechanical loads. The gate valves were equipped with a flexible wedge, hardened seats, weld ends, packed stem, and a bolted bonnet (see Figure 6). The valve was N-stamped and met all of the qualification requirements for installation in the Hope Creek Nuclear Power Plant. The system was assembled and pressure-tested at 300 psig prior to starting the design basis accident portion of the test. Piping welds were radiographed and inspected to ASME, Section III standards. Stem packings in the valves were replaced, and the valves were given baseline operability and leakage tests. The electrical heaters and insulation were installed on the inside valve. Instruments and heaters were checked for continuity and operability.

Temperature and displacement were increased during the 8-in. gate valve CPS test, as shown on Table 5. Both valves were kept closed except for specified operational tests. At each displacement increment, leakage was measured through each valve by pressurizing the piping between the valves to 100-110 psig and measuring leakage through calibrated variable-area flowmeters. Where valve operability tests were specified, the center section was again pressurized to 100-110 psig, and the upstream pipe was vented to the atmosphere. The inside valve was then opened and closed while monitoring operator current and measuring stroke times. The sequence was then repeated for the outside valve. Leak measurements were taken prior to proceeding with the next displacement step.

The pace at which the test was conducted depended on the heatup rate of the valve (limited to ∼0.6°F/min) and time required to perform leak checks and valve function tests and to fix problems in the test hardware, both mechanical and electronic. A plot of the horizontal displacement and average temperature of the inside valve vs. time is presented in Figure 15. As shown in this figure, there was an 8-h interruption at the end of the design basis accident simulation portion of the test, during which the temperature was reduced from 280 to 200°F. The temperature was increased to 280°F again in preparation for continuation of the experiment. The penetration position was held constant during the 8-h hold. Displacement and temperature were then gradually increased to 13.2 in. and 350°F during the severe accident simulation portion of the test. Displacement was interrupted at 25 h to add extensions under the base of the hydraulic ram.

There were no catastrophic failures during the testing of the 8-in. gate valve system. None of the supports parted, the valves continued to operate (with some increase in leakage through the inside valve), and the piping did not experience local buckling or any significant reduction in flow area.

With the exception of the horizontal strut, all strains increased with increasing penetration displacement. Valve leakage reached a maximum of about 0.89 scfm after the driving load was relieved from the penetration. The following sections provide a more detailed description of the behavior of the various components during the displacement and heatup cycle.

Table 5. Containment penetration displacement and valve temperature for 8-in. gate valve test

Horizontal Displacement (in.)	Inside Valve Temperature (°F)	Valve Function Test	Horizontal Displacement (in.)	Inside Valve Temperature (°F)	Valve Function Test
0.0	AMB	Yes	1.90	311	—
0.035	AMB	—	1.95	315	Yes
0.31	AMB	—	2.01	319	—
0.39	120	Yes	2.08	323	—
0.45	120	—	2.12	327	—
0.52	120	—	2.18	331	—
0.64	120	—	2.24	334	Yes
0.73	120	Yes	2.26	338	—
0.81	120	—	2.37	342	—
0.94	120	—	2.45	346	—
1.01	120	Yes	2.54	350	Yes
1.08	160	—	2.70	350	—
1.17	200	Yes	3.25	350	Yes
1.28	240	—	4.32	350	—
1.35	280	Yes	5.37	350	Yes
End DBA	—	—	6.43	350	—
Start SA	—	—	7.00	350	Yes
1.39	284	—	8.58	350	—
1.47	288	—	9.47	350	Yes
1.54	292	—	10.72	350	—
1.61	296	Yes	11.77	350	—
1.69	299	—	12.84	350	—
1.77	303	—	13.35	350	Yes
			Load release	350	—
1.84	307	—	9.50	—	Yes

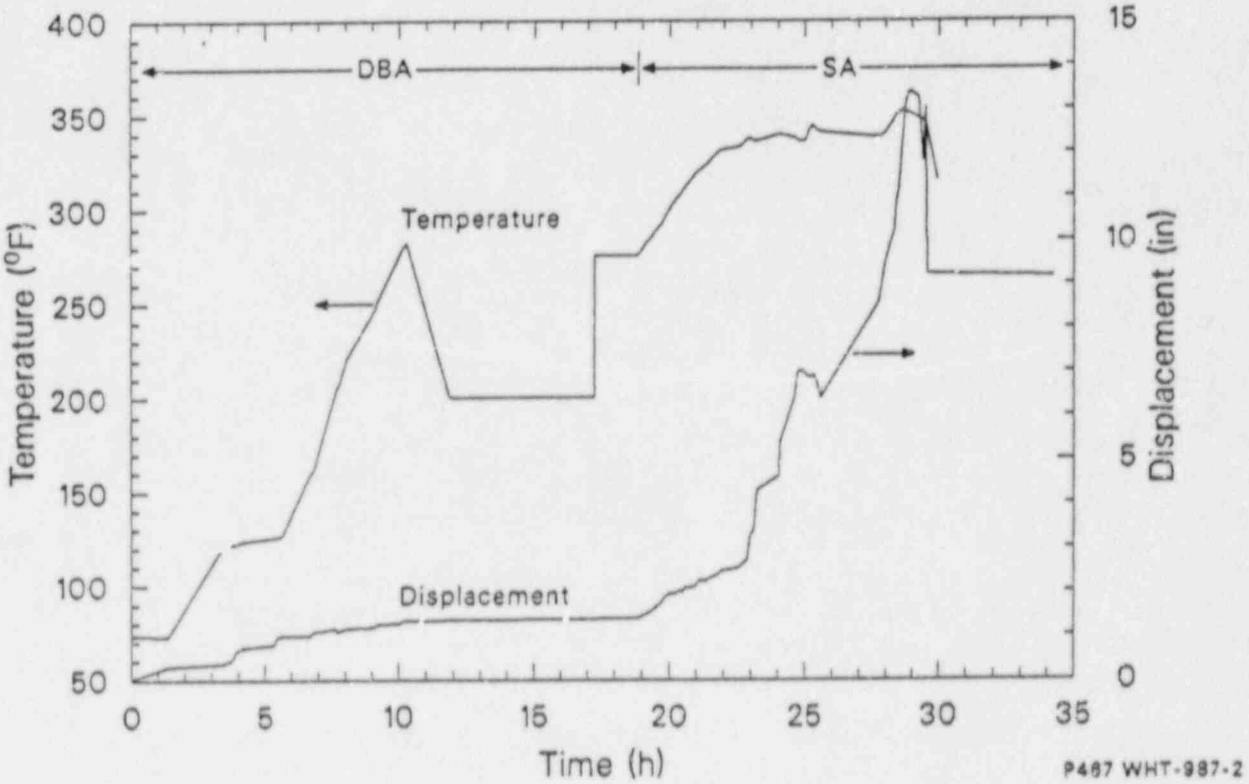

Figure 15. Horizontal displacement and average inside valve temperature during 8-in. gate valve test.

4.1.1 Valves. Valve performance was characterized by operator current, stroke time, and valve seat leakage. Typical current-vs.-time curves for opening and closing the inside valve are shown in Figure 16. The initial low-level spike on the opening stroke is attributed to motor startup; the operator was then loaded by the force required to *unwedge* the valve disk from the seat and to overcome friction drag between the disk and seat resulting from the pressure load of the applied 100 psid. Once these two loads were relieved, the operator motor attained the steady-state running current required to overcome stem packing load and friction in the gears of the operator. A position limit switch interrupted current to the operator once the valve reached its fully open position. The closing stroke also started with a small inrush current peak, then maintained a steady load until the disk made contact with the seat. The load and current then increased rapidly until the torque switch interrupted current. The highest currents occurred as the disk was lifting off the seat at the beginning of the opening stroke and at the end of each closing stroke. Since the start of the stroke was the time at which maximum pressure load (about 100 psid) was applied and the disk was simultaneously being unwedged from the seat, the higher current would be expected. The peak opening currents for the inside valve as a function of pipe displacement are shown in Figure 17. The opening and run currents were not influenced by the penetration displacements and were similar to the values measured before the test (baseline). At the end of the test, the valve was left in the fully closed position and allowed to cool from approximately 350°F to ambient. The first opening stroke after cooldown required a peak motor current of 1.46 A; subsequent cycles remained within the data extremes previously recorded. Valve stroke times for both valves remained essentially constant throughout the test and were from 36.6 to 37.5 s as measured from limit switch operation. Operator current traces for the outside valve are similar to those for the inside valve. The inside and outside valve operators were not measurably affected by the loads imposed on the piping.

The leakages through the seats of the inside and outside valves are plotted on Figure 18 versus displacement. The inside valve leakage remained below the 0.005 scfm required to meet specifications for tight shutoff until the displacement exceeded twice the design basis accident

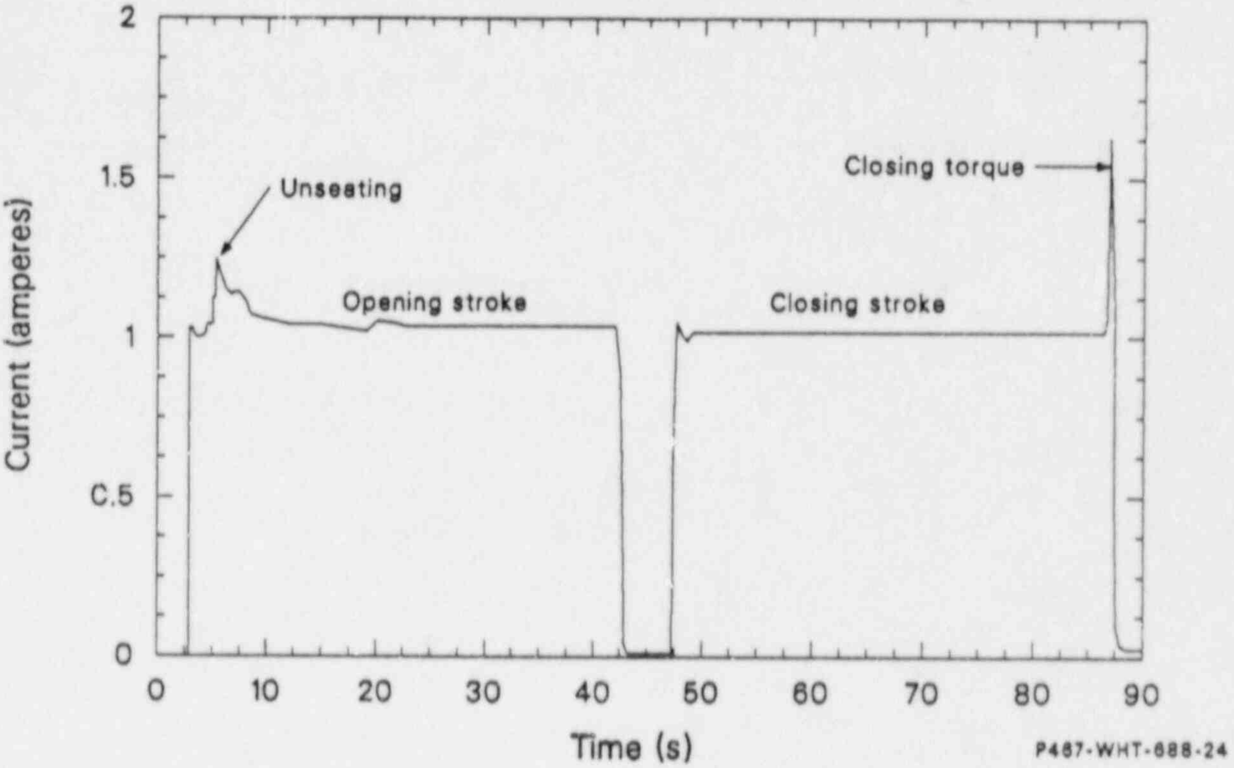

Figure 16. Typical current vs. time curves for inside valve during 8-in. gate valve test.

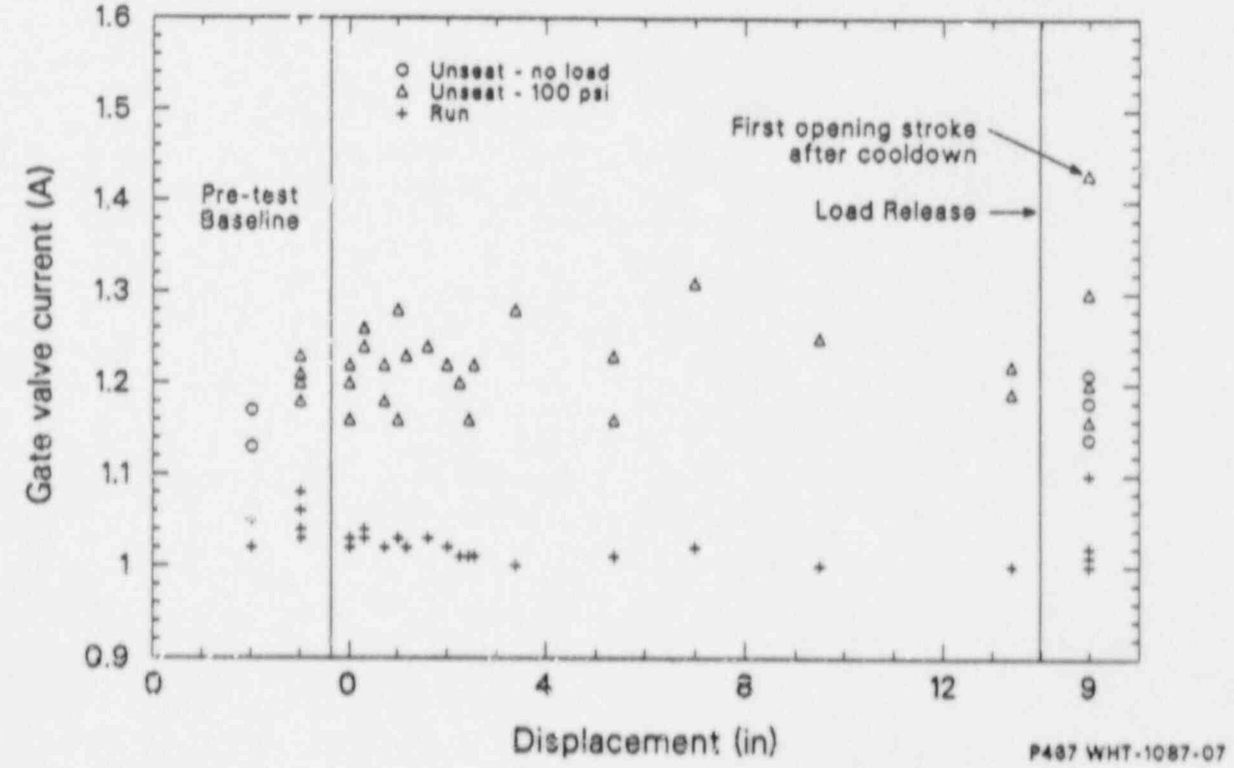

Figure 17. Opening currents for inside valve during 8-in. gate valve test.

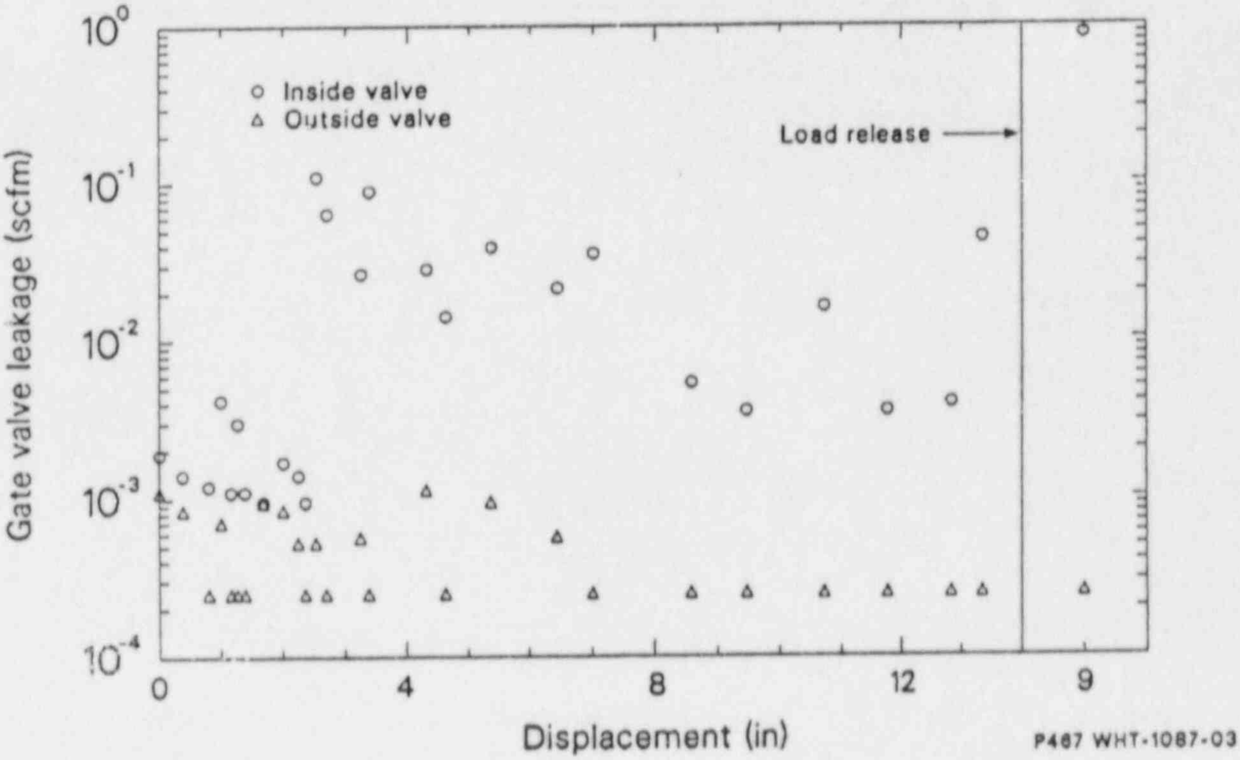

Figure 18. Gate valve leakage vs. horizontal displacement for 8-in. gate valve test.

specification. At a 2.6-in. horizontal displacement and 346°F, the leakage increased to about 0.103 scfm after cycling the valve. Leakage then decreased to a range of about 0.02-0.04 scfm for the remainder of the displacement ramp. When the load was released from the penetration, the piping system returned about 4.2 in. toward its original position, and the leakage through the inside valve immediately increased. This leakage, calculated on the basis of pressure changes, was 0.89 scfm. It remained at this level when closing the valve with the operator. By manually closing the valve with the integral handwheel, the leak could be reduced to levels similar to those measured at the beginning of the test.

Strain measurements on the piping next to the inside valve nozzle indicated that yield stress (approximately 1220 μin./in.) was exceeded in this area (see Figure 19). Posttest measurements have shown the bonnet gasket locating ring to be elongated by 0.010-in. in the axial direction. There was also 0.005-in. clearance on each side of the top of the gate. The measured strains on the valve body and piping suggest that the seat wedge at the top was in compression during the test. Therefore, the opening of the seat at the top of the wedge was caused by yield of the valve body and release of residual compressive stresses when the load was relieved after maximum displacement. This theory is consistent with the fact that the largest leak occurred upon relaxation of the load. Strains in the valve bonnet area remained well below yield throughout the tests. Moments calculated from the measured strains did not exceed the moments which would have been required in valve qualification testing to ANSI B16.41 (QV4).

A stem packing leak also occurred on the inside valve late in the displacement cycle and was calculated to be 0.81 scfm. It should be noted that the packing was dry, new, and had not been tightened during the test. The packing was sealing dry gas and had been at a temperature over 350°F for more than 12 h.

The outside valve leakages are also plotted on Figure 18 and indicate no significant leakage and no change in leakage throughout the test.

4.1.2 Pipe Supports. Strain was measured in the two highly loaded inside struts. On the basis of these measurements and strut geometry, the peak loads were calculated to be 35,000[a] lb for the

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[a] Based on 30,000-psi yield; strut body was elongated 0.25%.

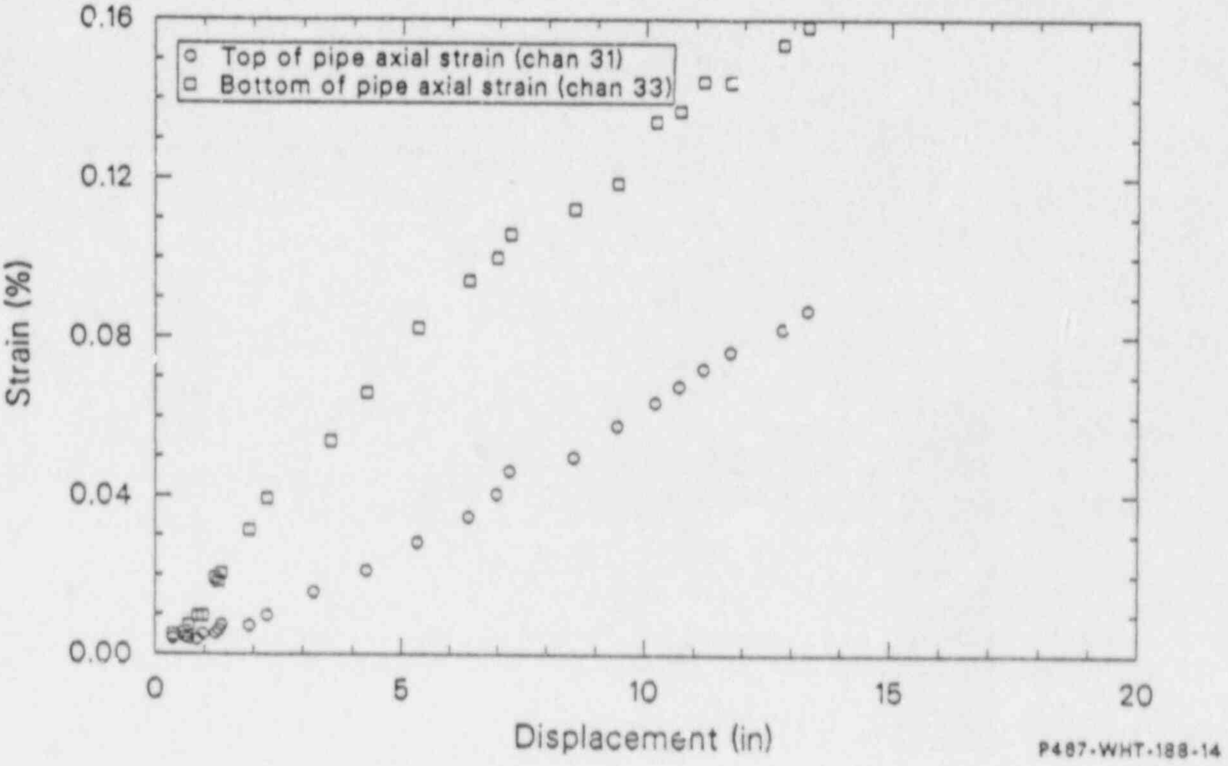

Figure 19. Strain on inside gate valve for 8-in. gate valve test.

horizontal strut (7.7 times the rated capacity) and 61,000 lb (7.6 times the rated capacity) for the vertical strut. Visual examination of the struts and attachments revealed the following: the bushing at the piping end of the vertical strut had broken; the bolt at the vertical strut attachment to the pipe clamp was severely bent; the pipe clamp was severely deformed (see Figure 20); the pipe under the clamp was locally yielded; and the clamp had slipped along the axis of the pipe. The pin in the fixture attaching the vertical strut to the frame was also bent. The end connections on the vertical strut had permanently elongated about 5%. The support loads calculated from the measured strains greatly exceeded the support design loads.

The horizontal strut was not damaged to the same degree, and there was no external evidence of bushing or pin failure. The pipe clamp for the horizontal strut was also deformed and had slipped along the pipe, and the pipe had locally yielded. The horizontal strut was permanently elongated 0.2% in the barrel section; no damage was apparent in the threaded end connectors. The attachments of the horizontal strut to the test fixture were undamaged.

The force vs. displacement curves for the struts are presented in Figure 21.

4.1.3 Piping. The piping behaved in a ductile manner and survived local deformations and large bending moments that caused significant yielding through the cross section. The highest measured strain occurred on the inside piping at its entry into the penetration assembly. As illustrated in Figure 22, this strain reached 4.7% (0.12% is approximately yield).

In addition to some minor and very localized deformations associated with pipe supports, the piping exhibited a significant amount of ovalizing in the last (farthest downstream) outside elbow. The external shape had changed from a circular cross section with a diameter of 8.67 in. to oval with major and minor axes of 9.16 and 8.36 in. respectively. The pipe strains measured at various locations throughout the system at the maximum horizontal displacement of 13.2 in. are listed in Table 6. Appendix A provides additional information on the location at which the strains were measured.

After the hydraulic pressure to the ram was relieved, the elastic strain in the piping system

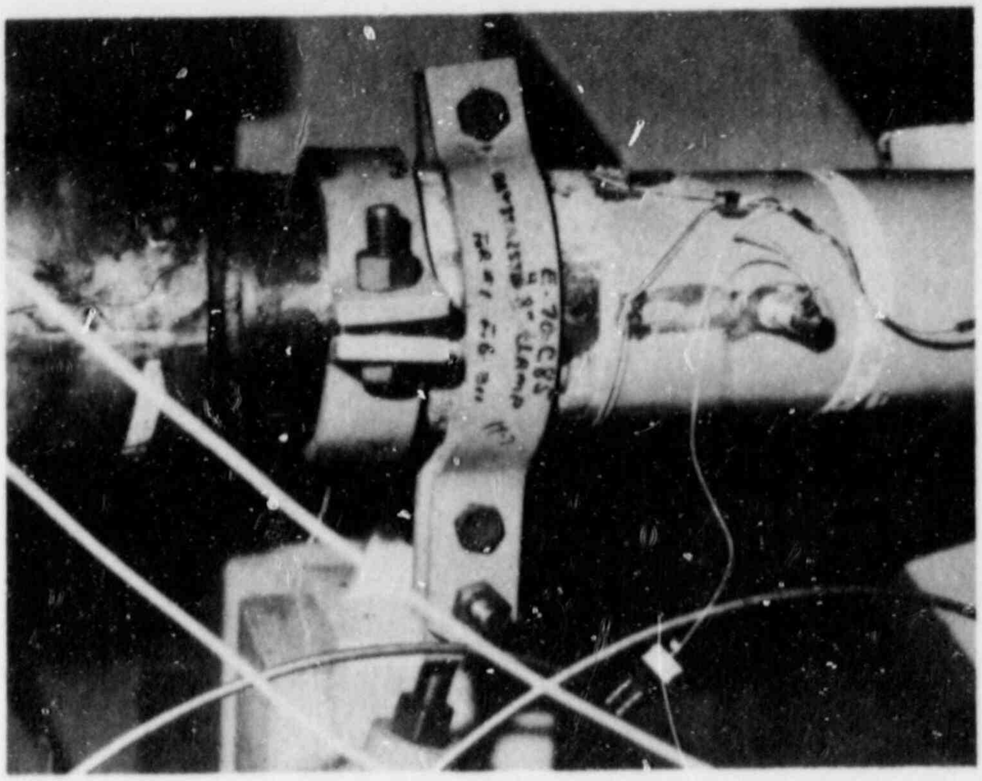

Figure 20. Distorted pipe clamps near inside 8-in. gate valve.

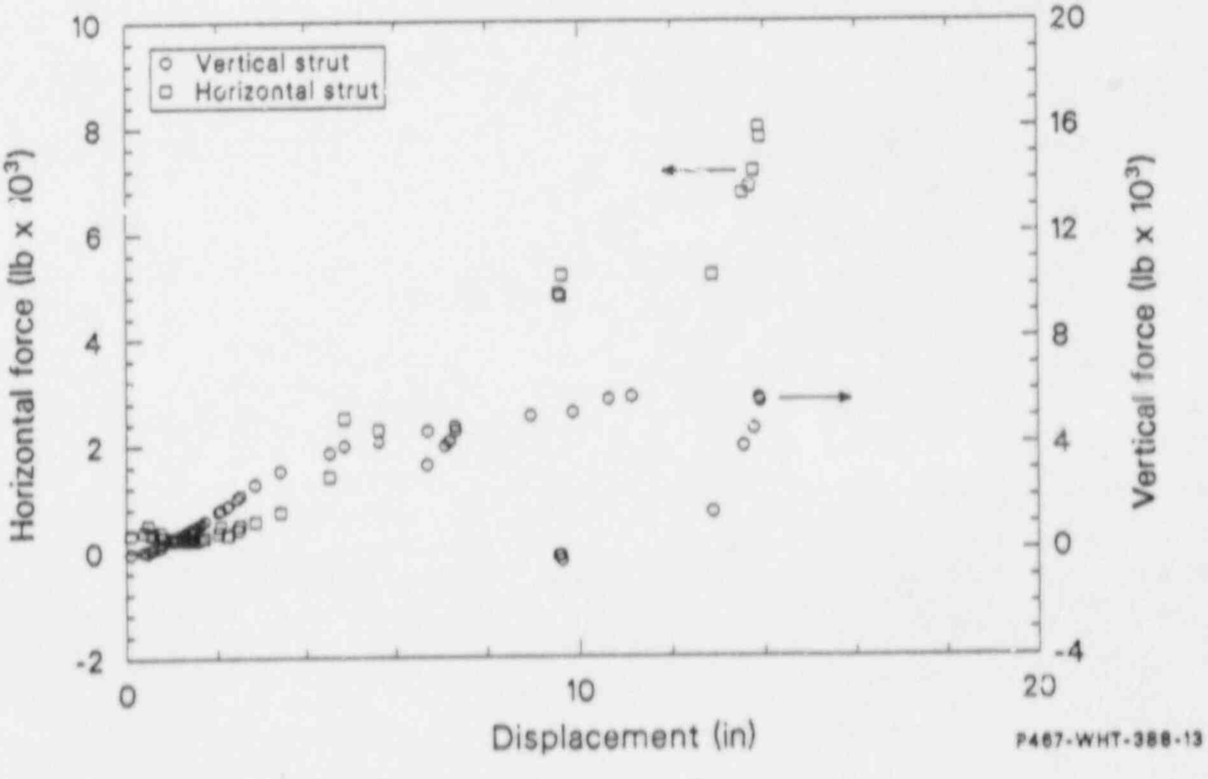

Figure 21. Strains on pipe supports near inside valve of 8-in. gate valve test.

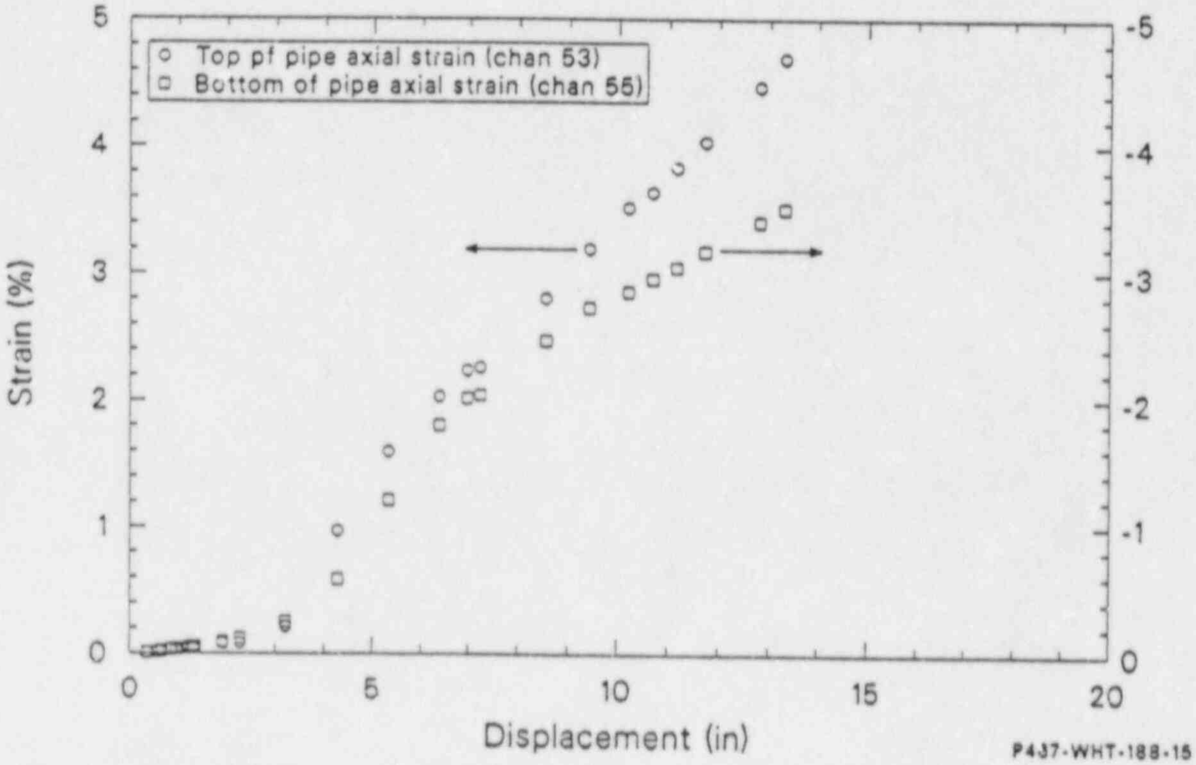

Figure 22. Strains on inside piping for 8-in. gate valve test.

Table 6. Maximum pipe system strains for 8-in. gate valve test

System Location	Gauge Orientation[a]	Strain Measurement (10^{-6} in./in.)
Horizontal piping near tee (right branch facing penetration from inside containment)	4	−13,450
Horizontal piping near tee (left branch)	4	20,330
Vertical piping near tee	5	1,470
Horizontal piping near inside elbow	5	3,200
Horizontal piping near inside valve, upstream	5	−1,750
Inside valve nozzle, downstream	1	−2,290
Piping near inside struts, downstream	1	−7,000
Near penetration, inside piping	1	46,860
Near penetration, outside piping	3	−17,750
Outside valve nozzle, downstream	2	−280
Near first downstream elbow, upstream	5	7,700
First downstream elbow	3	12,870

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a. Orientations of strain gauges were as follows: (1) on top of pipe measuring axial strain, (2) on right side of pipe, facing downstream, measuring axial strain, (3) on bottom of pipe measuring axial strain, (4) on left side of pipe, measuring axial strain, (5) on top of pipe, measuring circumferential strain.

caused the piping to return 4.2 in. horizontally (32% of the maximum displacement) toward its original position. Figures 23, 24, and 25 show the conditions of selected parts of the CPS following load removal. The strut immediately downstream of the outside valve is obviously misaligned and the pipe clamp has rotated around the pipe as can been seen in Figure 23. Figure 24 shows the misalignment of the inside vertical strut. Also apparent in this figure is the bending in the pipe between the inside valve and the penetration. Finally, Figure 25 shows the permanent bending in the long horizontal section of the inside piping.

4.1.4 Penetration and Test Fixture. A thorough visual inspection of the test fixture and the penetration assembly identified no significant damage to either. The box beam support located at the end of the right-side branch of the internal piping rotated about 15 degrees as a result of the piping loads during the test. Virtually all of this was elastic strain and final misalignment was less than three degrees. No other damage was observed.

4.1.5 Conclusions. The test on this representative containment spray CPS clearly demonstrates that there is a significant safety margin in such hardware with respect to proper performance under design basis accident conditions. At design basis conditions, the valve performance was unaffected, and maximum pipe strains and support loads were well within material yield levels. Valve operation and leak integrity remained unaffected until the horizontal displacement was in excess of twice the DBA specification.

At the maximum horizontal displacement of 13.2 in., the performance of the valves was still essentially unchanged—operator currents were normal and maximum leakage at 100 psid was less than 0.1 scfm. No struts had failed and the piping responded in a ductile manner with no local buckling. The pipe clamps distorted and slipped to a sufficient extent to accommodate much of the pipe movement. The pipe was locally indented at the clamp locations and at some of the rigid supports, but the pressure boundary showed no evidence of being near a failure condition. Although the inside valve leakage increased to between 0.003 and 0.1 scfm at displacements above 2.6 in. and increased again after the load was released, the outside valve remained leaktight throughout the test.

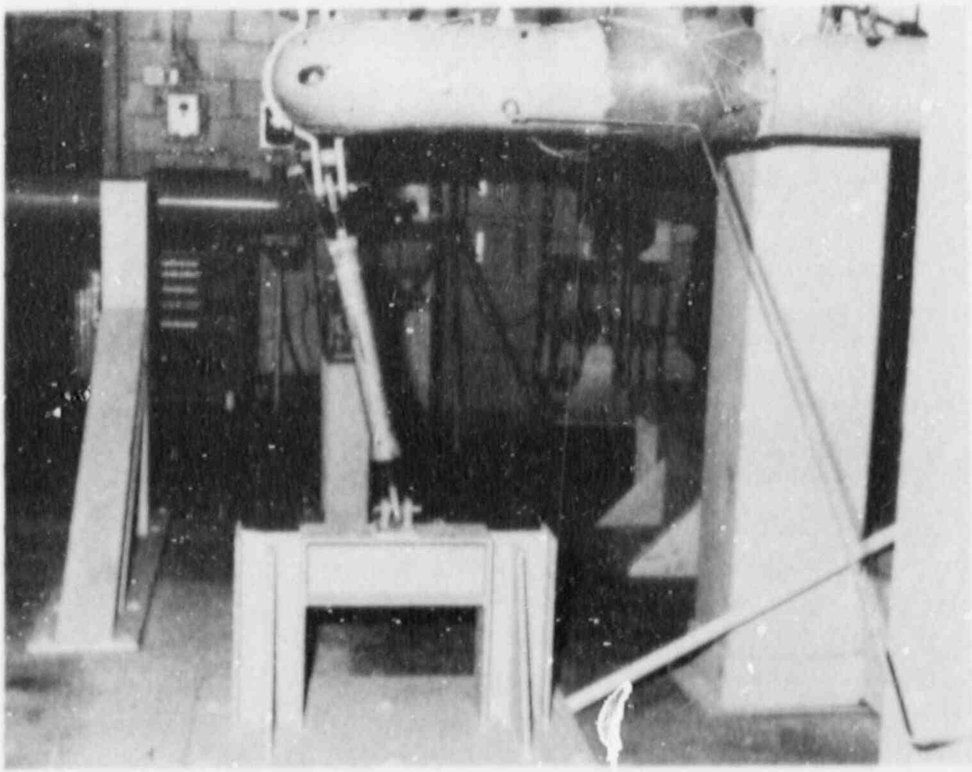

Figure 23. Misaligned outside strut and pipe clamp for 8-in. gate valve test.

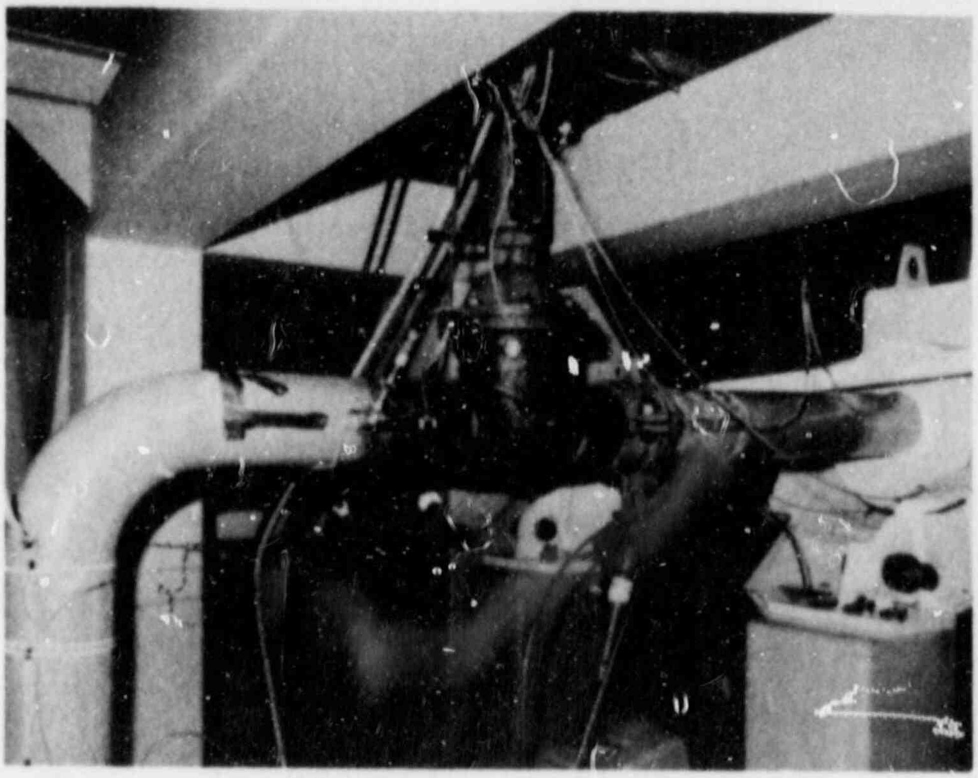

Figure 24. Misaligned inside vertical strut and bent piping between valve and penetration for 8-in. gate valve test.

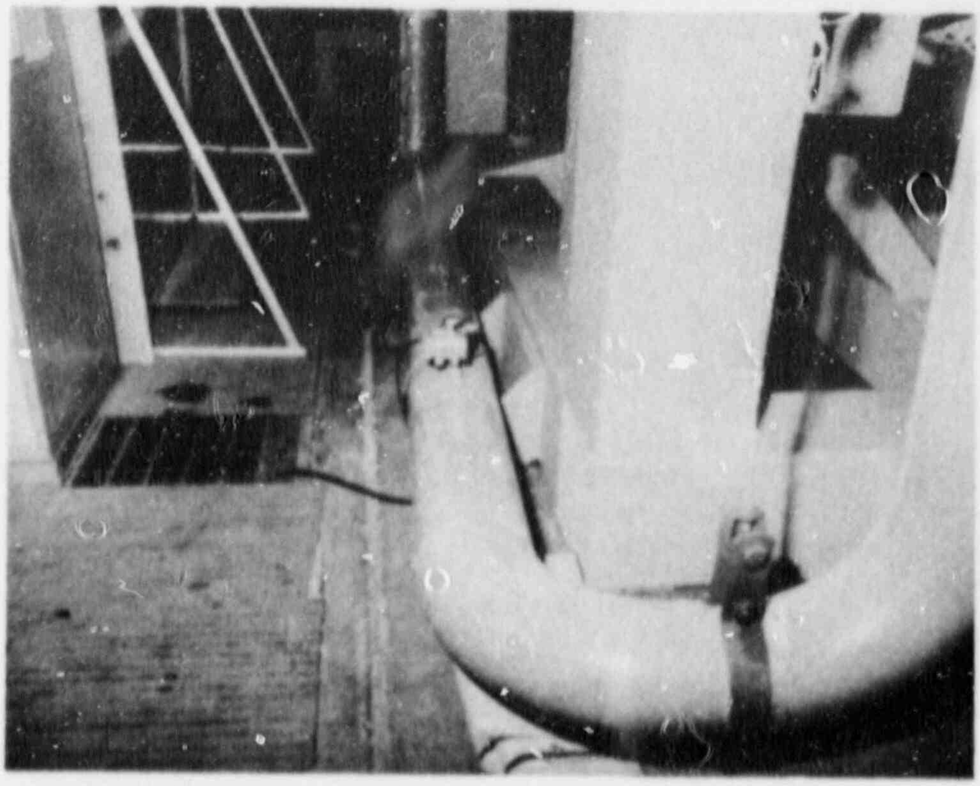

Figure 25. Bent horizontal section of inside piping for 8-in. gate valve test.

Given the judgment that the 13.2-in. horizontal and 3.3-in. vertical displacements and the 350°F temperature are near or exceed most containments' ultimate capacities, the results from this test show that typical containment spray piping penetrations are most likely capable of performing their intended safety functions during a severe accident.

4.2 Purge and Vent: 8-In. Butterfly Valve Testing and Results

The purpose of this part of the test program was to evaluate the ability of a containment purge and vent CPS with elastomerically sealed butterfly valves to remain leaktight and maintain valve operability when exposed to design basis and severe accident temperatures, pressures, and mechanical loads. The main concerns for failure were possible deterioration of the elastomeric valve seat due to prolonged exposure to heat and failure of the piping or pipe supports due to the large displacements.

Since the valves used in this test had been exposed to temperature and pressure loadings in previous single-component leak tests,[3] all the elastomeric seals were replaced in both valves before installation in the test system. Piping sections damaged during the gate valve testing were replaced, and the whole piping system was pressure-tested at 300 psig to ensure mechanical integrity. The valves were leak-checked after installation to ensure a bubble-tight seal at 120 psig. The whole system was checked for leak tightness at 135 psig. All pressure testing was done with nitrogen gas.

The upstream valve was checked for operability by opening the valve with differential pressures of 0, 60, and 120 psig. Differential pressures were applied from the upstream side with nitrogen. After operability tests, the center piping section was vented to zero pressure, reclosed, and connected to a flow meter which was monitored for 1-1/2 to 2 min to check for valve leakage. The downstream valve was checked for leakage by pressurizing the center piping section and monitoring the flow meter connected to the downstream piping. Since the downstream butterfly valve was not heated directly, it was felt nothing would be learned by operating the valve; therefore it was left closed throughout the test.

The upstream valve and penetration were then heated, displaced, pressurized, and checked for operability and leakage according to the schedule presented in Table 7. The downstream valve was also pressurized and checked for leakage.

After two hours at 350°F, due to electrical difficulties, the inside valve was allowed to cool down. Prior to reheatup, leakage was checked at 100°F. The valve was found to be leaking. It was decided to replace the seals in the valve and restart the test. The load on the piping was relaxed and the seals were replaced in the inside valve. Both valves were again checked for leakage at 120 psig and found to be bubble-tight. The flange upstream of the inside valve was tightened to hold 135 psig nitrogen pressure. The upstream valve was again checked for operability, and the test restarted from the new no-load equilibrium position of the piping.

The upstream valve and penetration were heated, pressurized, displaced, and checked for operability according to the schedule presented in Table 8. The time-at-temperature sequence was kept approximately the same as on the first butterfly valve test until the no-load equilibrium displacement of the initial test was exceeded. A plot of inside valve temperature and displacement-vs.-test duration is presented in Figure 26 for the first test and the initial part of the retest. A plot of the complete temperature and displacement history of the complete second test is presented in Figure 27.

During the test of the purge and vent system, the CPS displacement was large enough to cause the failure of two pipe supports (one in tension and one in compression). There were no other equipment failures or loss of function. There was no measurable leakage through either valve and no noticeable change in valve operation.

4.2.1 Valves. Valve performance was again characterized by operator current, stroke time, and valve seat leakage. Typical current-vs.-time curves for the inside valve are shown in Figure 28. The initial current spike on valve opening is attributed to motor startup and the initial breakaway of the disk from the elastomeric seat. After the initial startup, the motor settled into a steady-state operating condition of 0.54-0.60 A, with moderate oscillatory behavior of unknown origin. Shutoff on the opening cycle was accomplished with a position limit switch.

The closing stroke started with a smaller inrush of current and settled into the same oscillatory steady-state behavior until the seal disk made contact with the seat. The current then rose as the disk was forced into the seat and the closing limit switch interrupted the current. As shown on Figure 29, the unseating current was generally higher with higher upstream pressures as expected. Average steady-state operator current also varied

Table 7. Containment parameters for design basis accident/severe accident conditions for 8-in. butterfly valve test (first ramp)

Total Horizontal Penetration Displacement (in.)	Inside Valve Temperature (°F)	Pressure (psi)	Butterfly Valve Function Test
Design Basis Accident Conditions			
0.00	AMB	60	—[a]
0.23	140	60	Yes
0.53	140	60	—
0.53	160	60	—
0.82	160	60	Yes
0.82	200	60	—
0.89	200	60	Yes
0.89	240	60	—
0.96	240	60	—
0.96	280	60	—
1.05	280	60	Yes
Severe Accident Conditions			
1.05	315	90	—
1.75	315	90	Yes
1.75	350	120	—
2.38	350	120	—
3.00	350	120	Yes
5.00	350	120	—
6.63	350	120	—

---

[a] Baseline tests.

Table 8. Containment parameters for design basis accident/severe accident conditions for 8-in. butterfly valve test (second ramp)

Total Horizontal Penetration Displacement (in.)	Inside Valve Temperature (°F)	Pressure (psi)	Butterfly Valve Function Test
Design Basis Accident Conditions			
3.00	AMB	60	Yes
3.05[a]	120	60	Yes
3.05	160	60	Yes
3.05	200	60	Yes
3.05	250	60	—
3.05	280	60	Yes
Severe Accident Conditions			
3.05	315	90	Yes
3.05	350	120	—
3.05	350	120	—
5.00	350	120	Yes
7.01	350	120	—
9.04	350	120	—
12.7	350	120	—
14.77	350	120	—
18.01	350	120	Yes
16.33	350	90	Yes
15.50	350	60	Yes
14.33	350	60	Yes
14.33	100	60	—

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[a] Piping was maintained at no-load equilibrium position until time-at-temperature history from first test was replicated.

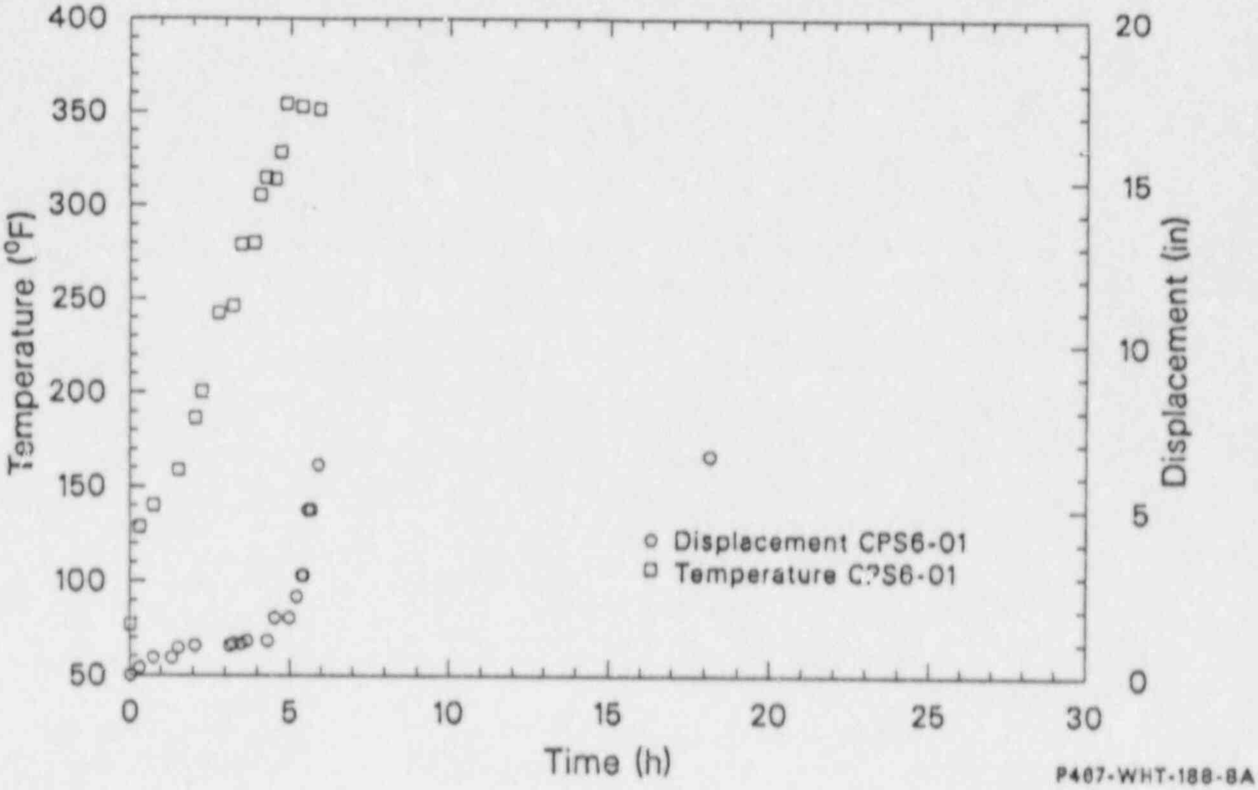

Figure 26. Valve temperature and displacement vs. test duration - first portion of 8-in. butterfly valve test.

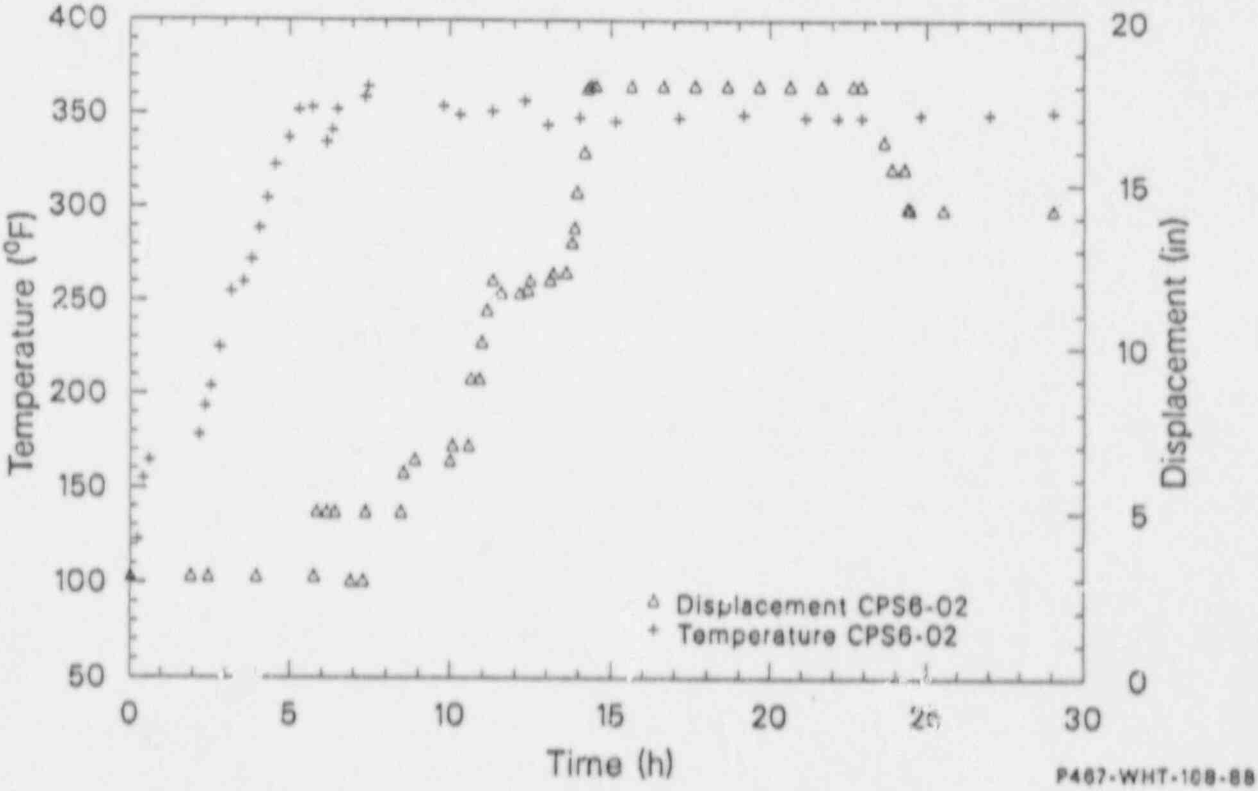

Figure 27. Valve temperature and displacement vs. test duration - second portion of 8-in. butterfly valve test.

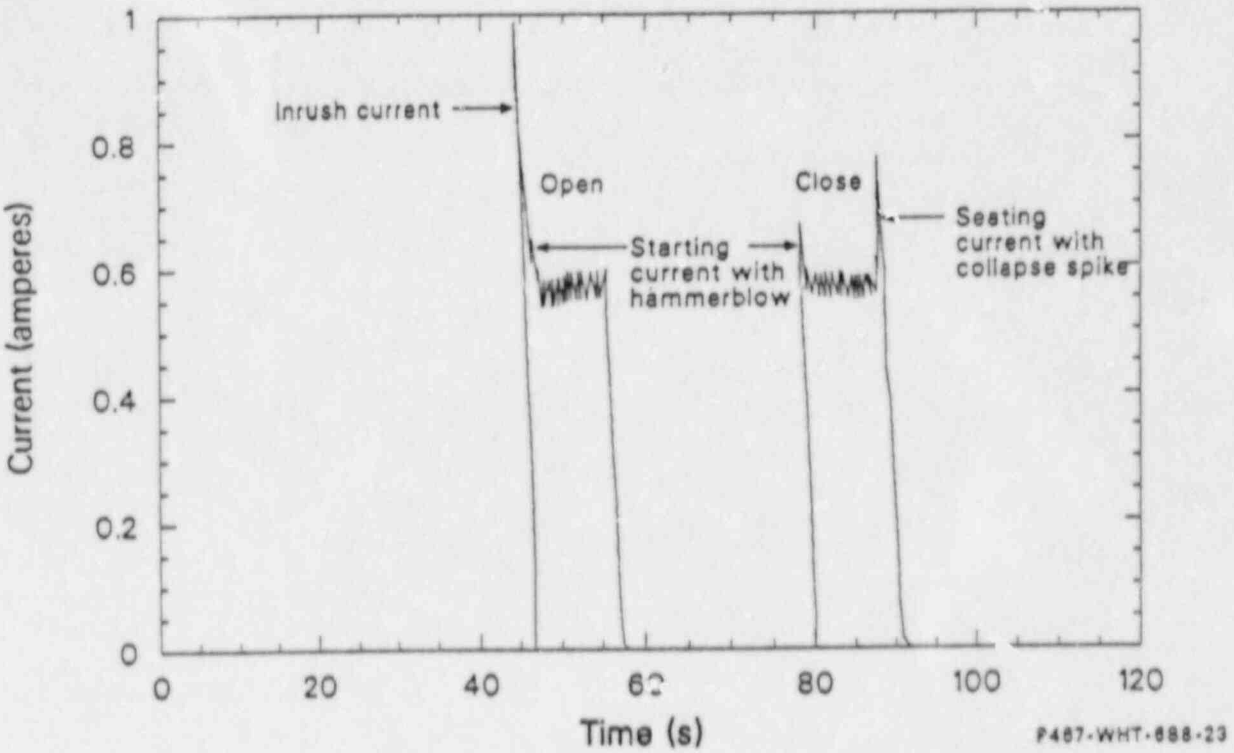

Figure 28. Typical current vs. time for inside valve of 8-in. butterfly valve test.

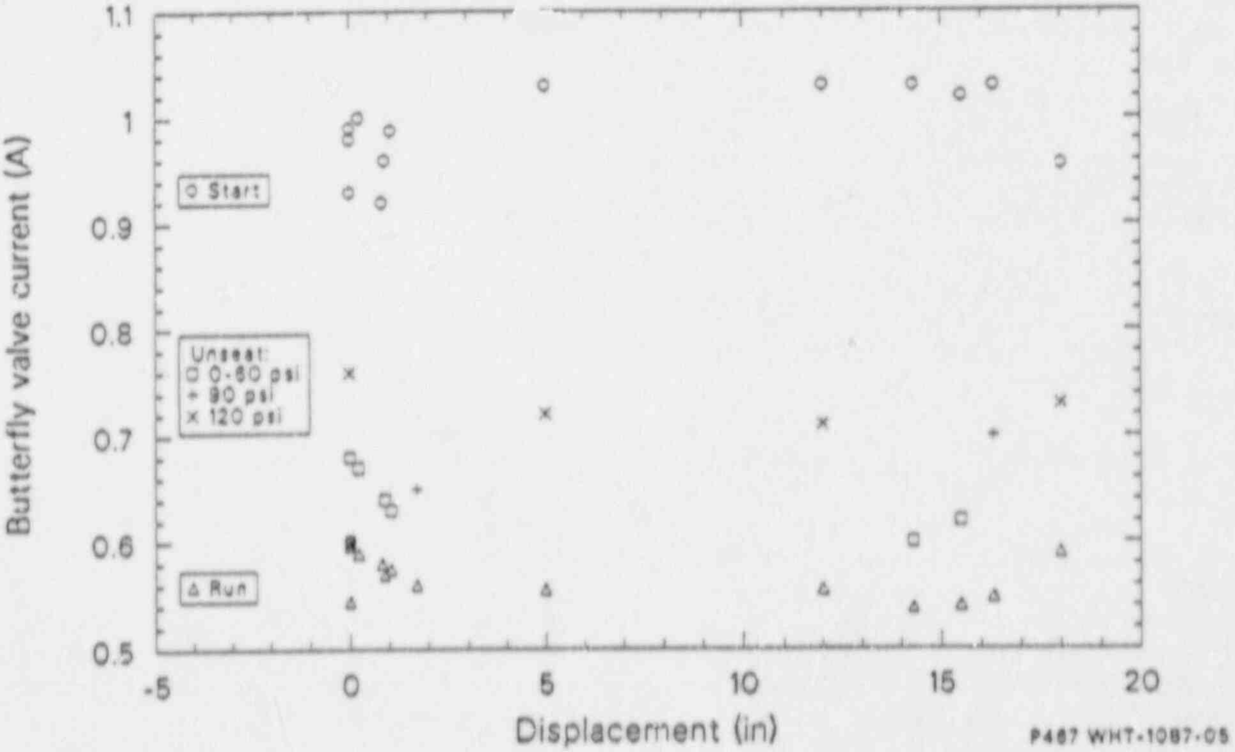

Figure 29. Current vs. displacement for 8-in. butterfly valve test showing unseating current generally higher with upstream pressures.

somewhat (0.54-0.61 A), but there was no obvious effect of the simulated accident conditions on the start, unseat, or run currents. Stroke time for the inside valve varied from 8.0 to 8.2 s for both opening and closing cycles. The outside valve was not operated.

Neither valve showed any measurable leakage during the heated portion of the test. The inside valve showed some slight leaks during heatup transients, but these went away when the valve reached temperature equilibrium. The inside valve showed a sustained leak of 0.88 scfm with 60 psig differential pressure when cooled below 210°F after the high temperature portion of the test.

4.2.2 Pipe Supports. The ends of the two struts near the inside valve which were highly loaded during the gate valve test were replaced for the butterfly valve test. Strain gauges were electronically rezeroed for the butterfly valve test. The horizontal strut was now equipped with a 2-in. Sch. 40 body with 1-in. rod ends while the vertical strut was equipped with a 2-in. Sch. 160 body and 1-1/4-in. rod ends. Due to the difference in the distribution of the stiffness of the two struts, they also had a different distribution of strain. The horizontal strut experienced its extension in the main body of the strut, while the rod ends and attachments were not damaged. The vertical strut experienced deformation in the ball joint rod ends, one of which failed completely at a load of about 7.5 times its rated capacity. Both clamps again slipped along the axis of the pipe during the test. The lower rod end of the vertical strut yielded enough to pull the pin through the end of the eye (see Figure 30). Force vs. displacement curves for the struts are presented in Figures 31 and 32. The horizontal strut on the right side of the upstream piping buckled under compression loading (see Figure 33).

4.2.3 Piping. A major problem with the 8-in. piping during the butterfly valve tests was the difficulty in maintaining a tight seal with the 150-lb-class raised face flanges and spiral-wound (stainless/asbestos) gaskets. Since the seal on the upstream face of the outside valve was critical to leak measurements, this joint was given special attention. The bolts were drawn up to give metal-to-metal contact on the compression gauge around the periphery of the gasket.

During the second butterfly valve test, the flange upstream from the inside valve experienced a major leak at a displacement of 5.0 in. and a temperature of 350°F. The load was released and the bolts retightened, which fixed the leak until another small leak developed at a displacement of 18 in. The leak continued until the vertical strut broke. A general observation concerning the piping is that it behaved in a ductile manner and survived local deformations and large bending moments that caused significant yielding through the cross section. The highest measured strain occurred on the inside piping at its entry into the penetration assembly. As illustrated in Figure 34, this strain reached 6.2%.

In addition to some minor and very localized deformations caused by the pipe supports, the piping became somewhat oval at both outside elbows. The external shape had changed from a nominally circular cross section with a diameter of 8.64 x 8.67 in. (inside) and 8.59 x 8.67 in. (outside) to an oval cross section with major and minor axes of 9.36 x 8.10 in. and 9.34 x 8.12 in. respectively. The elbow upstream from the inside valve was also deformed from a cross section of 8.68 x 8.65 in. to a cross section of 7.80 x 9.34 in. The pipe strains measured at various locations throughout the system at the maximum horizontal displacement of 18.0 in. are listed in Tables 9 and 10. Figure 14 provides additional information on the location at which the strains were measured.

After the hydraulic pressure to the ram was relieved, the elastic strain in the piping system caused the piping to return 3.2 in. horizontally (18% of the maximum displacement) toward its original position. Figures 35, 36, and 37 show the conditions of selected parts of the CPS following load removal. The strut immediately downstream of the outside valve is obviously misaligned and the pipe clamp has rotated around the pipe as can be seen in Figure 35. Figure 36 shows the broken inside vertical strut. Also apparent in this figure is the bending in the pipe between the inside valve and the penetration. Finally, Figure 37 shows the permanent bending in the long horizontal section of the inside piping.

4.2.4 Penetration and Test Fixture. A thorough visual inspection of the test fixture and the penetration assembly identified no significant damage to either. The box beam support located at the end of the right-side branch of the internal piping maintained the 3-degree misalignment carried over from the gate valve tests. No other damage was observed.

Figure 30. Broken eye of lower end of vertical strut from 8-in. butterfly valve test.

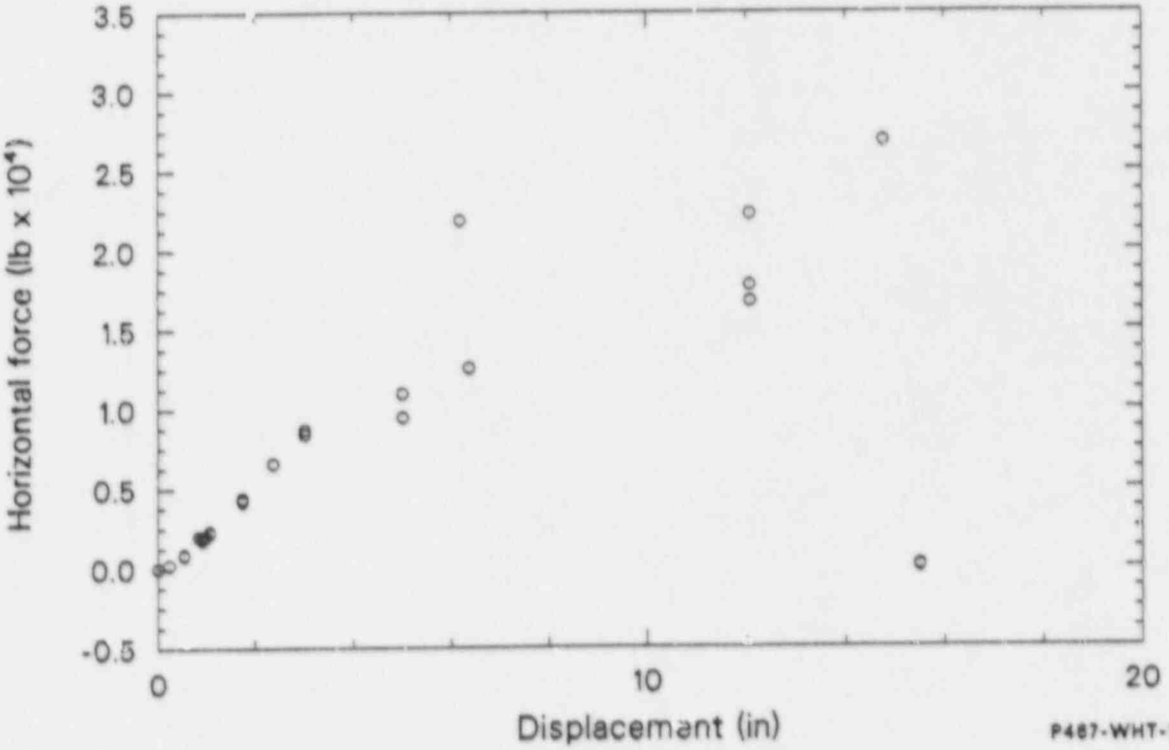

Figure 31. Strain vs. displacement for horizontal strut for 8-in. butterfly valve test.

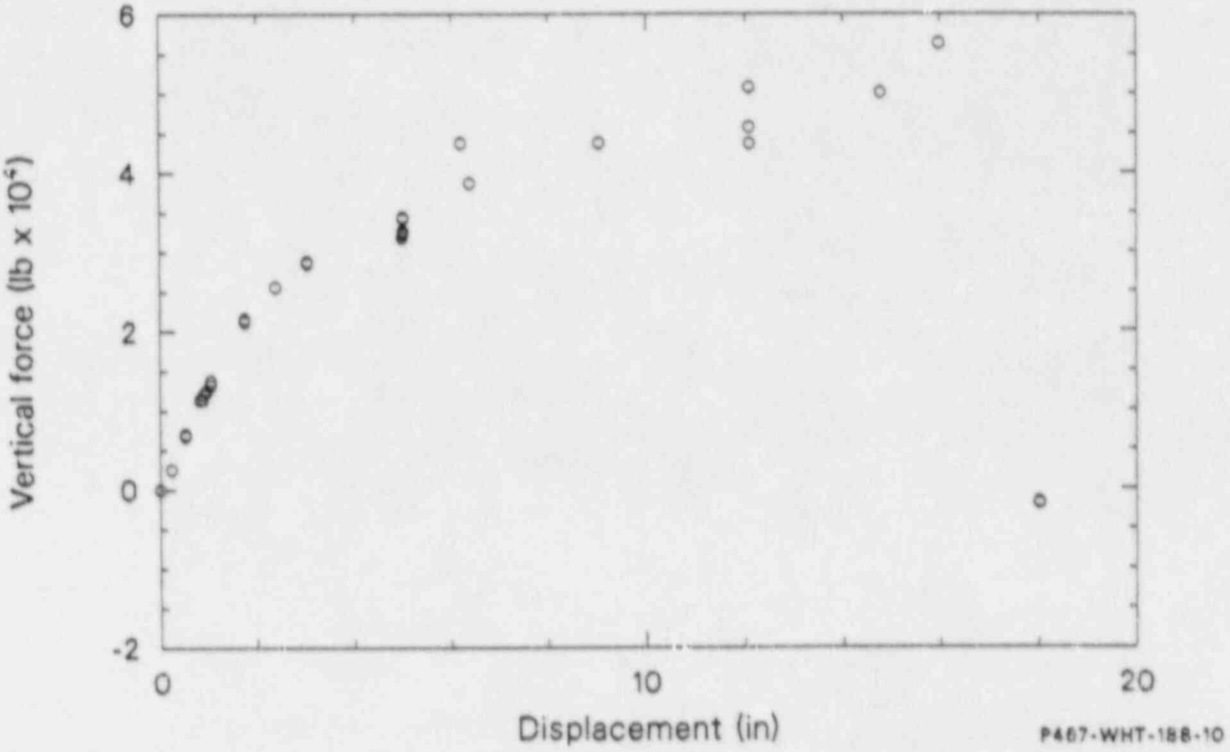

Figure 32. Strain vs. displacement for vertical strut for 8-in. butterfly valve test.

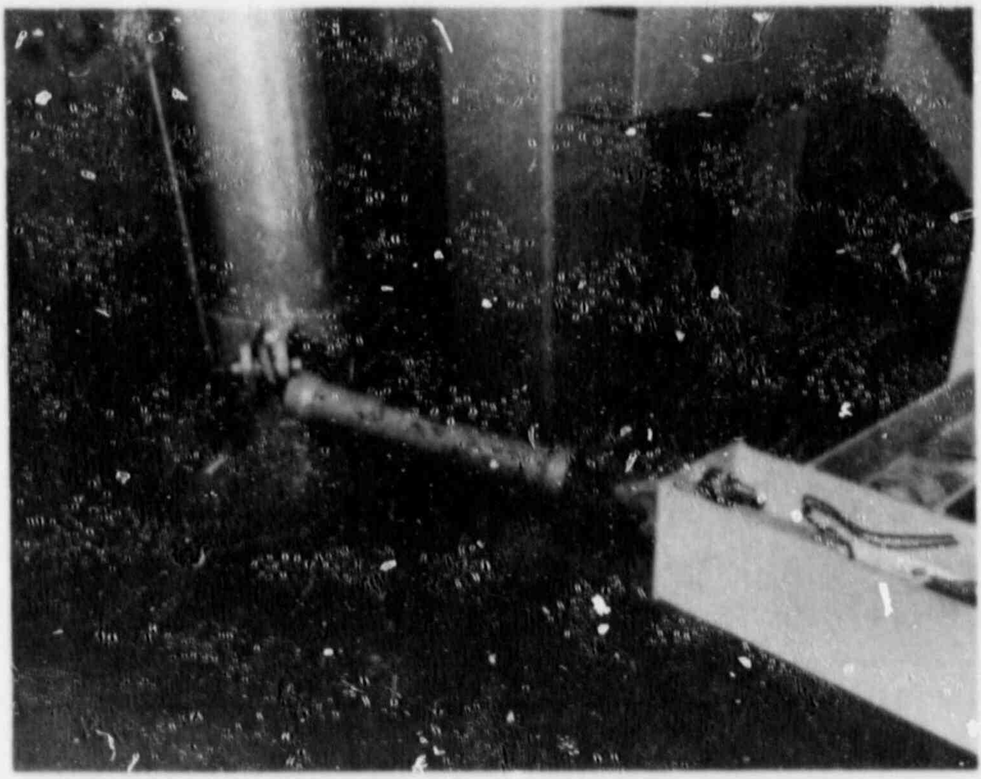

Figure 33. Buckled horizontal strut from 8-in. butterfly valve test.

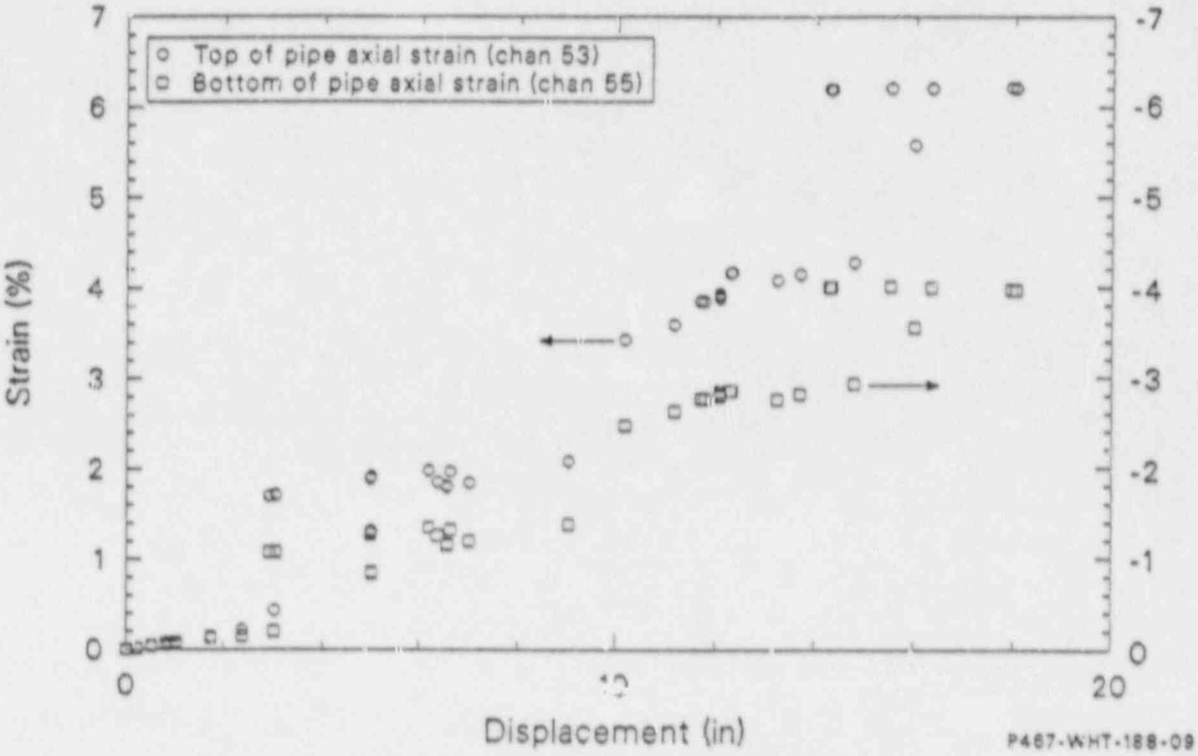

Figure 34. Strain on piping upstream of penetration for 8-in. butterfly valve test.

Table 9. Pipe system strains at maximum deflection for 8-in. butterfly valve test (first ramp)

System Location	Gauge Orientation[a]	Strain Measurement (10^{-6} in./in.)
Horizontal piping near tee (left branch facing penetration from inside containment)	2/4	−14429/20322
Vertical piping near tee	5	1470
Horizontal piping near inside elbow	2/4	−107.2/2364
Horizontal piping near inside valve, upstream	1/3, 2/4	864/1582, −699/1387
Inside valve weld neck, downstream	1/3, 2/4	−2293/−316, −587/411
Piping near inside struts, downstream	1/3, 2/4	−6964/6753, −998/3691
Near penetration, inside piping	1/3, 2/4	46881/−35016, 24580/−8954
Near penetration, outside piping	1/3, 2/4	16992/−17731, 1994/−1620
Outside valve weld neck, upstream side	1/3, 2/4	206/−241, −267/153
Near first downstream elbow, upstream	1/3, 2/4	−1359/−1692, 951/969
First downstream elbow	1/3, 2/4	8105/12868, −9399/650

---

[a] Orientations of strain gauges were as follows: (1) on top of pipe measuring axial strain, (2) on right side of pipe, facing downstream, measuring axial strain, (3) on bottom of pipe measuring axial strain, (4) on left side of pipe, measuring axial strain, (5) on top of pipe, measuring circumferential strain.

Table 10. Pipe system strains at maximum deflection for 8-in. butterfly valve test (second ramp)

System Location	Gauge Orientation[a]	Strain Measurement (10^{-6} in./in.)
Horizontal piping near tee (left branch facing penetration from inside containment)	1/3, 2/4	150/−1674, −20784/26748
Vertical piping near tee	1/3, 2/4	−981/2360, 6353/496
Horizontal piping near inside elbow	1/3, 2/4	−4265/3581, 1301/5435
Horizontal piping near inside valve, upstream	1/3, 2/4	−2355/2845, −1027/2152
Downstream from inside valve	Sheared off by sliding pipe clamps	—
Piping near inside struts, downstream	1/3, 2/4	−1653/1344, −260/1344
Near penetration, inside piping	1/3, 2/4	62134/39729, 17224/−150
Near penetration, outside piping	1/3, 2/4	18104/−18787, 3596/−2302
Pipe upstream from valve nozzle	1/3, 2/4	479/−523, −441/462
Pipe downstream from outside valve	1/3, 2/4	−452/−1030, 79/1696
Second downstream elbow	1/3, 2/4	15721/−272, 396/−6120

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a. Orientations of strain gauges were as follows: (1) on top of pipe measuring axial strain, (2) on right side of pipe, facing downstream, measuring axial strain, (3) on bottom of pipe measuring axial strain, (4) on left side of pipe, measuring axial strain, (5) on top of pipe, measuring circumferential strain.

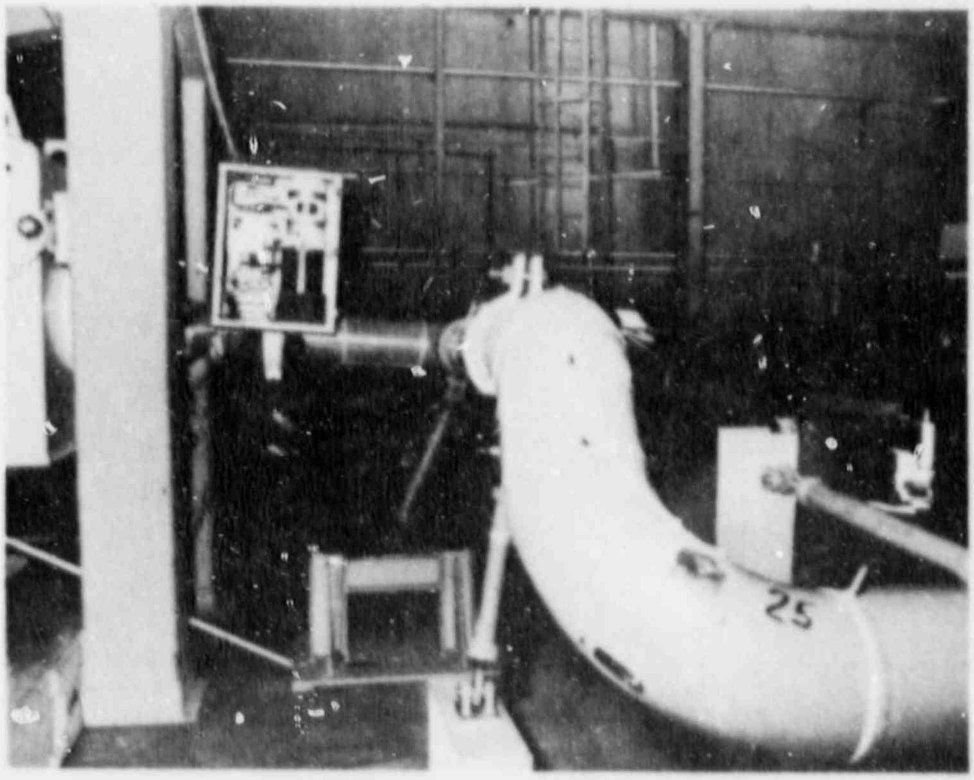

Figure 35. Clamp and strut downstream of outside valve for 8-in. butterfly valve test.

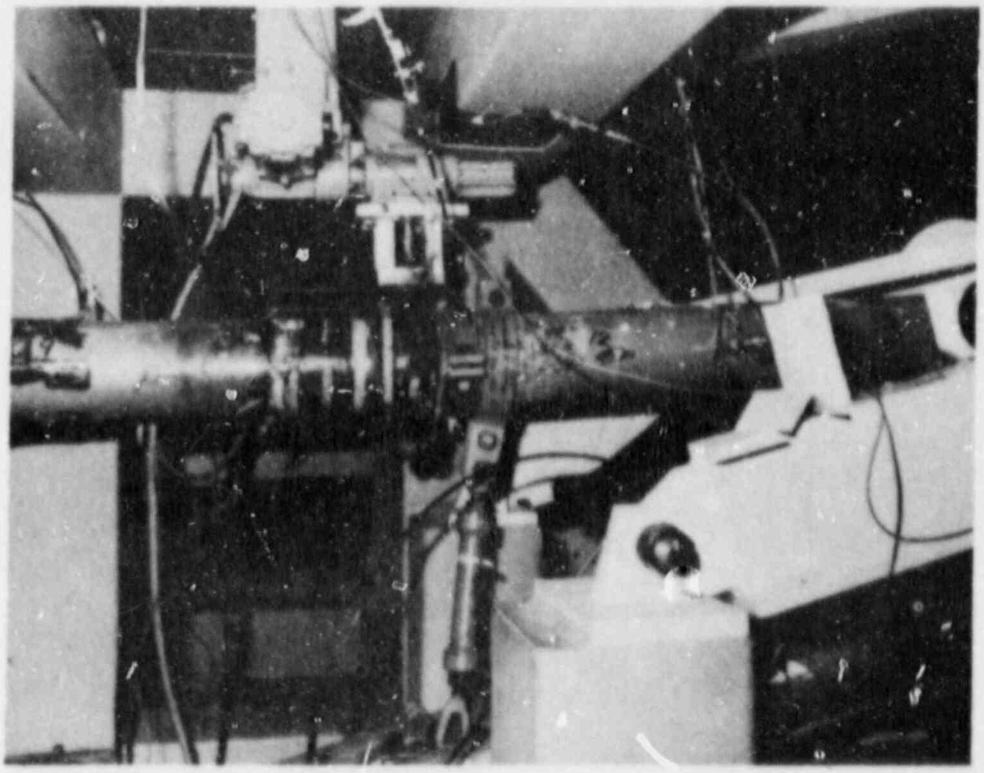

Figure 36. Broken inside vertical strut for 8-in. butterfly valve test.

Figure 37. Permanently deformed horizontal section of inside piping for 8-in. butterfly valve test.

4.2.5 Conclusions. The test on this representative purge and vent containment penetration system clearly demonstrates that there is a great deal of safety margin in such hardware with respect to proper performance under design basis conditions. At these conditions, the valve performance was unaffected, and maximum pipe strains and support loads were well within material yield levels. Valve operation remained unaffected throughout the design basis accident and severe accident tests. The inside valve leak integrity remained unaffected until the valve was cooled to 210°F after the severe accident test. The outside valve maintained leak integrity throughout the test program and thus prevented the potential of a containment leak to the outside atmosphere after the simulated severe accident.

At the maximum horizontal displacement of 18.0 in. in the severe accident portion of the test, the performance of the inside valve was still unchanged—operator current was normal and leakage at 120 psid was less than 0.001 scfm. Two struts failed (one in tension and one in compression), and the piping responded in a ductile manner with no local buckling. The pipe clamps distorted and slipped to a sufficient extent to accommodate much of the pipe movement.

Given the judgment that the 18.0-in. horizontal and 4.8-in. vertical displacements and the 350°F temperature exceed most containments' ultimate capacities, the results from this test show that typical purge and vent containment piping penetrations are capable of performing their intended safety functions during a severe accident.

4.3 Small-Bore CPS System Testing and Results

The purpose of this part of the test program was to evaluate the ability of a small-bore CPS system with a globe valve equipped with hardened seats to remain leak tight and operable when exposed to temperatures and mechanical loads typical of design basis and severe accidents. It was also intended to determine whether valves with hardened metal seats seal tightly enough to seal a heatup-driven water expansion pressure transient.

The test system was assembled and instrumented as shown in Figure 12. The globe valve was repacked and the entire system was hydrotested at 4750 psig. The flued head weld and socket welds were dye-penetrant tested to be sure there were no initial cracks. After the dye-penetrant tests, heaters were installed on the valve and on the pipe between the valve and the penetration. The heated valve and piping were then insulated. Baseline valve function and leakage tests were performed with zero pressure and 1500 psig (N_2) applied alternately under the plug and over the plug (upstream-to-downstream and downstream-to-upstream). Temperature, pressure, load, and strain data were recorded on strip charts.

The enclosed-volume water expansion test was performed first as part of the design basis accident simulation. This test was performed due to utility questions to the NRC over the need to backfit older plants with relief capabilities to prevent entrapped water from overpressurizing the system during an accident. The valve was closed and the downstream section was filled with water and vented at high points to remove all air. The valve and downstream piping were heated to 120°F. The end of the piping was then displaced (lifted) in 0.25-in. increments to 1.5 in. as shown on Table 11. The valve and piping were then heated to 200°F and displaced 1.75 in. Heatup to 280°F was then initiated. Power to the heaters was shut off when pressure in the downstream pipe reached 3875 psig. Pressure continued to rise until it reached a maximum of 4016 psig. A plot of the pressure-temperature transient is presented in Figure 38. The pipe was then vented to release pressure and heated to 280°F. The pipe was then cooled to 200°F, vented, and dried. After reheating to 280°F, a two-way valve function test was performed at 1500 psig, first pressurizing the downstream pipe and then the upstream pipe, with leak checks in both directions. This completed the design basis accident simulation sequence.

The heatup and displacement were continued to 350°F and 8.0 in. (end of severe accident simulation with leak checks and valve function tests as specified on Table 11). After reaching the full severe accident condition, arbitrarily set at four times the design basis accident displacement, the vertical support strut was disconnected, and displacement continued (according to Table 11). This was done to investigate the effects of high bending moments on the flued head and nearby piping. Since bending moments on the valve were reduced from the severe accident test levels after disconnecting the strut, leak rate and valve function tests were not performed during this portion of the test. Temperature was maintained at 350°F. The displacement range for this portion of the test was from 8 to 24 in.

The system was allowed to cool to ambient temperature. The support strut was reconnected, and

Table 11. Containment parameters for design basis accident/severe accident conditions for 2-in. globe valve test

Vertical Displacement (in.)	Temperature (°F)	Leak Check	Valve Function
0.0	—	x	x
Design Basis Accident Water Full			
0.25	120	—	—
0.50	120	—	—
0.75	120	—	—
1.00	120	—	—
1.25	120	—	—
1.50	120	—	—
1.75	200	—	—
2.0	280	x	x
End Design Basis Accident			
Severe Accident System Dry			
2.25	288	x	
2.5	315	x	x
3.0	350	x	x
3.5	350	x	
4.0	350	x	
5.0	350	x	x
6.0	350	x	
7.0	350	x	
8.0	350	x	x
End Severe Accident			
Penetration Bending Tests. Vertical Strut Disconnected.			
9.0	350		
10.0	350		
11.0	350		
12.0	350		
14.0	350		
16.0	350		
17.0	350		
18.0	350		
20.0	350		
22.0	350		
24.0	350		

Table 11. (continued)

Vertical Displacement (in.)	Temperature (°F)	Leak Check	Valve Function
Ambient temperature valve tests.[a] Vertical strut reconnected.			
20.0	Ambient	—	—
20.7	—	—	—
22	—	—	—
24	—	x	—
26	—	—	—
28	—	x	—
30	—	—	—
32	—	x	x
34	—	—	—
36	—	x	x
40	—	x	x
44	—	—	—
47	—	x	x

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a. Upstream pressure only @1500 psi.

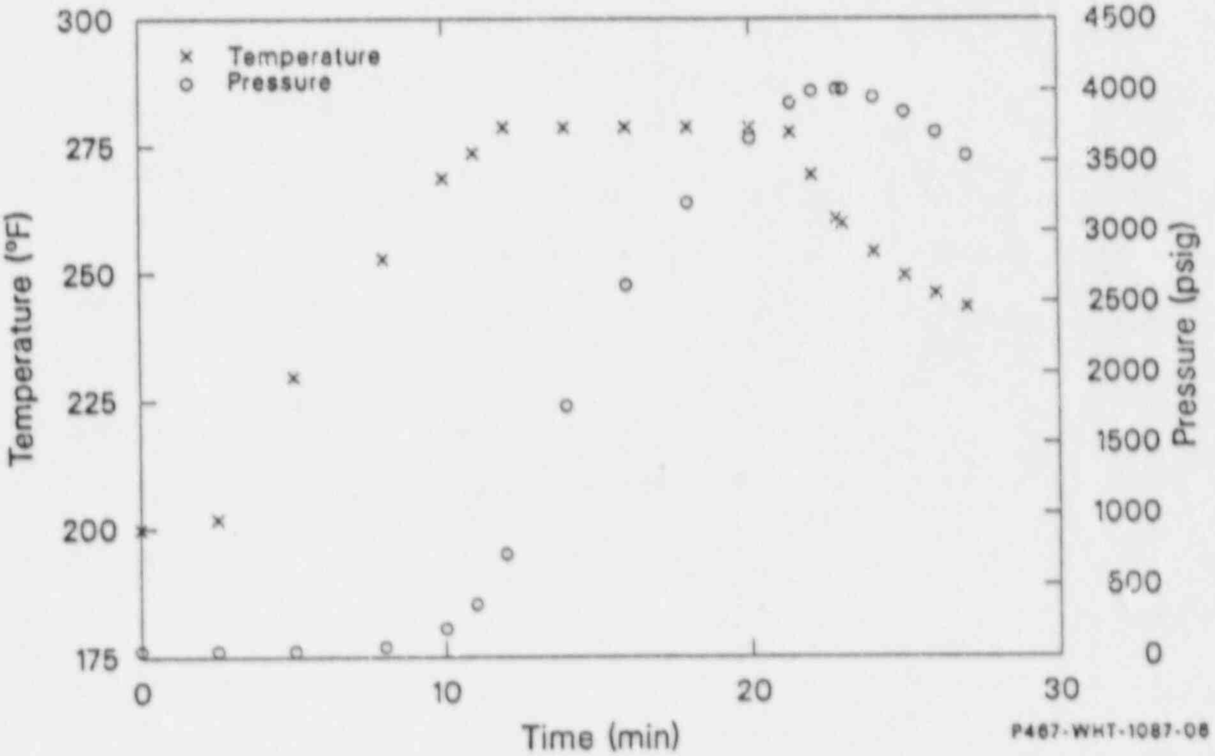

Figure 38. Thermal and pressure transient in piping of 2-in. globe valve test.

an attempt was made to load the valve and piping to effect a measurable change in valve performance. Leak checks and valve function tests were performed as according to Table 11. After final displacements, the valve socket welds and flued head butt weld were checked with dye penetrant for cracks. The system was also hydrotested to 4750 psig.

There were no failures nor loss of function of any of the equipment tested during the small-bore CPS test.

4.3.1 Valve. The valve used in the small-bore CPS tests was characterized by motor current, stroke time, and seat leakage. The main component of the motor current was the inductive current needed to operate the motor regardless of the load (~0.42 A). Stem packing friction added from 0.04 A for well-broken-in packing to 0.14 A for fresh packing. Lifting the plug off the seat against 1500 psi differential pressure required up to 0.14 additional amps. Closing the valve against 1000 psi typically took 0.02 A more current than opening it. This would indicate about 0.01 A for stem rejection load. None of the components of the valve motor current showed a response to valve temperature or pipe displacement. Motor starting current was also unaffected by system variables.

A plot of operator current vs. displacement is shown in Figure 39. Typical operator current curves for opening against upstream and downstream pressure are shown in Figures 40 and 41. Valve cycle times varied from 35.0 to 35.5 s for the opening stroke and from 34.2 to 35.0 s for the closing stroke.

For the most part, the valve leakage remained below the threshold of the flow meter (0.0003 scfm). After one valve function test at 280°F, and 1.75-in. displacement, with 1500 psi in the upstream section (under the plug), the valve showed a leak rate of 0.0195 scfm. After repeating the valve function test, the leak rate again dropped below the threshold of the flow meter.

Packing leakage was measured with 1400 psi internal pressure. At a temperature of 350°F and a displacement of 2.5 in., the packing leakage was 0.54 scfm. At ambient temperature and 48-in. displacement, the packing leakage was 1.25 scfm.

4.3.2 Pipe Support. The pipe support for the 2-in. globe valve test was constructed with a 1-in. Sch. 80 pipe section and 3/4-in. threaded end connections. Loads in the strut as measured by a strain gauge on the strut body reached the rated capacity of 650 lb at a piping displacement of 1 in. The measured load at 2.0-in. displacement (end of design basis accident simulation) was 1277 lb, which compares well to the pretest prediction of 1107 lb. The load reached 2200 lb at the end of the severe accident portion of the test (8.0-in. displacement) and 3550 lb at the maximum displacement of 48 in. Stresses in the strut remained well within the elastic limit throughout the test (5550 psi maximum at 47-in. displacement).

4.3.3 Piping. The piping behaved in a ductile manner with no cracking or buckling and no leakage, even after displacement under hydrotest pressure of 4750 psig. Although the pipe experienced significant yielding, the cross section remained circular, within 0.6%. There was no cracking, leakage, or noticeable yielding in the socket welds.

The load curve vs. deflection for the test system piping is shown in Figure 42. The measured load at a deflection of 1.992 in. (end of the design basis accident simulation) was 448 lb, which was very close to the pretest prediction of 469 lb at a deflection of 1.994 in. It is also interesting to note from the load-vs.-deflection curve that the design basis accident simulation condition is very near the elastic limit for this system. Figures 43 and 44 show the final deflected condition of the test piping.

4.3.4 Conclusions. The test on this portion of the small-bore containment penetration system demonstrates that there is a great deal of margin in such hardware with respect to proper performance under design basis or severe accident conditions and beyond. The valve and flued head are extremely stiff relative to the attached piping, and the piping is flexible enough to withstand large deflections without failure or transmitting failure-producing loads to the attached components.

Water-filled closed systems can develop significant elevated pressures due to thermal expansion of trapped water at design basis accident temperatures.

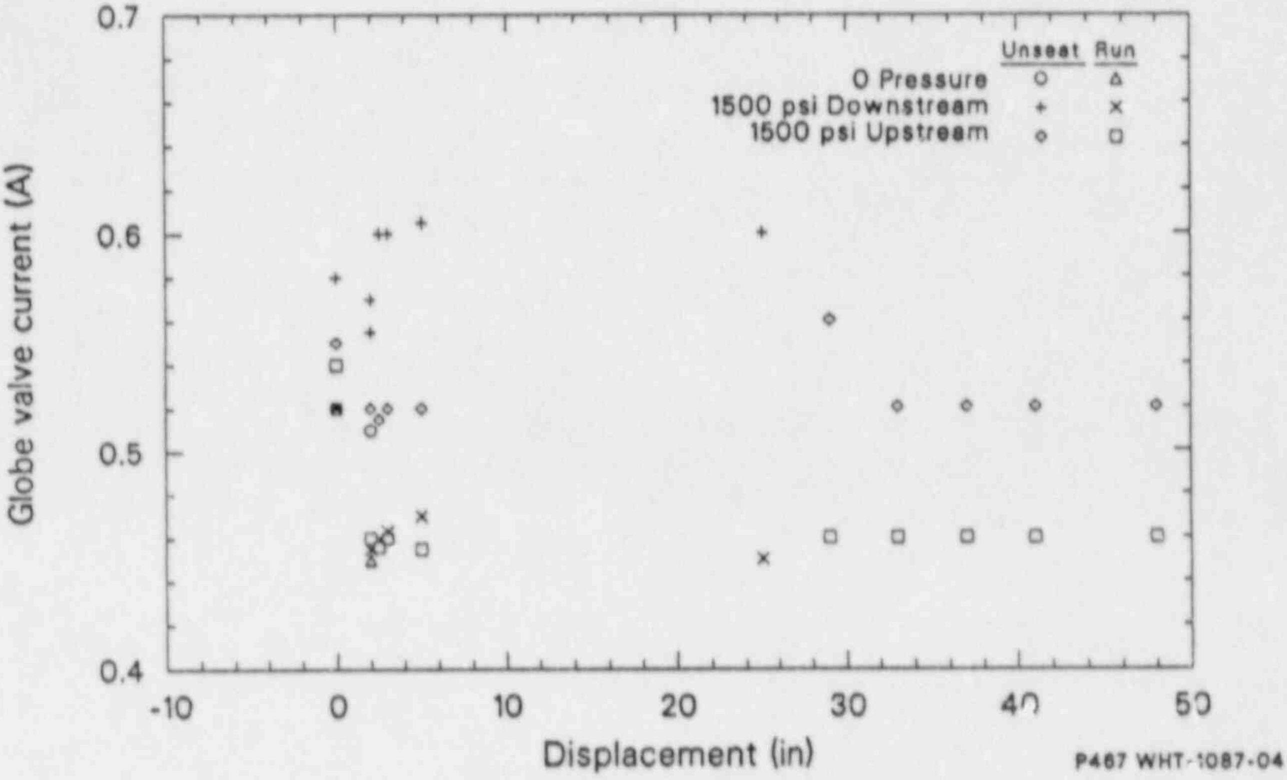

Figure 39. Two-in. globe valve test operator current vs. displacement.

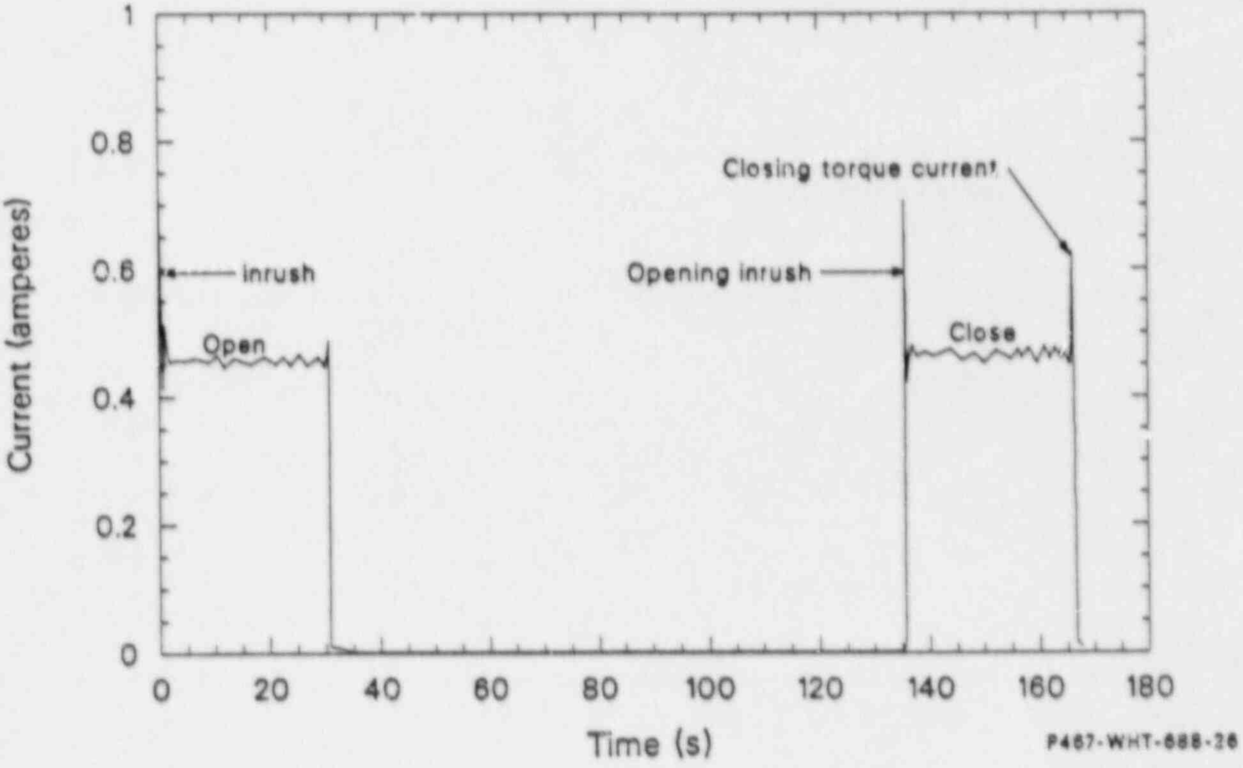

Figure 40. Two-in. globe valve test operator current opening against upstream pressure.

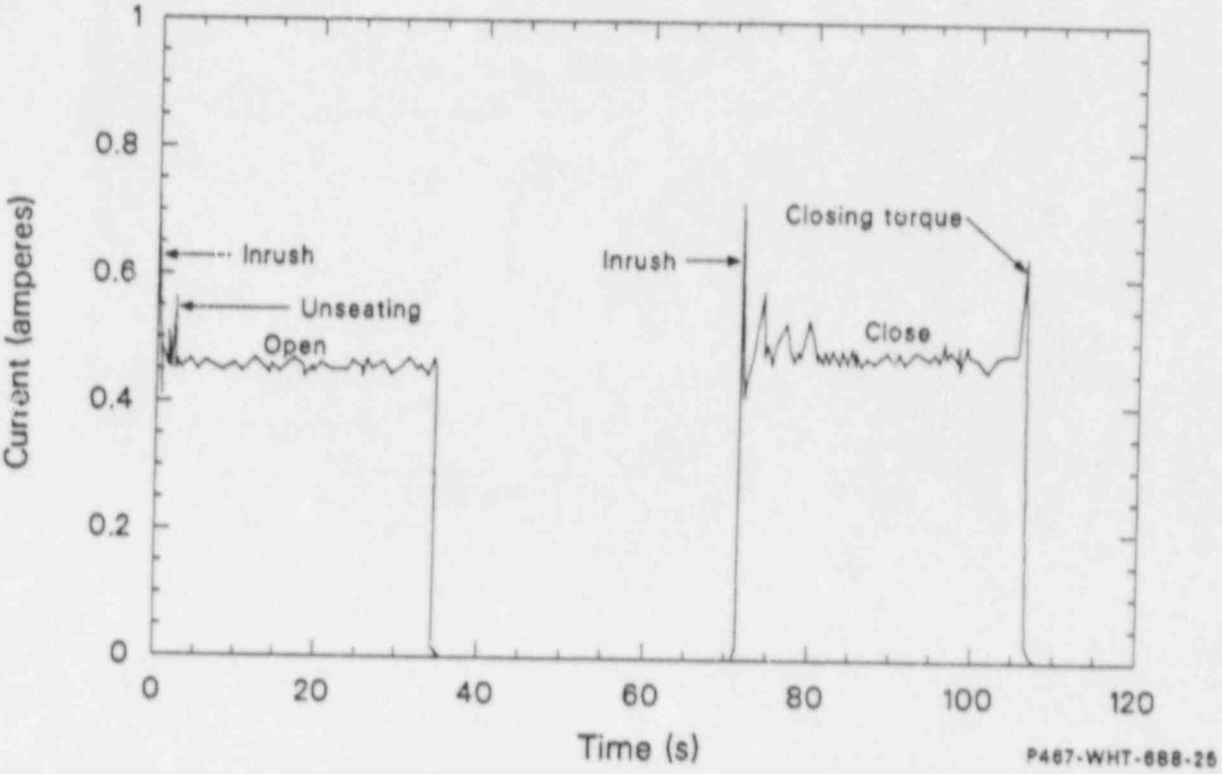

Figure 41. Two-in. globe valve test operator current opening against downstream pressure.

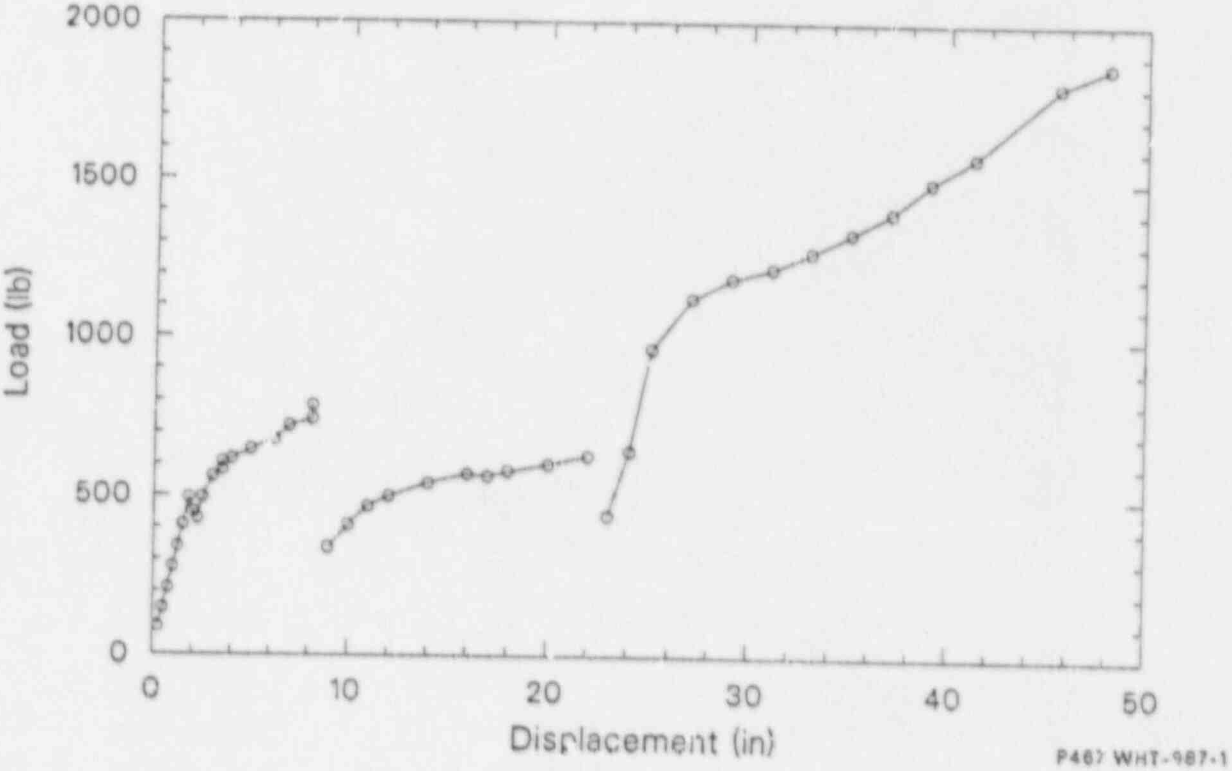

Figure 42. Load vs. deflection for system piping in 2-in. globe valve test.

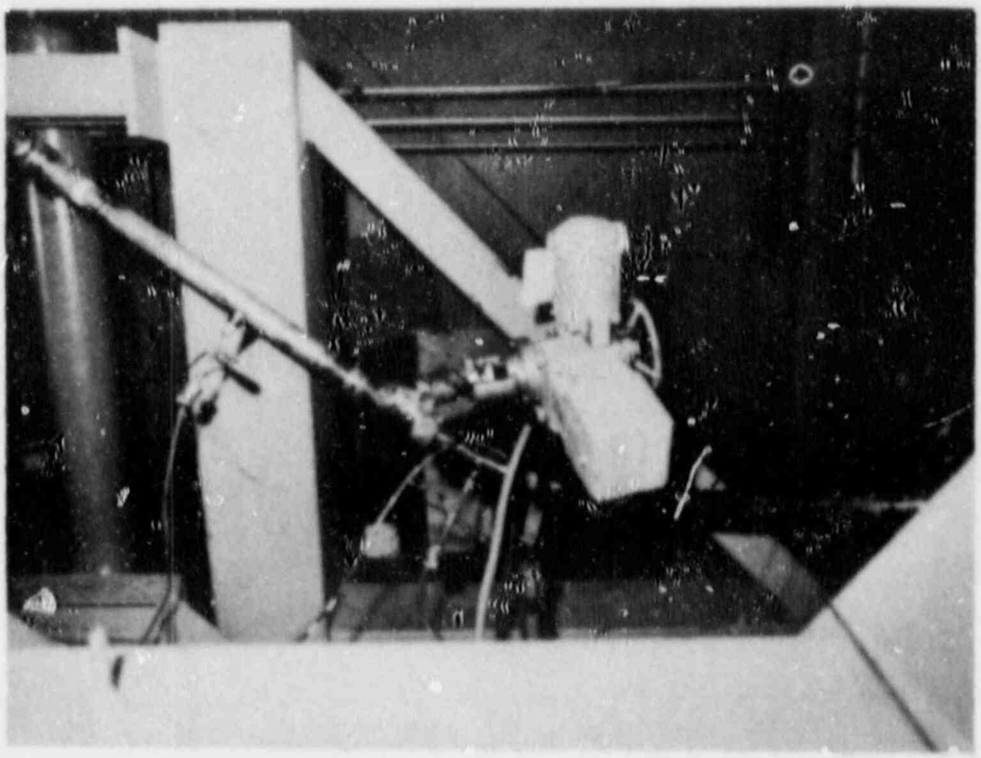

Figure 43. Left-side view of deformed pipe from 2-in. globe valve test.

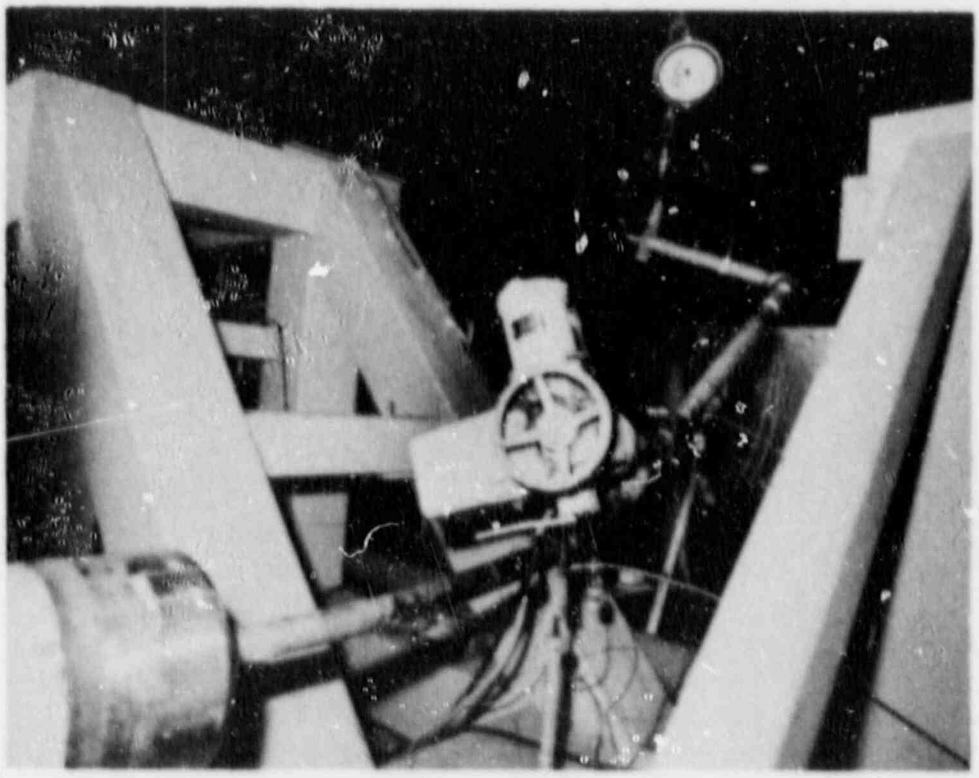

Figure 44. Right-side view of deformed pipe from 2-in. globe valve test.

5. FINAL CONCLUSIONS

Comparing the analyses of the experimental results with the project objectives provides the following insights:

> The measured response of these generic piping systems exposed simultaneously to pressure, temperature, and displacement loadings equal to a design basis containment response exhibits a great deal of performance margin, which is verified in the severe accident testing.
>
> Valve operability and leak integrity also show considerable safety margin at design basis loadings.
>
> Water-filled piping systems penetrating containment without relief capability can build up excessive pressure at design basis temperatures. The NRC's concern with this problem is valid. Not all valves will be as tight as the one tested in this project; however, the experimental results do show pipe rupture is possible.
>
> The analytic procedures of the ASME Code for Level "D" allowables are based on component limit load concepts. These are ultraconservative when one considers the load redistributions which generally occur in a system. ANCO Engineers (Culver City, CA), Energy Technology Engineering Center (Los Angeles, CA), and the INEL work all show piping system failure levels will be greater than 3% strain even when oscillating seismic loadings are considered.
>
> The response of the piping systems and valves under severe accident loadings up to ultimate containment capacity show that high levels of strain can be sustained without piping system or penetration failure, and the redundant valve outside of the harsh containment environment provides leak integrity. Operability was not affected even in the gate valve where some permanent plastic response was observed. A solid wedge gate valve may have had more problems than the flexible gates in these valves.

The experimental results from this testing provide insights in two areas where current qualification standards may require improvement. The first of these is the pipe reaction End Loading Qualification Test, Annex D of ANSI B16.41. During the analyses of the actual end loadings sustained during the CPS tests, analysts compared loadings to the qualification requirements of Annex D. Inconsistencies in the procedures were found particularly with valves mating with pipe thicknesses greater than Schedule 40. As previously mentioned, CEGB is using the US qualification standards at Sizewell. They also had trouble with the procedures of this annex. The ASME valve qualification subcommittee has been notified by both CEGB and the INEL, and they have agreed to review the problem.

The second area of concern is that the ASME does not have a released qualification document for nonmetallics. The purge valve elastomeric seal experiences compression set in the closed position over time, and the compression set is accelerated at temperature. This allows a potential leak path out of containment. The new standard is in draft review and our concerns about the valve seals have been made known to the committee. These concerns are being considered.

The only failures in the CPS tests were the two strut failures. The horizontal strut that failed due to buckling failed because the load caused the pipe clamp to slip. Friction pipe clamps cannot be expected to hold during this type of overload. The vertical strut end failed in tension at greater than seven times its rated load. Both failures reduced the stress on the piping system.

Reviewing the results of these CPS tests and those of the CPS seismic test provides confidence that the containment piping penetrations and valves have considerable margin to failure during any credible design basis or severe accident mechanical loading.

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APPENDIX A

INSTRUMENTATION LOG FOR GATE VALVE TEST (CPS-5)

APPENDIX A

INSTRUMENTATION LOG FOR GATE VALVE TEST (CPS-5)

Channel numbers refer to the Data Acquisition System.

Instrument identifiers containing the same numeric designator are nominally located at the same axial location on the system test pipe.

To define orientation, flow is assumed to be from the inside of the containment to the outside. "Left" and "right" assume the observer is facing in the direction of the flow, or toward the penetration, from inside the containment.

Pipe strain gauges (SG-XX) are welded or bonded to the pipe. Locations are referenced from the center of the gauge to the edge of the weld joining the pipe to the referenced fitting or component. Gauges designated "(R)" are part of a three-gauge rosette. Strain gauge data provided qualitative understanding of piping system performance, but generally was not consistent enough to allow reduction to forces and moments with unequivocal results.

Channel	Identification	Location	Comments
	Thermocouples	Upstream valve	Models inside valve (inside containment) Type K thermocouples (Chromel-alumel)
01	TCS-10	Outside surface	At longitudinal centerline
02	TCI-9	Inside valve	Top of flow path. 3 in. upstream from valve seat
03	TCI-10U	Upstream seat	Top, inside valve
04	TCI-10D	Downstream seat	Top, inside valve
		Horizontal pipe, near "Tee"	Bonded
05	SG-6A	Top, circumferential (R)	∼1-1/2 in. from weld
06	SG-6B	Top, 45° (R)	—
07	SG-6C	Top, axial (R)	—
08	SG-6D	Right side, axial (toward penetration)	Failed at a displacement of 1.74 in.
09	SG-6E	Bottom, axial	—
10	SG-6F	Left side, axial	—

Channel	Identification	Horizontal pipe, near "Tee"	Bonded
11	SG-7A	Top, circumferential (R)	1-1/2 in. from weld
12	SG-7B	Top, 45° (R)	—
13	SG-7C	Top, axial (R)	—
14	SG-7D	Right side, axial	—
15	SG-7E	Bottom, axial	—
16	SG-7F	Left side, axial	—
		Vertical pipe, near "Tee"	Bonded
17	SG-8A	Side opposite from penetration (R)	1-3/4 in. from weld
18	SG-8B	Same as above, 45° (R)	—
19	SG-8C	Same as above, axial (R)	—
20	SG-8D	Right side, axial	—
21	SG-8E	Opposite SG-8C, axial	—
22	SG-8F	Left side, axial	—
		Horizontal pipe, upstream of inside valve, near elbow	Welded
23	SG-9A-A	Top, circumferential (R)	1-1/4 in. from weld
24	SG-9A-B	Top, 45° (R)	—
25	SG-9A-C	Top, axial (R)	—
26	SG-9A-D	Right side, axial	1 in. from weld
27	SG-9A-E	Bottom, axial	1 in. from weld
28	SG-9A-F	Left side, axial	1 in. from weld

Channel	Identification	Short pipe, upstream of inside valve	Welded
29	SG-9B-A	Top, circumferential (R)	1-3/4 in. from weld (pipe to valve)
30	SG-9B-B	Top, 45° (R)	—
31	SG-9B-C	Top, axial (R)	—
32	SG-9B-D	Right side, axial	1-3/4 in. from pipe weld
33	SG-9B-E	Bottom, axial	1-3/4 in. from pipe weld
34	SG-9B-F	Left side, axial	1-3/4 in. from pipe weld

		Inside valve weld neck, downstream side	Welded
35	SG-10-S	Top, circumferential (R)	1-3/8 in. from valve body
36	SG-10-T	Top, 45° (R)	—
37	SG-10-U	Top, axial (R)	—
38	SG-10-V	Left side, axial	On cross section with SG-10-S
39	SG-10-W	Bottom, axial	On cross section with SG-10-S
40	SG-10-X	Right side, axial	On cross section with SG-10-S

		Valve body, upstream valve, circumferential 1-1/2 in. below bonnet flange	Welded
41	SG-10-AA	Downstream side	—
42	SG-10-DD	Right side	—
43	SG-10-EE	Upstream side	—
44	SG-10-FF	Left side	—

Channel	Identification	Horizontal pipe, downstream from inside valve	Bonded
45	SG-11-A	Top, circumferential (R)	~18 in. from valve
46	SG-11-B	Top, 45° (R)	—
47	SG-11-C	Top, axial (R)	—
48	SG-11-D	Right side, axial	—
49	SG-11-E	Bottom, axial	—
50	SG-11-F	Left side, axial	—
		Upstream from penetration	Bonded
51	SG-13-A	Top, circumferential	1-1/2 in. from penetration
52	SG-13-B	Top, 45°	—
53	SG-13-C	Top, axial	—
54	SG-13-D	Right side, axial	—
55	SG-13-E	Bottom, axial	—
56	SG-13-F	Left side, axial	—
		On pipe inside penetration	Bonded
57	SG-15A	Top, circumferential (R)	—
58	SG-15B	Top, 45° (R)	—
59	SG-15C	Top, axial (R)	—
60	SG-15D	Right side, axial	—
61	SG-15E	Bottom, axial	—
62	SG-15F	Left side, axial	—

Channel	Identification	Weld neck, downstream valve, upstream side	Bonded
63	SG-22-S	Top, circumferential (R)	1 in. downstream from machined diameter reduction
64	SG-22-T	Top, 45° (R)	—
65	SG-22-U	Top, axial (R)	—
66	SG-22-V	Right side, axial	As above
67	SG-22-W	Bottom, axial	As above
68	SG-22-X	Left side, axial	As above

		Body outside valve, circumferential 1-3/4 in. below bonnet flange	Bonded
69	SG-22-AA	Downstream side	—
70	SG-22-DD	Right side	—
71	SG-22-EE	Upstream side	—
72	SG-22-FF	Left side	—

		On outside pipe, near elbow	Bonded
73	SG-24-A	Top, circumferential (R)	—
74	SG-24-B	Top, 45° (R)	—
75	SG-24-C	Top, axial (R)	—
76	SG-24-D	Right side, axial	—
77	SG-24-E	Bottom, axial	—
78	SG-24-F	Left side, axial	—
79	SG-24-Q	Strut, near first outside elbow	Bonded

Channel	Identification	On centerline of first outside elbow	Bonded
80	SG-25-A	Top, circumferential (R)	—
81	SG-25-B	Top, 45° (R)	—
82	SG-25-C	Top, axial (R)	—
83	SG-25-D	Right side, axial	—
84	SG-25-E	Bottom, axial	—
85	SG-25-F	Left side, axial	—
		Strut Locations	Bonded
86	SG-25-Q	Vertical strut near far outside elbow	—
87	SG-11-Q	Vertical strut near inside valve	—
88	SG-11-R	Horizontal strut near inside valve	—
		External measurements	
89	SP-24	Hydraulic pressure to ram	S/N 205770
90	SP-21	Pressure, upstream pipe	S/N 662553
91	SP-22	Pressure, middle pipe	S/N 662552
92	SP-23	Pressure, downstream pipe	S/N 662555
93	DP-1	Vertical displacement	S/N 703
94	DP-2	In-line displacement	S/N A27609
95	VP-1	Position, inside valve stem	—
96	VP-2	Position, outside valve stem	—
97	VC-1	Electrical current, inside valve	—
98	VC-2	Electrical current, outside valve	—
99	VV-1	Valve voltage	—

APPENDIX B

INSTRUMENTATION LOG FOR BUTTERFLY VALVE TEST (CPS-6)

APPENDIX B

INSTRUMENTATION LOG FOR BUTTERFLY VALVE TEST (CPS-6)

Channel numbers refer to the Data Acquisition System.

Instrument identifiers containing the same numeric designator are nominally located at the same axial location on the system test pipe.

To define orientation, flow is assumed to be from the inside of the containment to the outside. "Left" and "right" assume the observer is facing in the direction of the flow, or toward the penetration, from inside the containment.

Channel	Identification	Location	Comments
	Thermocouples	Upstream valve	Models inside valve (inside containment) Type K thermocouples (Chromel-alumel)
01	TC-1	Flange, right side	Embedded 1-1/4 in. into 3/8-in.-thick seat retainer flange
02	TC-2	Flange, left side	As above
03	TC-3	Pipe surface	Near inside valve
04	TC-4	Pipe surface	Near outside valve
05	TC-5	Outside valve flange	
06	TC-6	Ambient temperature	

Pipe strain gauges (SG-XX) are welded or bonded to the pipe. Locations are referenced from the center of the gauge to the edge of the weld joining the pipe to the referenced fitting or component. Gauges designated "(R)" are part of a three-gauge rosette.

Channel	Identification	Horizontal pipe, near tee, right side	7-3/4 in. from C/L of tee, bonded
07	SG-6A	Top, circumferential (R)	1/2-in. from weld
08	SG-6B	Top, 45° (R)	—
09	SG-6C	Top, axial (R)	—
10	SG-6D	Right side, axial (toward penetration)	—
11	SG-6E	Bottom, axial	—
12	SG-6F	Left side, axial	—
		Horizontal pipe, near tee, left side	7-3/4 in. from C/L of tee, bonded
13	SG-7A	Top, circumferential (R)	—
14	SG-7B	Top, 45° (R)	—
15	SG-7C	Top, axial (R)	—
16	SG-7D	Right side, axial	—
17	SG-7E	Bottom, axial	—
18	SG-7F	Left side, axial	—
		Vertical pipe, near tee	1/2 in. from weld, bonded
19	SG-8A	Side opposite from penetration (R)	—
20	SG-8B	Same as above, 45° (R)	—
21	SG-8C	Same as above, axial (R)	—
22	SG-8D	Right side, axial	—
23	SG-8E	Opposite SG-8C, axial	—
24	SG-8F	Left side, axial	—

Channel	Identification	Horizontal pipe, upstream from inside valve	32 in. from valve flange face, bonded
25	SG-9A	Top, circumferential (R)	1/2 in. from weld
26	SG-9-B	Top, 45° (R)	—
27	SG-9-C	Top, axial (R)	—
28	SG-9A-D	Right side, axial	1/2 in. from weld
29	SG-9A-E	Bottom, axial	1/2 in. from weld
30	SG-9A-F	Left side, axial	1/2 in. from weld
		Inside valve weld neck, upstream side	**4-1/2 in. from valve flange face, welded**
31	SG-10-A	Top, circumferential (R)	—
32	SG-10-B	Top, 45° (R)	—
33	SG-10-C	Top, axial (R)	—
34	SG-10-D	Left side, axial	—
35	SG-10-E	Bottom, axial	—
36	SG-10-F	Right side, axial	—
		Horizontal pipe downstream from inside valve	**Sheared off during test by sliding clamp**
37	SG-11-A	Top, circumferential (R)	—
38	SG-11-B	Top, 45° (R)	—
39	SG-11-C	Top, axial (R)	—
40	SG-11-D	Right side, axial	—
41	SG-11-E	Bottom, axial	—
42	SG-11-F	Left side, axial	—

Channel	Identification	Between clamp and penetration	37-1/4 in. from penetration plate, bonded
43	SG-12-A	Top, circumferential	—
44	SG-12-B	Top, 45°	—
45	SF-12-C	Top, axial	—
46	SG-12-D	Right side, axial	—
47	SG-12-E	Bottom, axial	—
48	SG-12-F	Left side, axial	—
49	—	Not used	—
50	—	Not used	—
		On pipe upstream from penetration	**1 in. from penetration plate, bonded**
51	SG-13A	Top, circumferential (R)	—
52	SG-13B	Top, 45° (R)	—
53	SG-13C	Top, axial (R)	—
54	SG-13D	Right side, axial	—
55	SG-13E	Bottom, axial	—
56	SG-13F	Left side, axial	—
		On pipe inside penetration	**Bonded**
57	SG-15A	Top, circumferential (R)	—
58	SG-15B	Top, 45° (R)	—
59	SG-15C	Top, axial (R)	—
60	SG-15D	Right side, axial	—
61	SG-15E	Bottom, axial	—
62	SG-15F	Left side, axial	—

Channel	Identification	Weld neck, on downstream valve, upstream side	4-3/4 in. from valve flange face. bonded
63	SG-22-A	Top, circumferential (R)	—
64	SG-22-B	Top, 45° (R)	—
65	SG-22-C	Top, axial (R)	—
66	SG-22-D	Right side, axial	—
67	SG-22-E	Bottom, axial	—
68	SG-22-F	Left side, axial	—
69-72	—	Not used	—
		On outside pipe, near elbow	1-3/4 in. upstream from clamp, bonded
7[illegible]	SG-24-A	Top, circumferential (R)	—
74	SG-24-B	Top, 45° (R)	—
75	SG-24-C	Top, axial (R)	—
76	SG-24-D	Right side, axial	—
77	SG-24-E	Bottom, axial	—
78	SG-24-F	Left side, axial	—
79	SG-24-Q	Outside strut, near first downstream elbow	Bonded
		On centerline of first outside elbow	Bonded
80	SG-25-A	Top, circumferential (R)	—
81	SG-25-B	Top, 45° (R)	—
82	SG-25-C	Top, axial (R)	—
83	SG-25-D	Right side, axial	—
84	SG-25-E	Bottom, axial	—
85	SG-25-F	Left side, axial	—

Channel	Identification	Strut Locations	Bonded
86	SG-25-Q	Vertical strut near far outside elbow	—
87	SG-11-Q	Vertical strut near inside valve	—
88	SG-11-R	Horizontal strut near inside valve	—
		External measurements	Bonded
89	SP-24	Hydraulic pressure to ram	S/N 205770
90	SP-21	Pressure, downstream pipe	S/N 3315
91	—	Not used	—
92	SP-22	Pressure, middle pipe	S/N 662555
93	DP-1	Vertical displacement	S/N 703
94	DP-2	In-line displacement	S/N A27609
95	VP-1	Position, inside valve stem	—
96	SP-23	Pressure, upstream pipe	S/N 662553
97	VC-1	Electrical current, inside valve	—
98	—	Not used	—
99	VV-1	Valve voltage	—

APPENDIX C

INSTRUMENTATION LOG FOR 2-IN. GLOBE VALVE TEST (CPS-7)

APPENDIX C

INSTRUMENTATION LOG FOR 2-IN. GLOBE VALVE TEST (CPS-7)

Since the Data Acquisition System was in use for CPS-6, during CPS-7 strip chart recorders were used for data acquisition.

To define orientation, flow is assumed to be from the inside of the containment to the outside. "Left" and "right" assume the observer is facing in the direction of flow.

Recorder #/ Pen Color (#)	Identification	Location	Comments
Strain gauges			All strain gauges are welded
[illegible]RN	SG-1	Top, downstream from valve, near valve, axial	—
1-RED	SG-2	Top, downstream from SG-1, 45°	—
1-BLU	SG-3	Top, downstream from SG-2, circumferential	—
1-BRN	SG-4	Top, downstream from SG-3, axial	—
1-BLK	SG-5	Left side	At same cross section as SG-2
2-GRN	SG-6	Bottom	At same cross section as SG-2
2-RED	SG-7	Right side	At same cross section as SG-2
2-BLU	SG-8	Bottom, near penetration weld, axial	—
2-BRN	SG-9	Bottom, downstream from penetration weld	—
2-BLK	SG-10	On body of support strut, axial	—
Displacement		—	Cable reel potentiometer
1-PUR	DISP-1	Upstream end of pipe	Used as correlation signal
2-PUR	DISP-1	Upstream end of pipe	Used as correlation signal
3-#6	DISP-1	Upstream end of pipe	Used as correlation signal
4-#6	DISP-1	Upstream end of pipe	Used as correlation signal
4-#5	DISP-2	Near pipe support strut	Used only when strut is disconnected

Recorder #/ Pen Color (#)	Identification	Location	Comments
Valve Parameters			
3-#1	POSITION	—	Open/Closed signal
3-#2	AMPS	—	—
3-#3	VOLTS	—	—
Pressures			
3-#4	P-UPST	Upstream pressure	Tap between elbow and valve
3-#5	P-DWNST	Downstream pressure	Tap at penetration end of pipe
Temperatures			Type K thermocouples
4-#2	TC-V	On valve body	—
4-#3	TC-P	On pipe between valve and penetration	—
Load cell			
4-#4	LC	In series with lifting link at end of pipe	—

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13 ABSTRACT (200 words or less)

This report provides the results of accident simulation tests of three typical light water reactor containment penetration systems to provide a technical basis for the support and development of equipment qualification procedures at design basis load levels and to determine safety margins at severe accident load levels. The three systems tested were (a) an 8-in. gate valve system modeling a containment spray system; (b) an 8-in. butterfly valve system modeling a purge and vent system; and (c) a 2-in. globe valve system modeling the numerous small-bore piping systems. The valve types, valve sizes, piping configurations, penetrations, and supports used for the tests are typical of those found in commercial U.S. nuclear power plants for containment isolation applications. The three systems tested were mounted in a fixture and exposed to simulated severe accident mechanical loads by displacing the penetrations relative to the piping. Thermal and pressure loads were also applied. The test results indicate that valve, penetration, or piping system failure during hypothesized accident events is unlikely due to accident-induced loads.

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