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NUREG-2240

Flood Penetration Seal Testing Protocol Research

Office of Nuclear Regulatory Research

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ABSTRACT

Flood protection features are commonly incorporated into nuclear power plants (NPPs). The most common flood protection features are seals for penetrations in external and internal walls of safety related structures that allow cables, conduits, cable trays, piping, etc. to pass through the walls. Other common flood protection features include water-tight doors, as well as temporary flood barriers (e.g., temporary walls, stop-logs). The potential safety significance of NPP flood penetration seal performance during internal or external flooding events has long been recognized. The U.S. Nuclear Regulatory Commission (NRC) issued Information Notices (INs) related to flood barrier performance in 1988 and 2007. In a 1999 external flooding event at the French Le Blayais NPP, flood barrier failures resulted in underground rooms containing safety-related equipment being flooded. More recently, in the aftermath of the 2011 Fukushima Dai-ichi accident, walkdowns of licensing-basis flood protection features conducted by U.S. NPP licensees found examples of degraded or nonconforming flood protection features, including penetration seals. Inspections by NRC staff resulted in a number of findings related to flood penetration seals and barriers that were evaluated through the NRC's Significance Determination Process (SDP). Subsequently, in 2015, NRC issued another IN discussing degraded barrier ability to mitigate flooding events.

Although there is abundant operational experience indicating the potential safety significance of flood penetration seal performance, quantitative risk information is lacking. Both industry and the NRC have appropriate analysis tools for addressing the risk-significance of flood barrier performance (i.e. PRA models), but basic performance/reliability data on in-service components is not available. This is due, in part, to the lack of a widely recognized standard or protocol for evaluating flood penetration seal performance. For example, during the post-Fukushima flood protection walkdowns, flood penetration seals were assessed mainly through ad-hoc visual inspection.

As part of the Probabilistic Flood Hazard Assessment (PFHA) research program, the NRC's Office of Nuclear Regulatory Research conducted a research project to investigate how flood penetration seal performance might be evaluated. The research comprised three steps: (1) profiling of flood penetration seals currently used in U.S. NPPs, (2) developing an ex situ performance testing protocol, and (3) evaluating and refining the testing protocol by using it in limited testing of several seal types and applications. It is hoped that this initial research effort can be further refined or adapted by appropriate standards-making organizations (e.g., ANS, ASME, ASTM) in order to support development of basic performance/reliability data for flood penetration seals and, subsequently, quantitative risk information.

The first step in this research project comprised reviewing NRC documents, licensee submittals, and other sources of penetration seal information. The review included NPP licensee post-Fukushima flood protection walkdown reports, licensee responses to NRC requests for additional information, licensee event reports, fire seal testing literature, information available from seal vendors, and NRC-generated documents, such as NUREGs, information notices, and inspection reports. This review summarized seal types and seal materials, as well as penetration shapes, penetration sizes, and penetrants used in NPPs.

In the second step of this project, researchers developed a draft protocol for ex situ (i.e., laboratory-based) flood penetration seal performance testing. This testing protocol was designed for evaluating the flood mitigation performance of penetration seals installed to protect

openings in barriers (e.g., internal and external walls, floors, ceilings). The protocol focuses on pressure testing. It includes the definition of terms, test scope, the significance and use of the test procedures, the test specimens and test equipment, test conduct, and proposed documentation of the testing procedures. The draft protocol was published for public comment in 2018, and revisions were made based up on comments received from stakeholders (e.g., Nuclear Energy Institute, Electric Power Research Institute).

In the third part of this project, researchers assessed the effectiveness of the revised draft testing protocol by conducting a limited series of penetration seal performance tests using a number of seal types and penetrants, as well as various penetration types, shapes, and sizes. The results of this test series largely confirmed the viability of the test protocol and its applicability to flood penetration seal performance testing. The testing protocol was further revised to incorporate lessons learned from the limited test series.

A draft of this report was published for public comment in 2020. This final report includes revisions made in response to stakeholder comments. It includes a summary of information derived from the review performed step 1, the proposed testing protocol initially developed in step 2 and revised based on the limited performance testing series conducted in step 3 and stakeholder comments, as well as overall lessons learned from the testing series.

The performance testing protocol developed in this project provides NRC staff and other interested parties with information on how to measure flood penetration seal performance in a controlled laboratory setting. Note that the data and observations from the limited testing series conducted in this project were designed to exercise the test protocol and should not be interpreted as qualifying or disqualifying any specific flood penetration seal or installation design.

Overall, insights developed from this research project could be used to inform future NRC activities related to flood penetration seals (e.g. inspection procedures, guidance development). This initial research effort can be further refined or adapted by appropriate standards-making organizations in order to advance development of basic performance/reliability data for flood penetration seals and support development of quantitative risk information and risk insights.

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EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research has completed a project to develop a test protocol for evaluating flood penetration seals using simulated flooding conditions in a laboratory setting. The contractor for this research effort was Fire Risk Management, Inc. (now part of Fisher Engineering, Inc.). The main project goals were (1) to develop an understanding of the types, sizes, and application of flood seals in nuclear power plants (NPPs); and (2) to develop a testing protocol that could be used to evaluate seal performance. This research effort was divided into three steps. The first step included a review of available NPP flood penetration seal information. This review summarized seal types and materials, as well as penetrants and penetration shapes and sizes. In the second step of the project, researchers used the information developed in step one to construct a draft test protocol providing recommendations and procedures for water pressure testing of penetration seals. The third step of the project applied the draft test protocol to a limited series of water pressure tests using candidate seal penetrations and assemblies. The objective of this experimental series was to exercise the test protocol and identify strengths or shortcomings.

This testing protocol developed in this project is a research product that provides the NRC staff and other interested parties with a basic, introductory understanding of how a flood penetration seal testing protocol could be formulated. These insights could potentially be used to inform future NRC activities such as development of inspection procedures or guidance. However, this testing protocol itself is not an NRC-approved testing standard, and there is no intent for it to carry binding regulatory effects.

The first step of the project comprised included a review of available NPP flood penetration seal information, mainly from publicly available NRC documents and databases. These publicly available sources included but were not limited to licensee event reports, NUREGs, information notices, and flooding walkdown reports. The publicly available NRC information contained numerous references to flood barrier penetration seals. This NRC literature review provided important insights as to the types and configurations of flood-barrier penetration seals typically found at NPPs. For example, this review summarized seal types and materials, as well as penetrants and penetration shapes and sizes. The most common of these were later included in the testing phase of this research project.

In the second part of the research, the contractor developed a draft flood penetration seal performance testing protocol with NRC input. Researchers studied other standards (e.g., fire seal testing standards developed by the American Society for Testing and Materials and Underwriters Laboratories standards) and incorporated insights and other lessons learned into the draft test protocol. The draft performance testing protocol is focused on pressure testing. It includes the definition of terms, test scope, the significance and use of the test procedures, the test specimens and test equipment, test conduct, and proposed documentation of the testing procedures. The draft protocol was published for public comment in 2018, and revisions were made based up on comments received from stakeholders (e.g., Nuclear Energy Institute, Electric Power Research Institute).

In the third part of the research, the revised draft test protocol was used to conduct a trial series of water pressure tests on a limited selection of penetration/seal combinations. These tests were performed at a Framatome facility in Lynchburg, VA, in August 2018. Five test decks were constructed for these tests, with each incorporating multiple penetrations and seal types into its

construction. This allowed for multiple penetration/seal combinations to be tested at one time using the test apparatus at this facility.

Six tests were conducted using the guidance and specifications detailed within the draft test protocol. Applied pressures were varied during each test following predetermined pressure time series. The maximum water pressure achieved during any of the tests was 19 pounds per square inch gauge (131 kilopascals; 44 feet of water). Along with water pressure and temperature recordings, researchers measured water leakage (if any) through each seal penetration during each test. Although this NUREG presents performance data for each test, its function is to demonstrate the data collection guidelines in the test protocol rather than to qualify the performance of a given seal assembly.

The test series largely demonstrated that the draft test protocol provides an adequate set of guidelines for performance testing of the candidate seal assemblies. However, the tests also identified shortcomings within the draft test protocol, and a number of sections were subsequently amended.

The appendix to this NUREG includes the final testing protocol based on the draft initially developed in step 2 and subsequently revised based on the limited performance testing series conducted in step 3 and stakeholder comments. However, this flood penetration test protocol is not an NRC-approved testing standard. Instead, the test protocol, as published within this NUREG, is intended to serve as an example of one testing approach. This test protocol will provide the NRC staff and other interested parties with information on how one could conduct such tests. The initial steps taken by this research effort can provide useful insights and a basis for future efforts to quantify the performance of these flood barriers. For example, the test protocol developed could be used as a starting point or framework for the future development of an industry consensus standard by appropriate standard-making organizations.

There are several potential follow-on research directions that could complement or supplement the work reported on in this report. The proposed protocol developed in this project focused on ex situ, laboratory-based testing, which would be appropriate for testing of new seals or seals harvested from aged components from decommissioned plants. An alternative would be to develop an in situ testing protocol that could be used to perform testing of seals that have been in service for years and in their actual installed arrangements (likely performed at decommissioned NPPs). This could provide the most accurate performance/reliability data on component fragilities for subsequent probabilistic risk assessments. Future research (either ex situ or in situ) could investigate approaches for including other factors such as vibration, or debris loading.

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The Nuclear Energy Institute and Electric Power Research Institute staff made public comments on certain interim project materials in response to a February 2018 *Federal Register* notice (Docket No. NRC-2018-0028). These public comments provided valuable insight and recommendations for the draft test protocol.

The NRC published a draft of this NUREG in the *Federal Register* in August 2020 (85 FR 46734) requesting public comments. The NRC received comments from numerous interested parties, including the Nuclear Energy Institute, the Electric Power Research Institute, the Pressurized-Water Reactor Owners Group, and Kevin Hawks of Transco Products Inc. The NRC revised the draft NUREG using the recommendations provided by these helpful comments.

ABBREVIATIONS AND ACRONYMS

ADAMS	Agencywide Documents Access and Management System
ASTM	American Society for Testing and Materials
CFR	*Code of Federal Regulations*
cm	centimeter
F	Fahrenheit
GPM	gallons per minute
IN	information notice
kPa	kilopascal
LER	licensee event report
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
PRA	probabilistic risk assessment
psi	pounds per square inch
psig	pounds per square inch gauge
PVC	polyvinyl chloride
UL	Underwriters Laboratories, Inc.

1 INTRODUCTION

1.1 Background and Motivation

Nuclear power plant (NPP) buildings have many penetrations or transits through interior and exterior walls and foundations, as well as floors and ceilings, to allow such equipment as cables, cable trays, conduits, pneumatic lines, steam pipes, water lines, and ducts to exit or enter. These penetrations are typically sealed to protect NPP structures, systems, and components from the effects of water, fire, smoke, or gases. In particular, certain penetration seals are credited for internal or external flood protection of structures, systems, and components important to safety.

Following the accident at the Fukushima Dai-ichi nuclear power plant resulting from the 2011 Great Tohoku Earthquake and tsunami in Japan, the U.S. Nuclear Regulatory Commission's (NRC's) Near-Term Task Force was tasked with conducting a systematic and methodical review of NRC processes and regulations to determine whether improvements were necessary (Agencywide Documents Access and Management System (ADAMS) Accession No. ML11186A950). Pursuant to Near-Term Task Force Recommendations 2.1 and 2.3, the NRC issued a request for information under Title 10 of the *Code of Federal Regulations* (10 CFR) 50.54(f) requiring all operating NPPs in the United States to perform walkdowns of their current design-basis flood protection and to reevaluate their design-basis flood hazard estimates (ADAMS Accession No. ML12053A340). The flooding protection walkdowns found numerous examples of degraded or nonconforming flood protection features, the majority of which were penetration seals.

Currently, there are no known standard test methods for penetration seals and their effectiveness to withstand water pressure. Thus, the NRC staff began this research effort to develop a test protocol that could provide the agency and other interested parties with knowledge about how such a protocol could be formulated and how it could be used to evaluate the effectiveness and performance of penetration seals. Since the March 22, 1975, fire at the Tennessee Valley Authority Browns Ferry Nuclear Plant, extensive research and testing procedures supported by the NRC and the industry have been developed for fire-barrier penetration seals. These seals are installed to seal fire-barrier openings and maintain the fire-resistive integrity of fire barriers to offer reasonable assurance that a fire will not spread from one plant area to another. For flood penetration seals, this project made use of the lessons learned from research and studies conducted for fire-barrier penetration seals, such as NUREG 1552, "Fire Barrier Penetration Seals in Nuclear Power Plants," issued July 1996.

Furthermore, the regulatory interest for much of this research activity related to flood barriers stems from 10 CFR Part 50, "Domestic licensing of production and utilization facilities," Appendix A, "General Design Criteria for Nuclear Power Plants," General Design Criterion 2, "Design bases for protection against natural phenomenon," which states the following:

> Structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The design bases for these structures, systems, and components shall reflect: (1) Appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and

period of time in which the historical data have been accumulated,
(2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena and (3) the importance of the safety functions to be performed.

1.2 Research Approach

1.2.1 Task 1 Summary

This task began with a review of NRC documentation related to the various seal materials used for flood penetrations seals at NPPs. This summary included information on the size and shape of typical penetrations, the types of seal material, and the design configurations that permit various piping through the penetrations. The primary sources for much of this literature review are publicly available through ADAMS, at https://www.nrc.gov/reading-rm/adams.html). Additional sources included NPP responses to NRC requests for additional information, licensee event reports (LERs), fire tests, information available from vendors, and other NRC-generated documents such as NUREGs, information notices (INs), and inspection reports.

The second part of this task was the development of a proposed protocol for testing the performance of flood penetration seals (see Appendix A). Within this test protocol was proposed documentation of the testing procedures, including test scope, referenced documents, definition of terminologies, the significance and use of the test procedures, the specimens and test equipment, and test conduct. The overall intent of this draft test protocol and subsequent testing (Task 2) was to provide initial background research and knowledge for the NRC staff or the industry that could be used to support future evaluations of flood mitigation performance of penetration seals. This test protocol may also be used as a starting point or framework for the future development of an industry consensus standard.

1.2.2 Task 2 Summary

The objective of Task 2 was to test the effectiveness and adaptability of the draft test protocol with a limited series of water pressure (i.e., flood) tests. These flood tests were conducted on a variety of candidate seal assemblies identified in Task 1.1 as being typically found at NPPs. These seal assemblies were engineered and constructed to reflect their “as-built” configurations, using qualified installation personnel. Before testing, a test plan was designed to fully exercise the test protocol with a diverse set of pressure tests. The rate and duration of the applied water pressure were planned to vary for each of the tests.

In August 2018, six water pressure tests were performed on five test decks. Multiple flood penetration seal assemblies were installed in each test deck to test a wide range of assembly types during the limited test series. Chapter 5 reports the observations and data from this test series. Upon the completion of the flood test series, the test protocol was updated to incorporate the lessons learned. Chapter 6 includes these insights.

Overall, the test protocol provided appropriate procedures for measuring the performance of the penetration seals during the laboratory pressure tests. Although the series found no significant faults, the observations and insights from the six water pressure tests led to minor revisions to the test protocol. Appendix A includes the final test protocol.

2 FLOOD PENETRATION SEAL OVERVIEW

Before the development of a test protocol for flood penetration seal performance, researchers reviewed relevant NRC documents to identify typical penetration seal types and configurations found at NPPs and related operational experience. The main sources of this information included INs, LERs, NUREGs, and plant responses to the 10 CFR 50.54(f) requests for information.

2.1 NRC Regulatory Information

2.1.1 Information Notices

NRC INs communicate operating or analytical experience to the nuclear industry (referred to as "addressees"). Many past INs included relevant information about penetration seals. Table 2-1 lists some relevant INs that this research effort surveyed.

Table 2-1 Select NRC Information Notices on Penetration Seals

Information Notice	Relevant Information
IN-88-04 Inadequate Qualification and Documentation of Fire Barrier Penetration Seals	This IN outlined multiple shortcomings related to penetration seals installed at NPPs. Discrepancies between tested designs and in-plant designs were identified. Modifications to installed seals also were not evaluated with an associated technical review.
IN-88-56 Potential Problems with Silicone Foam Fire Barrier Penetration Seals	This IN alerted addressees of the possibility that some installed silicone foam penetration seals may contain nonconforming conditions such as splits, gaps, voids, and lack of fill in the silicone foam.
IN-88-60 Inadequate Design and Installation of Watertight Penetration Seals	This IN alerted addressees to potential problems resulting from inadequate design and installation of penetration seals. Specifically, certain penetration seals may not have provided watertight barriers between redundant safe-shutdown trains.
IN-92-69 Water Leakage from Yard Area Through Conduits into Buildings	This IN alerted addressees to the potential large amounts of water leaking into the reactor building through electrical conduits. In the cited incident, stormwater leaked through an electrical conduit with inadequately installed internal penetration seals near the wall of the auxiliary building.
IN-94-27 Facility Operating Concerns Resulting from Local Area Flooding	This IN documented an incident where local area flooding impacted the safe operation of an NPP. Flooding from an adjacent river and heavy rainfall caused a licensee to shut down the operating reactor. Afterwards, it was found that flooding in the lower levels of the turbine building came from water leaking through safety-related underground cable trays.
IN-94-28 Potential Problems with Fire-Barrier Penetration Seals	This IN alerted addressees to potential problems in installed fire-barrier penetration seals. It was found that many seals were nonfunctional and had gone undetected as a result of inadequate inspection procedures and inadequate acceptance criteria. These nonconformities had also gone undetected when thermal insulation or damming material covered the surface of the seals.

Table 2-1 Select NRC Information Notices on Penetration Seals (cont'd.)

Information Notice	Relevant Information
IN-02-12 Submerged Safety-Related Electrical Cables	This IN informed addressees of multiple circumstances where safety-related electrical cables in underground conduits were becoming submerged in water as the result of ineffective water barriers. Some of these incidents resulted in tripped electrical equipment.
IN-07-01 Recent Operating Experience Concerning Hydrostatic Barriers	This IN informed addressees of operating experience concerning water leaking into buildings or between rooms due to deficient hydrostatic (watertight) barriers. These barriers were either degraded, missing, or composed of nonwatertight materials such as fire stop (e.g., silicone foam).
IN-15-01 Degraded Ability to Mitigate Flooding Events	This IN addressed operating experiences related to external flood protection where deficiencies with equipment, procedures, and analyses resulted in a degraded ability to mitigate flooding events. For certain licensees, the majority of these deficiencies were degraded or otherwise nonconforming flood penetration seals.

2.1.2 Licensee Event Reports

In 10 CFR 50.73, "Licensee event report system," the NRC requires commercial nuclear reactor licensees to report certain event information within 60 days after the discovery of the event. This research effort identified multiple LERs containing information related to penetration seals. Table 2-2 includes a representative sample of these LERs.

Table 2-2 LERs with Relevant Information on Flood Penetration Seals

LER Number	Missing Conduit Internal Seals	Deficient or Missing Conduit Seals	Deficient Penetration Seal	Missing Penetration Seal
50-313/2014-001-00	X	X	X	X
50-259/1988-023-00				X
50-346/1989-004-01				X
50-237/1995-017-00			X	
50-413/2006-002		X		
50-285/2011-003		X		X
50-244/2013-003		X		X
50-213/1988-006-00	X			
50-336/2012-003-01	X	X		
50-410/1986-026-01		X		
50-410/1989-002-01	X	X	X	X
50-410/1987-075-00			X	
50-277/1988-009-01	X	X		X
50-440/1993-010-00		X		
50-266/2015-001-00			X	
50-361/1984-033				X
50-443/2006-003-00			X	X
50-335/2014-001	X			
50-271/1997-002-01		X		
50-271/2012-001-01		X		

Table 2-2 LERs with Relevant Information on Flood Penetration Seals (cont'd.)

LER Number	Missing Conduit Internal Seals	Deficient or Missing Conduit Seals	Deficient Penetration Seal	Missing Penetration Seal
50-271/2013-001-00	X	X		
50-271/2013-002-00	X	X		
50-397/1992-034-02		X	X	
50-410/1987-016-01			X	X

For greater detail, each of the LERs listed in Table 2-2 can be found the NRC ADAMS database. For example, LER 50-313-2014 resulted from a flood protection walkdown in response to the 10 CFR 50.54(f) request for information. The licensee identified deficient design features and procedures related to missing or deficient conduit seals, ground water intrusion through building conduits, and degraded hatch gaskets. A root cause evaluation identified the lack of configuration control of external flood barriers and the lack of robust design control. Corrective actions implemented by the licensee included new training related to maintaining flood barriers, work orders to fix deficient barriers, and increased oversight of followup flood walkdowns.

2.1.3 NUREG Reports

NRC NUREG publications are reports or brochures on regulatory decisions, results of research, results of incident investigations, and other technical and administrative topics. The NRC staff prepares a NUREG publication, while a contractor prepares a NUREG/CR publication.

Past NUREG publications served as a substantial source of information on penetration seals. The majority of these NRC publications emanate from fire penetration seal research. Although these reports do not explicitly address flooding concerns, researchers used the lessons learned from the reported tests and investigations in the development of the flood test protocol.
Table 2-3 summarizes the NUREG reports researched as part of this project.

Table 2-3 NUREG Reports with Relevant Information on Penetration Seals

NUREG	Relevant Information
NUREG/CR-0152 Development and Verification of Fire Tests for Cable Systems and System Components (1978)	This report, prepared by Underwriters Laboratories Inc. (UL), summarized the results of flame test experiments on cable trays. Lessons learned included the necessity to restrain cables to prevent random, unpredictable cable movement during testing.
NUREG/CR-2321 Investigation of Fire Stop Test Parameters Final Report (1981)	This report was prepared by UL. The effects of pressure differential, fire exposure conditions, and sample construction on penetration seal performance were reported. Testing showed that seal performance was affected by seal sample construction. Prior damage (e.g., cracks) to seals significantly affected performance during tests.
NUREG/CR-2377 Test and Criteria for Fire Protection of Cable Penetrations (1981)	This report was prepared by Lawrence Berkeley National Laboratory, and it documented testing to evaluate the effects of test furnace pressure differential and excess pyrolyzates on cable penetrations. It

Table 2-3 NUREG Reports with Relevant Information on Penetration Seals (cont'd.)

NUREG	Relevant Information
	recommended the updating of testing standards based on experimental testing results.
NUREG/CR-4112 Investigation of Cable and Cable System Fire Test Parameters (1985)	This report (prepared by UL) investigated the flame test in Institute of Electrical and Electronics Engineers Standard 383, "IEEE Standard for Qualifying Electric Cables and Splices for Nuclear Facilities." The investigation looked into possible test procedure and equipment modifications to increase repeatability and generate additional testing data. Evaluated modifications included cable wire ties, differential pressures, and cable jacket materials.
NUREG-1552 Fire Barrier Penetration Seals in Nuclear Power Plants (1996)	This report was a comprehensive technical assessment of fire-barrier penetration seals, addressing reports of potential problems to determine their safety significance. It determined that previous staff actions and continued NRC inspections were adequate to maintain public safety. This report included minor recommendations; for example, it recommended that any test configurations reflect "as-built configurations."

2.2 Typical Flood Penetration Seal Types and Properties

The following describes common flood penetration seals found at NPPs. This should not be interpreted as an exhaustive list.

2.2.1 Silicone Foams

Silicone foam seals are widely used in NPPs. These seals are formed in place within penetrations. They are usually reliant upon a two-component mixture. The chemical reaction that results from the two-component mixture causes the foam to expand in volume, thus forming a tight seal in the penetration opening. Additives can be used during this process to alter properties such as density, radiation protection, or cure time. Cure times are usually 2–24 hours.

2.2.2 Elastomers

Elastomer seals are formed in place within penetrations. Like silicone foam seals, they are usually reliant upon a two-component mixture. After the formulation components are properly mixed, a dense, rubber-like material is formed in the penetration opening. These seals do not appreciably expand in volume like silicone foams seals. Additives can be added to elastomers to change their density or radiation protection properties. Cure times are typically shorter than those of silicone foams, ranging from 10 minutes to 8 hours.

2.2.3 Mechanical Seals

Boot and modular seals are the most common types of mechanical seals found at NPPs. Modular seals are also referred to as compression seals and include most Link-Seals®.

Boot seals are mechanical seals installed around pipe penetrations. They typically consist of a flexible, fiberglass sheet wrap secured around a pipe penetration. Their installation allows for more pipe movement than that of formed-in-place seals.

Modular seals are mechanical seals that consist of connecting modular links that fill the space between a penetrant and the barrier opening. These modular links can be tightened together to create a water-resistant barrier around the pipe or conduit penetrant. They are often made of a heavy rubber or plastic material with built-in tightening bolts.

2.2.4 Other Penetration Seal Types

Caulk is often used to seal building joints, penetrations, or other voids at NPPs. Caulk can be used in conjunction with other seal materials. For example, it is sometimes used to repair cracks or other damage to existing penetration seals.

Cement grout or mortar is another penetration seal material. Formed by mixing a cement powder with water, this material possesses similar water-resistant properties as concrete. It can be found in concrete joints and voids between precast-concrete slabs.

2.2.5 Blocking Materials

Blocking (also known as damming) materials are used to close the cross-sectional areas of penetrations before the application of seal materials (e.g., silicone foams, elastomers). They close off the open space within the penetration and provide backing material for the seal material. Blocking material may be permanent or temporary, depending on the seal installation. In regard to testing the seal assemblies, such material can be removed or left in place after the foam or elastomer seal has set, depending on whether it is integral to the design of the seal assembly. Ceramic fiber board, calcium silicate board, and rigid insulation foam are types of blocking materials often used. IN 88-56 provides further background on the installation and inspection of blocking materials for seal assemblies.

2.2.6 Penetration Sizes

A survey of approximately 54 licensee responses to the 10 CFR 50.54(f) request for information, Recommendation 2.3 Flooding, was performed using the NRC ADAMS public documents database. Only four of these licensee responses were judged to have provided sufficiently detailed information on the size and types of penetrations to generate the following summary figures. Although this sample set covers different reactor types and vintages, the limited sample size means that it is not all encompassing. However, it does provide a basic indication of the types and sizes of penetrations found at NPPs and serves as a sufficient starting point for this exploratory research project.

Figure 2-1 depicts conduit internal diameters across the four licensee plants. These conduits are typically provided with internal seals. Figure 2-2 presents the internal diameters for sleeve or core-bored penetrations. Unlike the conduits in Figure 2-1, the sleeve or core-bored penetrations are set into the wall/barrier and directly interface with wall/barrier material. These are often used to run multiple penetrants like cabling. The majority of sleeve or core-bored penetrations are 6 inches or less in diameter. Figure 2-3 depicts the diameters for pipe penetrants. The majority of these penetrants are 4 inches or less in diameter. Figure 2-4 presents the dimensions for rectangular penetrations. These larger openings can allow for multiple cable trays and pipes as penetrants.

The data gathered by this survey of the 10 CFR 50.54 (f) responses provided additional insight for the testing phase of this research project. The main objective of this testing phase was to assess the test protocol using the most common seal types and configurations. The survey data specifically aided in identifying these most common configurations before the construction of the test deck samples.

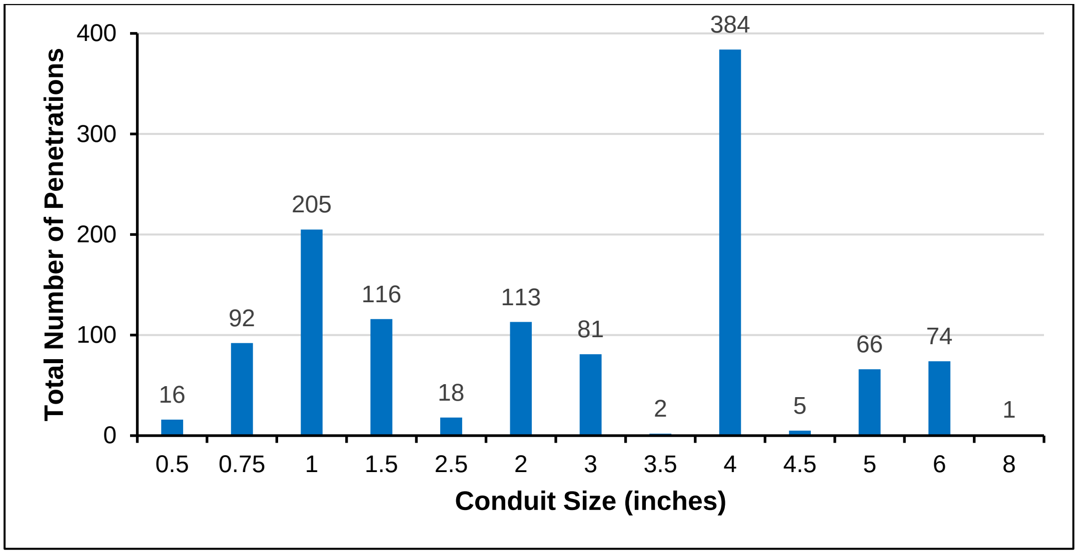

Figure 2-1 Circular Conduit Internal Diameters

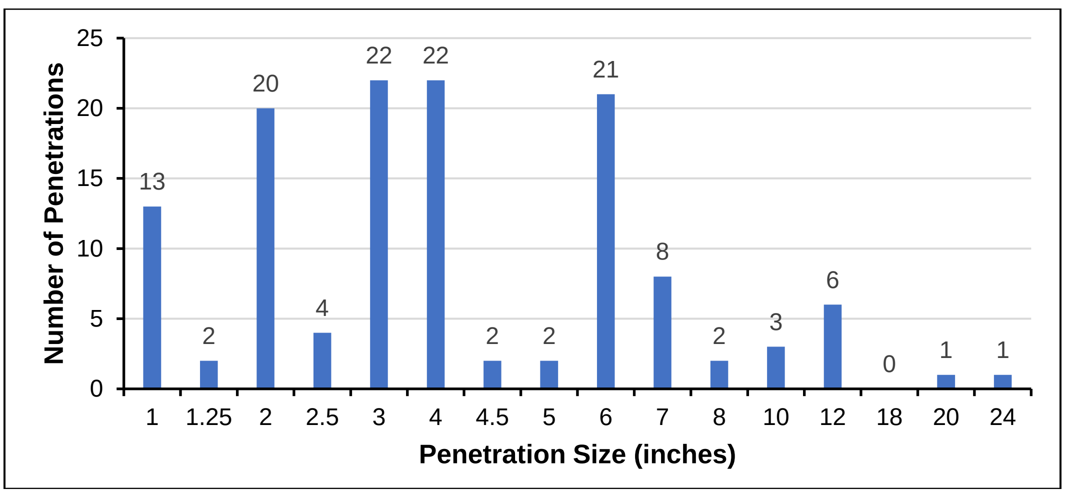

Figure 2-2 Sleeve/Core-Bored Penetration Internal Diameters

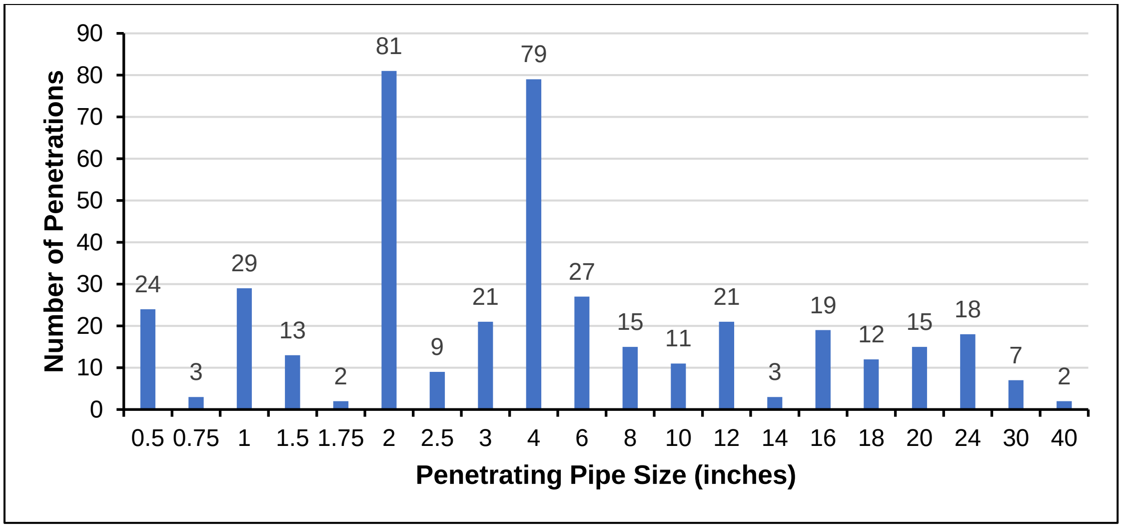

Figure 2-3 Pipe Penetrant Diameters

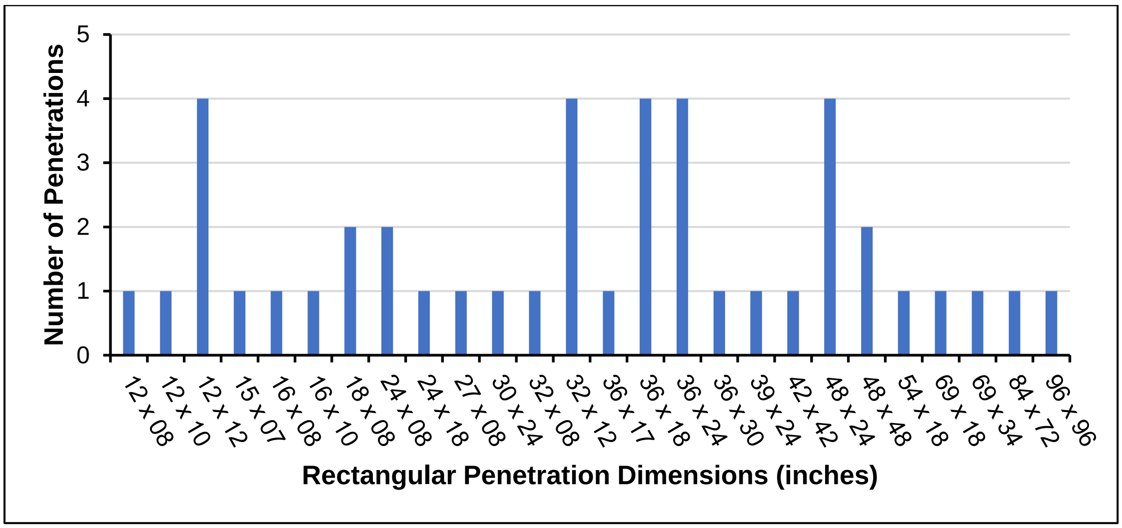

Figure 2-4 Rectangular Penetration Dimensions

3 FLOOD PENETRATION SEAL TEST PROTOCOL

3.1 Protocol Development

The test protocol was developed as a demonstrative research product. In its current form, the test protocol was designed to evaluate the flood mitigation performance of penetration seal assemblies or materials that are typically found in barriers within commercial NPPs and that themselves are designed to prevent the intrusion of water into specific plant areas. This test protocol is designed for laboratory (i.e., ex situ) testing. The laboratory testing of new flood penetration seals does not necessarily yield results that apply directly to aged flood penetration seals currently installed in NPPs. Consequently, additional research work would be needed to develop an in situ testing protocol or to test harvested or aged flood penetration seals in a laboratory setting after they are extracted intact from an NPP.

A number of existing standards and testing procedures were studied before developing the test protocol. American Society for Testing and Materials (ASTM) E814 (2017), “Standard Test Method for Fire Tests of Penetration Firestop Systems,” provided insights for this development process. UL 1479 (2015), “Standard for Fire Tests of Penetration Firestops,” provided additional testing insights. Although established standards were referenced during this development process, the flood penetration seal test protocol as outlined in this document is not intended to be an NRC-approved or otherwise accepted standard. The results from this research effort may be used as a framework for the development of a future industry consensus standard.

Additionally, the basic testing methods and terminology outlined within the demonstrative test protocol were included to enable a hypothetical user to generate test data with a level of confidence that results would be potentially replicable and comparable among testing facilities, regardless of the specific test equipment design.

3.1.1 ASTM E814 (2017), “Standard Test Method for Fire Tests of Penetration Firestop Systems”

The purpose of the ASTM E814 standard is to describe a test method for measuring the fire-resistive performance of firestop barriers. These firestop barriers are similar to flood penetration seals in that they are often applied around penetrations found in walls and floors of buildings. This ASTM standard is mature, widely used, and accepted throughout the testing industry. Although the standard focuses on deterministic pass/fail criteria, its overall approach provided insights during the development of the flood penetration seal test protocol.

3.1.2 UL 1479 (2015), “Standard for Fire Tests of Penetration Firestops”

This UL standard outlines testing requirements and methods for through-penetration firestops of various materials. It is also an American National Standards Institute-approved standard. Like the ASTM standard, the basic framework of UL 1479 was influential in the development of the flood penetration seal test protocol. This UL standard describes performance tests beyond just water leakage tests, including fire exposure and air leakage tests.

3.1.3 MIL-DTL-24705B, "General Specification for Penetrators, Multiple Cable, for Electric Cable"

This U.S. military standard covers multiple cable penetrator frames, accessories, and insert material items for sealing electric cables passing through bulkheads, decks, and other electrical equipment on ships. Section 4.6.5 of this standard defines watertightness requirements. This section specifically states the following:

> The multiple cable penetrator test specimen mounted on the test plate shall be bolted to the hydro chamber so that one side of the test specimen is exposed to water, and the opposite side of the test specimen is exposed to air. The hydro chamber shall then be filled with water and pressurized to 1.9 Bars (27.5 pounds per square inch). This pressure shall be maintained for a minimum of 10 minutes unless specimen failure occurs sooner. The test specimen shall be considered as having failed the watertightness test if, after 10 minutes, the water pressure has decreased to less than 1.9 Bars.

Although the protocol developed in this NUREG was drafted to measure performance rather than set pass/fail criteria, MIL-DTL-24705B provides helpful guidance with its terms, definitions, and other testing nomenclature. It notably includes verifications for shock and vibration tests.

3.2 Performance Criteria

As mentioned previously, the test protocol was developed to be performance based without any prescriptive language detailing pass/fail or acceptance criteria. This development choice differs with the aforementioned industry consensus standards, which often include rating criteria (e.g., firestop systems are assigned *F ratings*). This test protocol instead would enable a hypothetical end user to make performance-based determinations (i.e., leak rates as a function of applied pressure). This type of test data is better suited to support probabilistic risk assessments (PRAs), although the NRC does not intend for this test protocol (as written) to now be used to generate such actionable data. More test work and uncertainty analysis would be required before any such application. Additionally, a given PRA could incorporate factors (e.g., types of systems protected, number of penetrations, sump pump capacity) into its event trees that would determine whether a specified leakage rate through a specific penetration could be a significant safety issue. Manufacturers could also use insights from this research project when establishing their own performance ratings.

3.3 Public Comment Process

The NRC published a draft of the test protocol and a flood penetration seal literature review document in the *Federal Register* with Docket Number NRC-2018-0028 on February 20, 2018, with a comment period ending March 22, 2018. The agency received two sets of public comments, one set from the Electric Power Research Institute (EPRI) and one set from the Nuclear Energy Institute. All these comments were reviewed, and the draft test protocol was amended as necessary. Many comments provided valuable insights for the flood testing phase of this research project.

The following descriptions represent the scope and type of comments received and the subsequent amendments. A full listing of all public comments can be found at https://beta.regulations.gov/document/NRC-2018-0028-0001.

Beyond general editorial issues, some public comments addressed the potential limitations with the initial wording found within the test protocol. Where the NRC agreed, it amended the test protocol as necessary. For example, Section 4.6 was modified with less prescriptive language about penetrant installation in the test samples. The previous wording recommended a minimum 12-inch (30-centimeter) extension of the penetrating item on the exposed side of the test sample. This wording was removed and replaced with a new section that states, "install any through-penetrating items so that they extend beyond the surface of sample test deck as/if necessary to protect against internal leakage and to prevent undue stresses on the seal assembly/material." Similar editorial changes were made to other sections of the test protocol as a result of issues raised by public comments.

Another concern addressed potentially limiting the protocol to a specific testing vendor and any associated potential conflicts of interest. This is not the intent of the test protocol. Although it is a demonstrative research product, it was developed to allow for a broad range of implementations and not to limit it to any one specific type or design of test apparatus or test sample design. Section 5.1 was added to the test protocol for clarification purposes. This new section states, "flood testing should be performed by an independent testing laboratory/facility; one having no financial or other interests in the production or end use of the assembly being tested."

Many public comments addressed the lack of deterministic language in the test protocol. Specific, quantitative requirements like test duration, acceptance criteria, and other test parameters were left out of the test protocol to keep it performance based. The approach outlined in the test protocol allows for the end user to make such determinations depending on the testing needs. Such determinations would be made before testing and should be outlined in the test plan.

Some public comments expressed interest in in situ testing. Although such testing is beyond the scope of this initial research effort, it presents a possible future research area.

4 PROTOCOL EVALUATION—TEST DESIGN

4.1 Test Objective

The test objective was to evaluate the effectiveness of the draft test protocol and ensure it provided the necessary methods to adequately evaluate the flood protection or mitigation performance of penetration seals found at NPPs. Lessons learned from the test series were incorporated into a revised final test protocol. The NRC had no intention for this research effort to generate qualification testing data to establish flood or pressure ratings for any of the candidate flood seal assemblies or materials.

The test apparatus used during the test series was constructed by the testing facility used to support this research (Framatome Laboratory). The apparatus was designed using the general guidance outlined in the draft test methodology. The specific design specifications of that test apparatus are proprietary to the test facility.

The following test apparatus description and flood penetration seal designs can be considered as an example of the testing approach. As a demonstrative research product, the test protocol was intentionally formulated to allow for a broad range of implementation and not to limit its use to one specific test apparatus or test sample design. It was designed such that a hypothetical user would have the ability and discretion to design and implement a test that met his or her specific needs.

4.2 Test Apparatus Overview

The test apparatus (Figure 4-1) used to evaluate the performance-based test protocol was constructed to meet all the recommendations listed within the draft test protocol. The testing apparatus consisted of three main components: a pressure chamber, a test deck, and a water leakage measurement system.

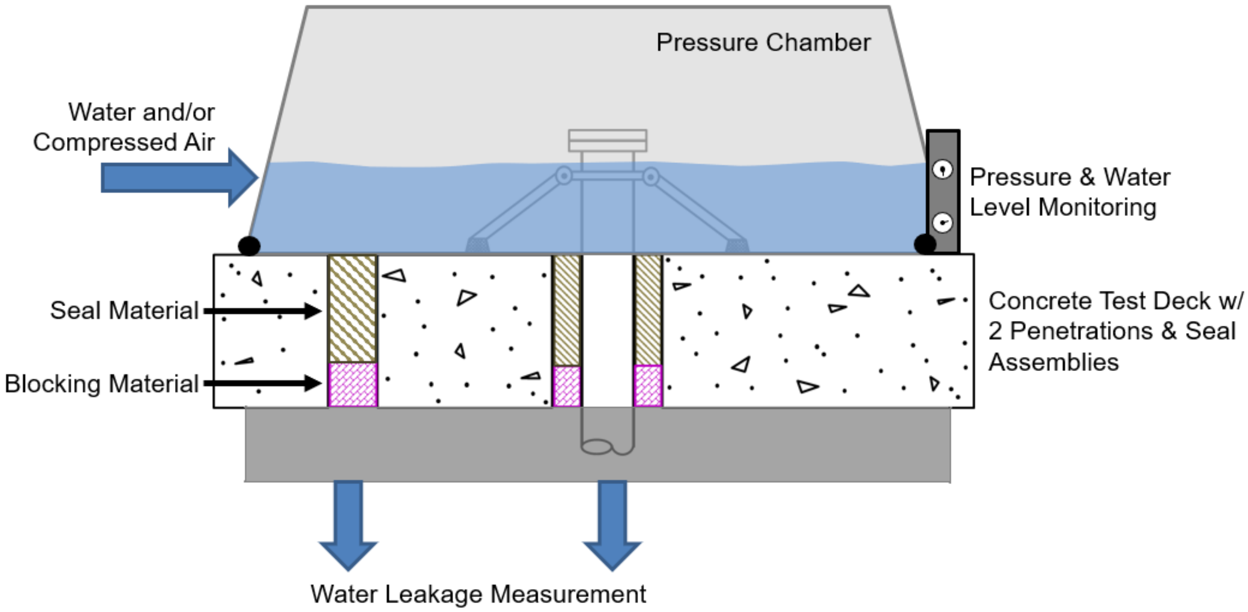

Figure 4-1 Generic Testing Apparatus Illustration (Cross Section)

A pressure chamber was affixed to the top of the test deck. Water and air connections filled the chamber to a desired water level and allowed for subsequent pressurization. The data acquisition system monitored and recorded internal water level and pressure parameters.

A concrete test deck was constructed to support the installation of various penetrations (with varying sizes and configurations) used for installing the candidate seal assemblies. It was then mounted horizontally beneath the pressure chamber for each test. The following section outlines the specific design in greater detail.

The leakage collection system was located beneath the test deck. This testing component allowed the data acquisition system to monitor and record water leakage from individual seal assemblies. However, for seal assemblies with conduits and other penetrating items, leakage from multiple seals found within that given assembly (e.g., outer and inner seals) could not be measured separately from one another.

This report will not discuss detailed design specifications and schematics (beyond this cursory overview) of the test apparatus, as they are proprietary to the testing laboratory.

The NRC does not intend to limit the test protocol to this specific test apparatus or test deck design. The test protocol is demonstrative research product and has been developed for generic application so that various apparatus designs could meet its recommendations. The choice to evaluate the test protocol with this particular test apparatus was made after drafting the test protocol.

4.3 Test Deck Design Overview

4.3.1 Concrete Test Deck Design and Construction

The testing apparatus design required the construction of “test decks” into which seal assemblies would be installed. Five tests decks were constructed. Each test deck consisted of a

square concrete slab with an overall approximate thickness of 12 inches (30 cm). Testing of samples with differing thicknesses is possible with the test protocol. The test decks included connections to allow for mounting the test deck to the testing apparatus. Each concrete test deck was allowed to cure before the installation of the penetration seals and penetrants (e.g., pipes, conduits, cables).

4.3.2 Seal Assembly Design and Installation

The size, number, and configuration of seal assemblies varied among the five constructed test decks. All seal assemblies were installed by qualified personnel directly from the manufacturer or by other certified individuals with the requisite experience. The installers took care to ensure that all seals and penetrants represented typical “as-built” configurations found in NPPs. Pipes, conduits, and other penetrating items were sometimes braced with metal brackets to restrain the movement of penetrants where this would reflect installed conditions.

This report uses the terms “penetration seal assembly,” “penetration seal,” and “seal assembly,” synonymously to describe such equipment as mechanical devices and material(s) used to prevent water migration through a penetration, including all voids around and between penetrating items such as pipes and conduits. Since each seal assembly is only associated with one penetration in each of the test decks, the term “penetration” is also used throughout this document as a general term when referencing the performance of a penetration seal within a test deck. For example, in Test Deck 4, a failure of Penetration Seal #4.2 is a failure of Seal Assembly #4.2.

With the exception of those seal assemblies installed by a manufacturer’s representative, all “formed in place” seal assemblies (e.g., low-density foams, elastomers, caulks) were installed at a uniform depth of approximately 8 inches (20 cm) as measured from the exposed face of the test deck. This was to allow a better comparison of the performance of the various materials being tested. Blocking material filled the remaining void (depth) of the test deck penetrations. For this test series, the blocking material was lightweight polystyrene foam. Figure 4-2 provides an illustrative example of this seal assembly installation.

A number of penetrations within the test decks were “sleeved” before the seal installation. In these cases, a hollow, metal, or polyvinyl chloride (PVC) sleeve was built into the concrete test deck. A given penetration seal would then be installed within the sleeve of the test deck. This allowed the seal material to bond directly to the sleeve material as opposed to concrete, which was the case for penetrations that were designed to mimic “core drills.” Figure 4-2 and Figure 4-3 are illustrative examples of a sleeved seal assembly installation.

Some seal assemblies incorporated penetrating items. These consisted of pipes, cables, conduits, and cable trays. The size and specific material type varied among the five test decks. Figure 4-4 illustrates the typical installation for pipe penetrants, including pipe bracing. Additionally, the ends of the pipes and cables were capped to ensure water tightness of the penetrating item(s) and to prevent any water migration “through” the penetrants. This was especially important for the multiwire cable. Figure 4-5 illustrates a complex conduit seal assembly with a capped multiwire cable penetrant. For these complex assemblies, only overall leakage could be measured and leakage from inner versus outer seals was not distinguishable.

Modular and boot seals were two types of mechanical seals installed and evaluated by the performance-based test protocol. The modular seal was installed in the annulus between the concrete test deck and the penetrant (pipe). Figure 4-6 illustrates the typical installation for a

modular seal. The boot seal was installed between a sleeve and a pipe penetrant. Its installation mirrored “as-built” configurations typically found at NPPs. Figure 4-7 illustrates the typical installation for a boot seal.

Since the testing objective was not to obtain actionable data but instead to exercise the test protocol, some efficiencies were gained during penetrant material procurement. For example, pipe and other penetrant material may not have been exactly representative of the nuclear-grade steel material found at NPPs. The purchase and installation costs with certain nuclear-grade penetrants were determined to be cost prohibitive in meeting the test objective. As a result, PVC pipes were used in some test deck designs despite PVC being a material not typically found at most NPPs. Testing to obtain experimentally significant data (for possible use in, for example, flood fragility analysis and PRAs) would require the installation of materials that are fully representative of the material found at the NPP for the specific assembly being tested and evaluated. Furthermore, before such applications are considered, more refinement of this test protocol would be required, including additional testing and uncertainty analysis.

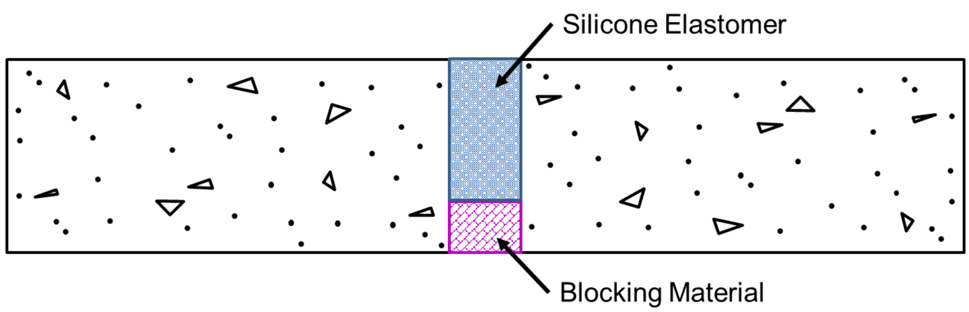

Figure 4-2 Test Deck Cross Section with Silicone Elastomer Seal

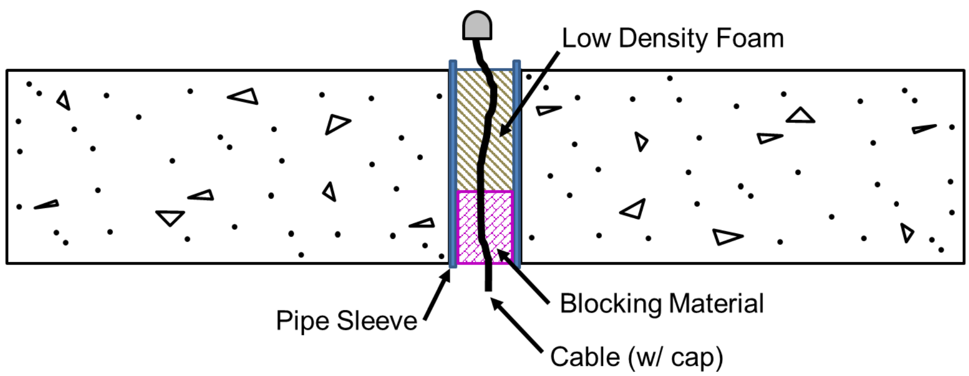

Figure 4-3 Test Deck Cross Section with Sleeved Penetration with Low-Density Foam Seal

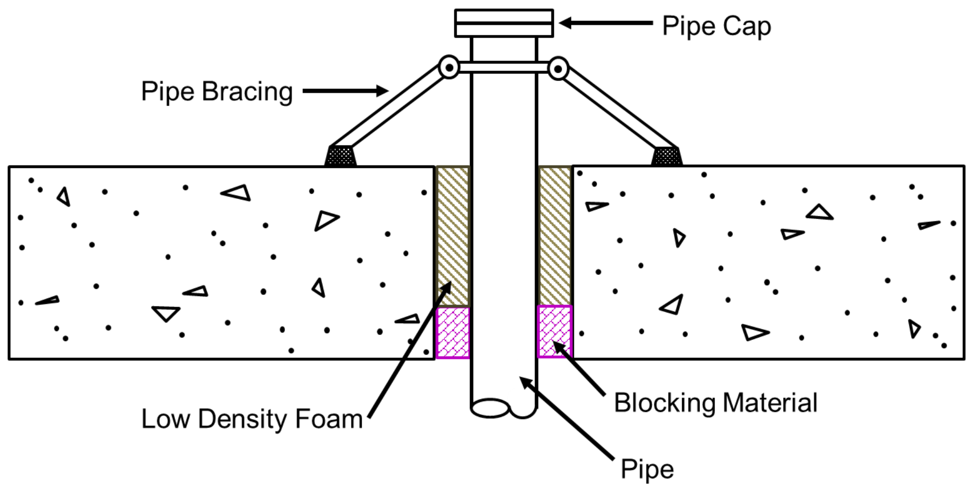

Figure 4-4 Test Deck Cross Section with Braced Pipe Penetrant

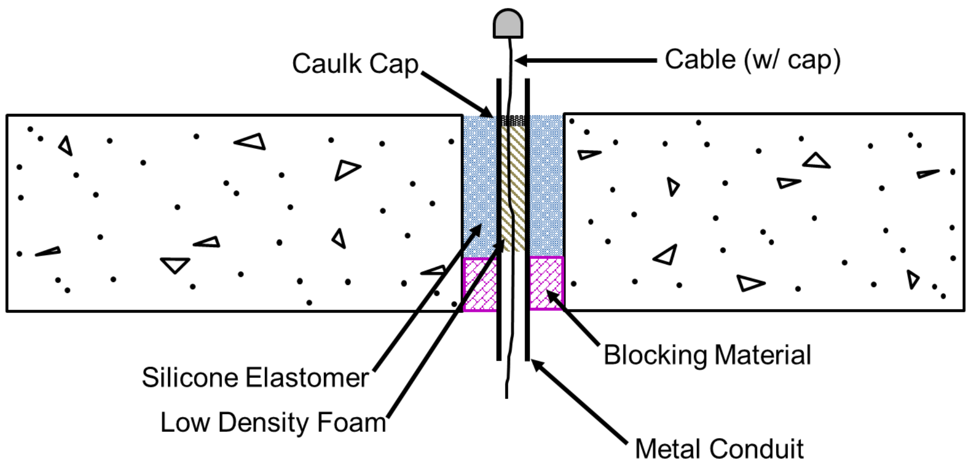

Figure 4-5 Test Deck Cross Section with Conduit and Capped Cable Penetrant

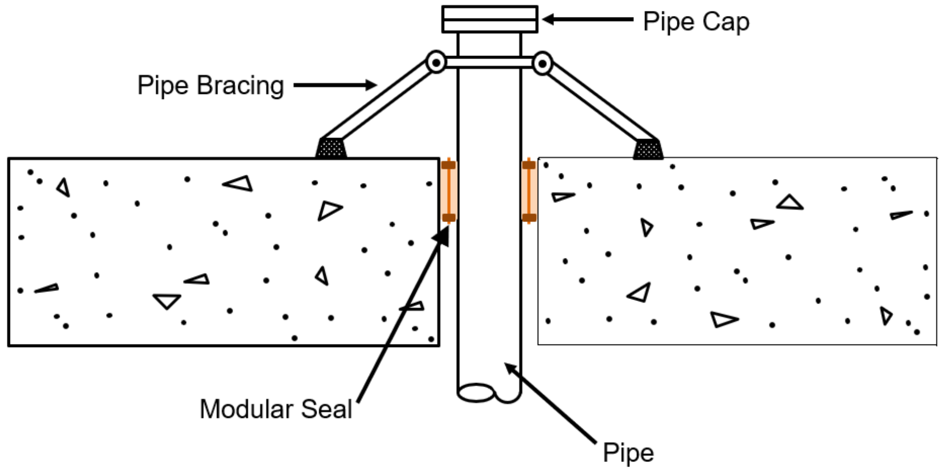

Figure 4-6 Test Deck Cross Section with a Modular Seal

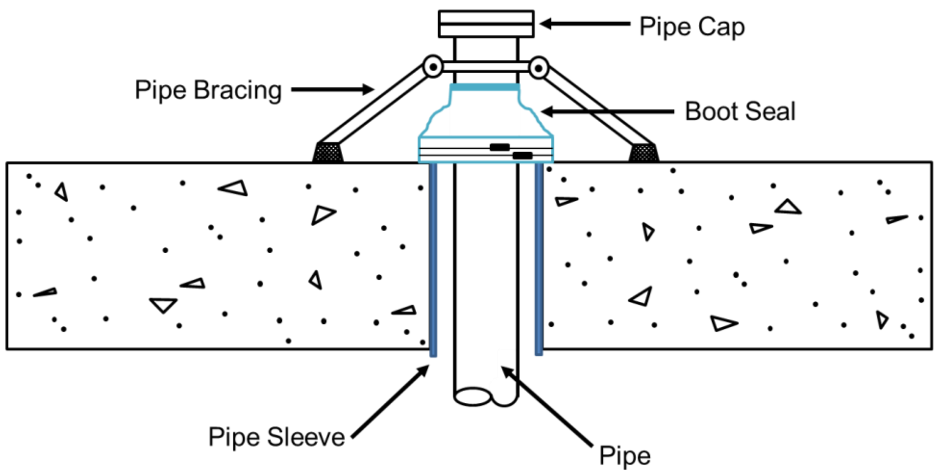

Figure 4-7 Test Deck Cross Section with a Mechanical Boot Seal

4.4 Test Deck 1 Design and Materials

Test Deck 1 consisted of low-density foams and silicone elastomers installed in a variety of configurations and sizes. The test matrix in Table 4-1 describes the six seal assemblies installed in this test deck.

Table 4-1 Test Matrix for Test Deck 1

	Penetration			Seal Assembly		Penetrant(s)	
No.	Shape	Size (in.)	Sleeved	Type	Materials(s)	Type(s)	Bracing
1.1	Round	12 (diameter)	No	Form in Place	Low-Density Foam—Dow Corning 3-6548	6-inch PVC pipe	Pipe brace
1.2	Square	6 (width)	No	Form in Place	Low-Density Foam—Dow Corning 3-6548	Cables	n/a
1.3	Round	4	No	Form in Place	Low-Density Foam—Dow Corning 3-6548 (repair configuration w/ Dow Corning 790 silicone caulk)	n/a	n/a

Table 4-1 Test Matrix for Test Deck 1 (cont'd.)

	Penetration			Seal Assembly		Penetrant(s)	
No.	Shape	Size (in.)	Sleeved	Type	Materials(s)	Type(s)	Bracing
1.4	Round	8	Yes (steel)	Form in Place	Silicone Elastomer—Sylgard 170	3-inch PVC pipe	Pipe brace
1.5	Round	2	No	Form in Place	Low-Density Foam—Dow Corning 3-6548	n/a	n/a
1.6	Round	4	No	Form in Place	Low-Density Foam—Dow Corning 3-6548	n/a	n/a

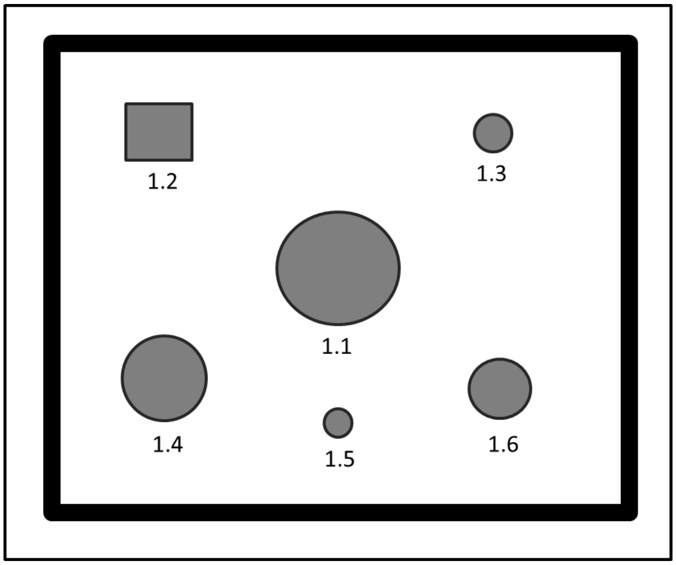

Figure 4-8 Illustrative Diagram of Penetration Layout for Test Deck 1 (Not Drawn to Scale)

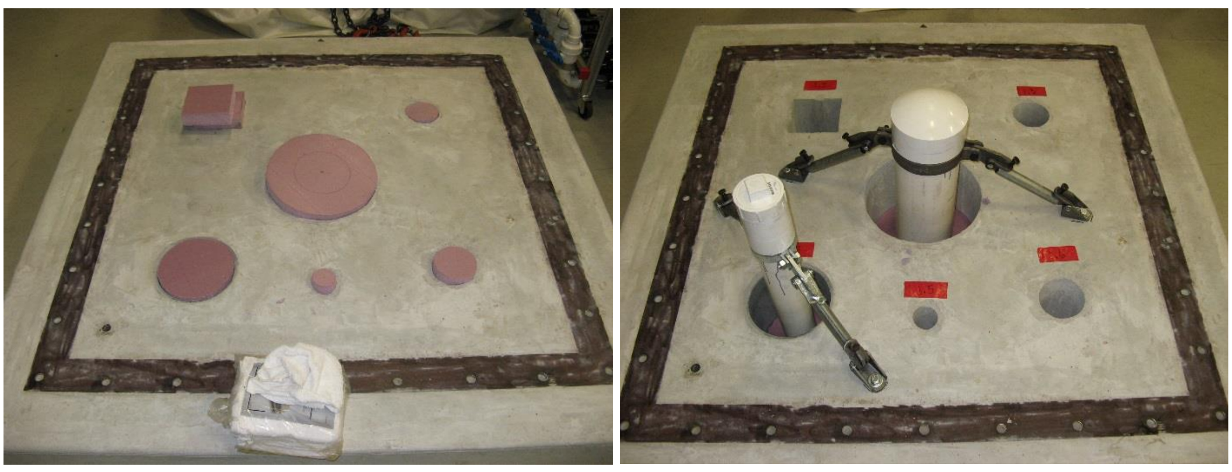

Figure 4-9 Photos of Test Deck 1 Construction. Pink-Colored Material is the Blocking Material Installed Behind Each Seal Assembly (Precut Before Seal Installation)

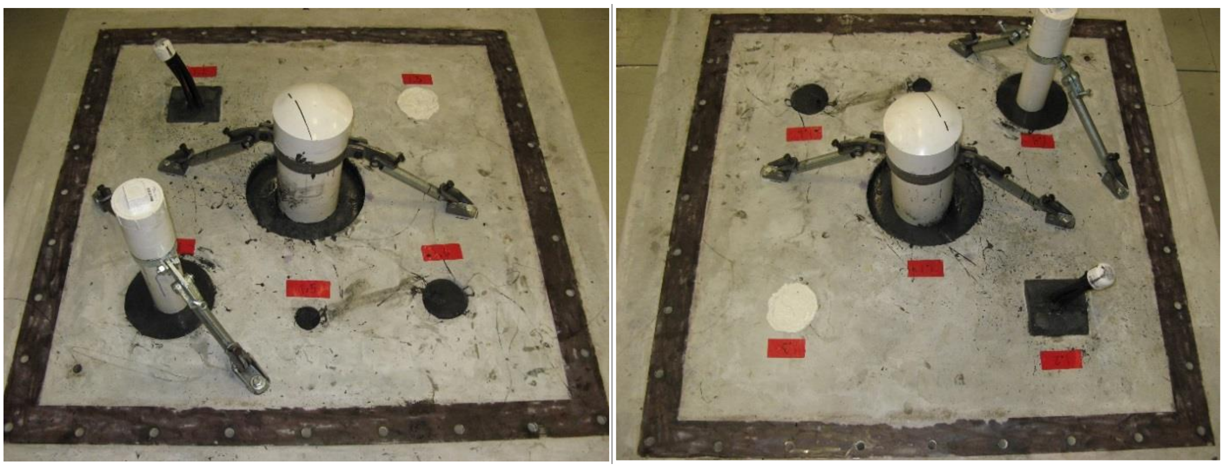

Figure 4-10 Photos of Test Deck 1 After Seal Assembly Installation

4.5 Test Deck 2 Design and Materials

Test Deck 2 also consisted of low-density foam and silicone elastomers installed in a variety of configurations and sizes. The test matrix in Table 4-2 describes the six seal assemblies installed in this test deck.

Table 4-2 Test Matrix for Test Deck 2

	Penetration			Seal Assembly		Penetrant(s)	
No.	**Shape**	**Size (in.)**	**Sleeved**	**Type**	**Materials(s)**	**Type(s)**	**Bracing**
2.1	Round	12 (diameter)	No	Form in Place	Silicone Elastomer—Sylgard 170	6-inch PVC pipe	Pipe brace
2.2	Round	2	Yes (PVC)	Form in Place	Silicone Elastomer—Sylgard 170	Cables	n/a
2.3	Round	2	No	Form in Place	Silicone Elastomer—Sylgard 170	n/a	n/a
2.4	Round	6	No	Form in Place	Silicone Elastomer—Sylgard 170	n/a	n/a
2.5	Round	4	No	Form in Place	Silicone Elastomer—Sylgard 170	n/a	n/a
2.6	Round	4	Yes (steel)	Form in Place	Low-density foam—Dow Corning 3-6548 w/cap; using Dow Corning 790 silicone caulk	Cables	Wire bundle restrained with unistrut (not shown in photos)

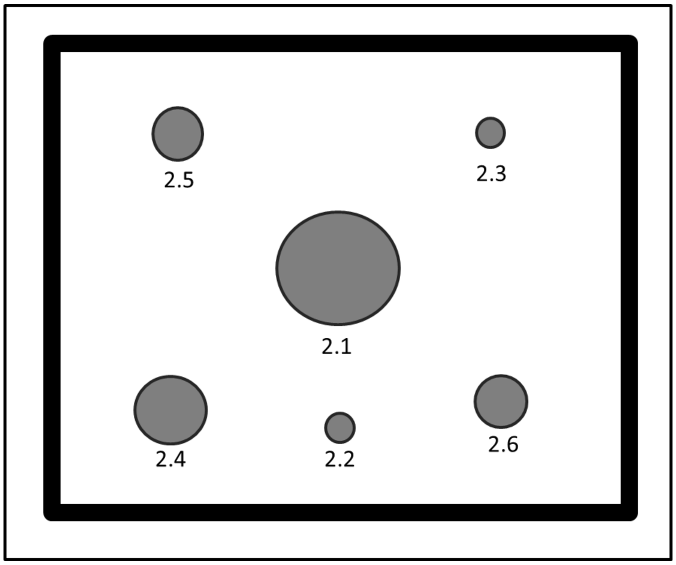

Figure 4-11 Illustrative Diagram of Penetration Layout for Test Deck 2 (Not Drawn to Scale)

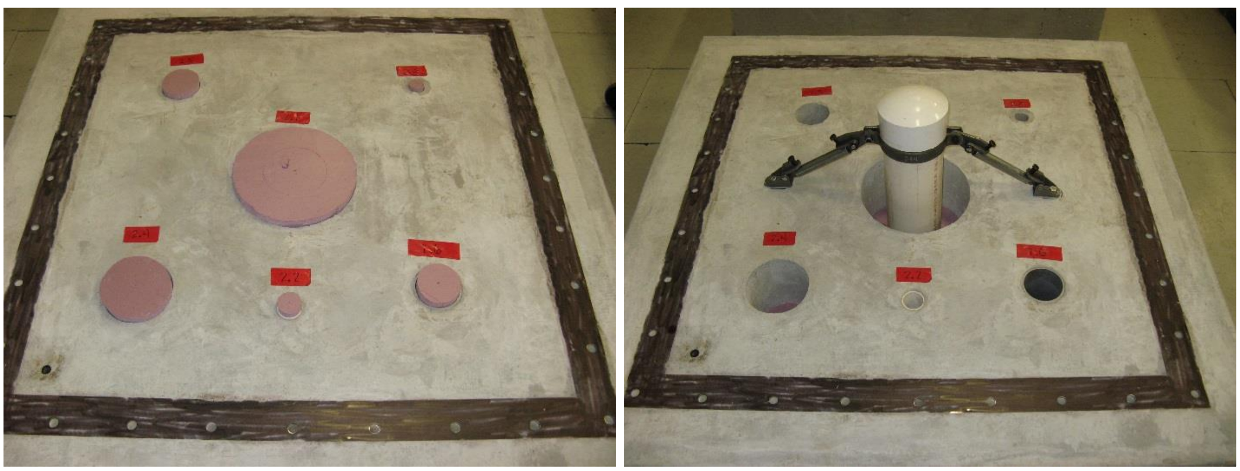

Figure 4-12 Photos of Test Deck 2 Construction

Figure 4-13 Photos of Test Deck 2 After Seal Assembly Installation

4.6 Test Deck 3 Design and Materials

Test Deck 3 used the same seal materials as Test Decks 1 and 2. This test deck introduced a greater variety of penetration sizes and types. Larger, rectangular penetrations with multiple penetrants were installed in Test Deck 3. The test matrix in Table 4-3 describes the five seal assemblies installed in this test deck.

Table 4-3 Test Matrix for Test Deck 3

	Penetration			Seal Assembly		Penetrant(s)	
No.	**Shape**	**Size (in.)**	**Sleeved**	**Type**	**Materials(s)**	**Type(s)**	**Bracing**
3.1	Square	6	No	Form in Place	Silicone Elastomer—Sylgard 170	Cables	n/a
3.2	Round	3	No	Form in Place	Silicone Elastomer—Sylgard 170	2-inch metal conduit	n/a
3.3	Round	6	Yes (steel)	Form in Place	Silicone Elastomer—Sylgard 170	Cables	n/a
3.4	Rectangular	8 x 24	No	Form in Place	In penetration: Silicone Elastomer—Sylgard 170 In Conduit: Dow Corning 3-6548 w/cap consisting of Dow Corning 790 silicone caulk	2-inch metal conduit w/cables & 6-inch PVC pipe	Pipe brace & conduit braced w/clamp and unistrut
3.5	Rectangular	8 x 16	No	Form in Place	Silicone Elastomer—Sylgard 170	Cable tray & cables	n/a

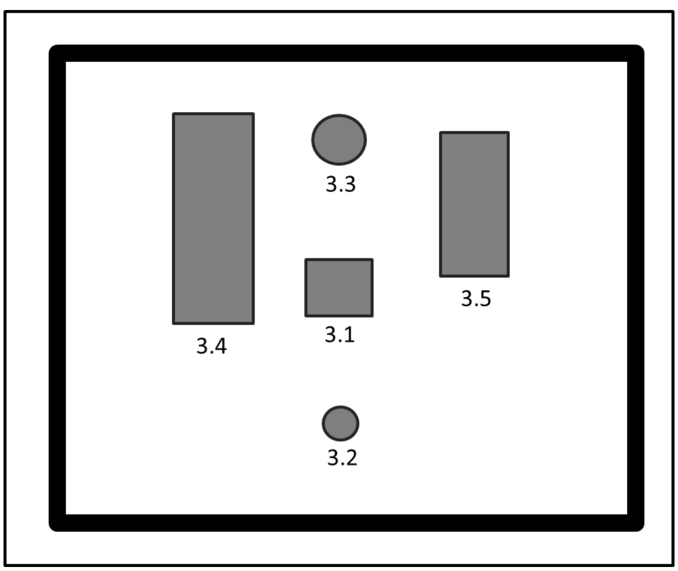

Figure 4-14 Illustrative Diagram of Penetration Layout for Test Deck 3 (Not Drawn to Scale)

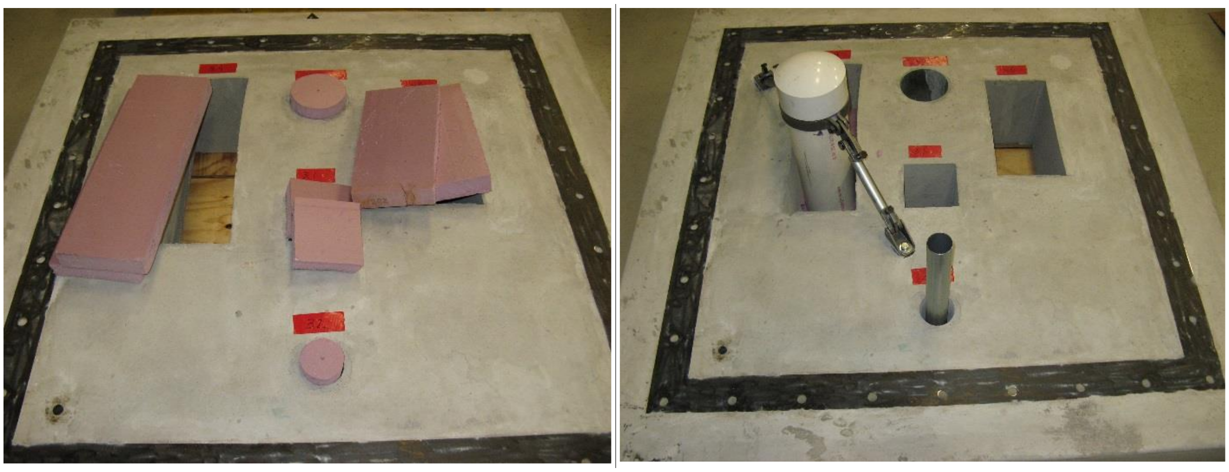

Figure 4-15 Photos of Test Deck 3 Construction

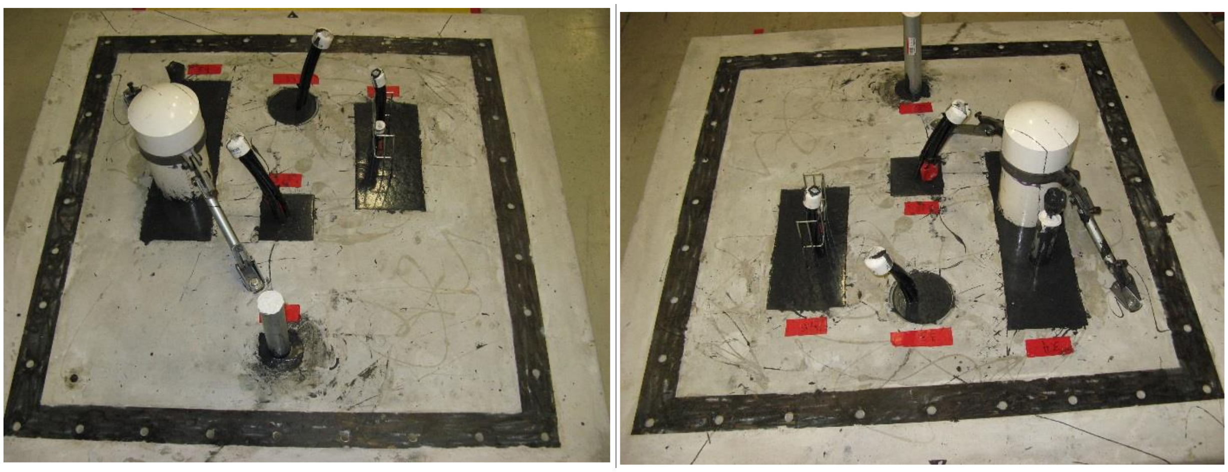

Figure 4-16 Photos of Test Deck 3 After Seal Assembly Installation

4.7 Test Deck 4 Design and Materials

Test Deck 4 included penetration seal material donated from an established nuclear industry vendor henceforth known as “Manufacturer A,” which constructed and formed this material. The test matrix in Table 4-4 describes the six seal assemblies installed in this test deck.

Table 4-4 Test Matrix for Test Deck 4

	Penetration			Seal Assembly		Penetrant(s)	
No.	Shape	Size (in.)	Sleeved	Type	Materials(s)	Type(s)	Bracing
4.1	Rectangular	6 x 22	No	Form in Place	Silicone Elastomer—Sylgard 170	Cable tray and cables	n/a
4.2	Rectangular	6 x 22	No	Form in Place	6-inch of Silicone Elastomer—Sylgard 170 over 2-inch ceramic wool	Cable tray and cables	n/a
4.3	Round	4	No	Form in Place	In Penetration: Silicone Elastomer—Sylgard 170 In Conduit: Sylgard 170 w/2-inch cap of Dow Corning 790 silicone caulk	2-inch metal conduit	Conduit braced with clamp and unistrut

Table 4-4 Test Matrix for Test Deck 4 (cont'd.)

	Penetration			Seal Assembly		Penetrant(s)	
No.	Shape	Size (in.)	Sleeved	Type	Materials(s)	Type(s)	Bracing
4.4	Round	6	Yes (steel)	Form in Place	Manufacturer A's Foam w/top coat	n/a	n/a
4.5	Round	6	Yes (steel)	Form in Place	Manufacturer A's Elastomer	n/a	n/a
4.6	Round	2	No	Form in Place	Silicone Elastomer—Sylgard 170. Conduit sealed with end cap.	1-inch metal conduit	Conduit braced with clamp and unistrut

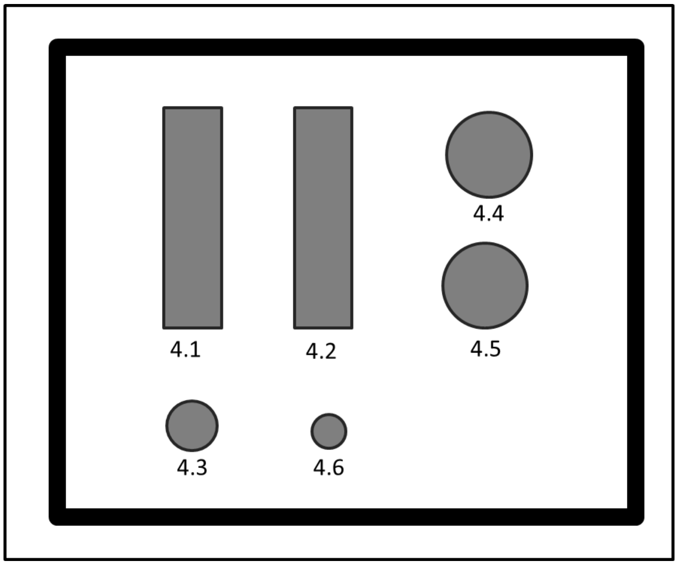

Figure 4-17 Illustrative Diagram of Penetration Layout for Test Deck 4 (Not Drawn to Scale)

Figure 4-18 Photos of Test Deck 4 After Seal Assembly Installation

4.8 Test Deck 5 Design and Materials

Test Deck 5 included penetration seal material donated from an established nuclear industry vendor henceforth known as “Manufacturer B,” which constructed and formed this material. This test deck also included the only modular and boot seals installed and tested. The test matrix in Table 4-5 describes the six seal assemblies installed in this test deck.

Table 4-5 Test Matrix for Test Deck 5

	Penetration			Seal Assembly		Penetrant(s)	
No.	**Shape**	**Size (in.)**	**Sleeved**	**Type**	**Materials(s)**	**Type(s)**	**Bracing**
5.1	Round	2	No	Form in Place	Manufacturer B foam sealant	Cables	n/a
5.2	Round	12	No	Form in Place	Silicone Elastomer—Sylgard 170	4-inch PVC pipe	Pipe brace
5.3	Round	4	No	Form in Place	In Penetration & Conduit: Manufacturer B foam sealant	2-inch metal conduit	n/a
5.4	Round	6	Yes (steel)	Modular	Mechanical seal	4-inch PVC pipe	Pipe brace
5.5	Round	6	Yes (steel)	Boot	Mechanical boot seal (installed using “typical” configuration used at NPPs)	4-inch PVC pipe	Pipe brace
5.6	Round	4	No	Form in Place	Manufacturer B foam sealant	Cables	n/a

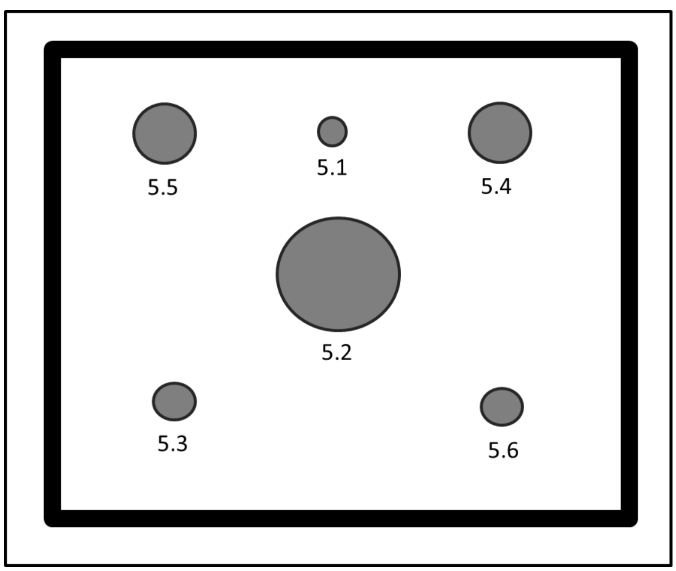

Figure 4-19 Illustrative Diagram of Penetration Layout for Test Deck 5 (Not Drawn to Scale)

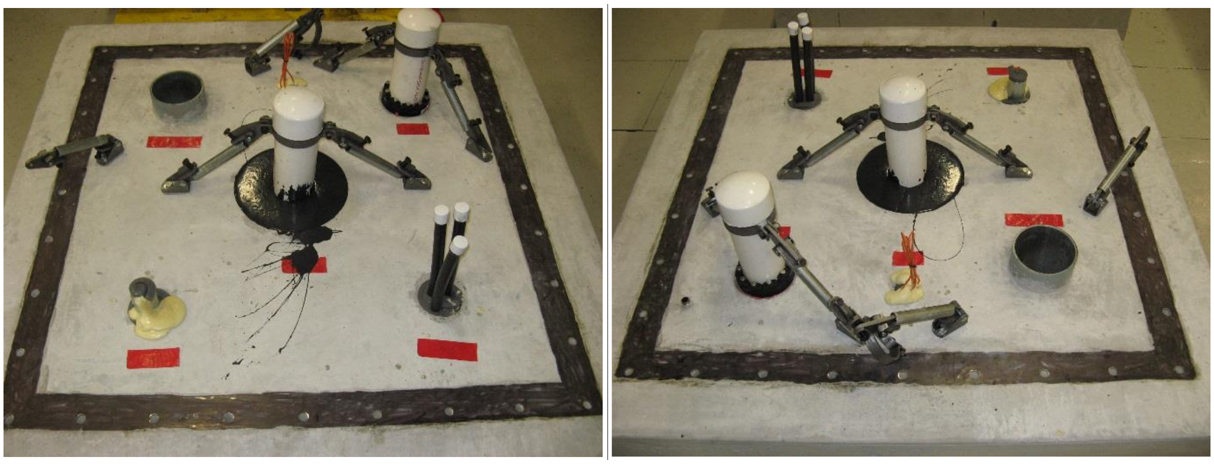

Figure 4-20 Photos of Test Deck 5 Construction Before Boot Seal Installation

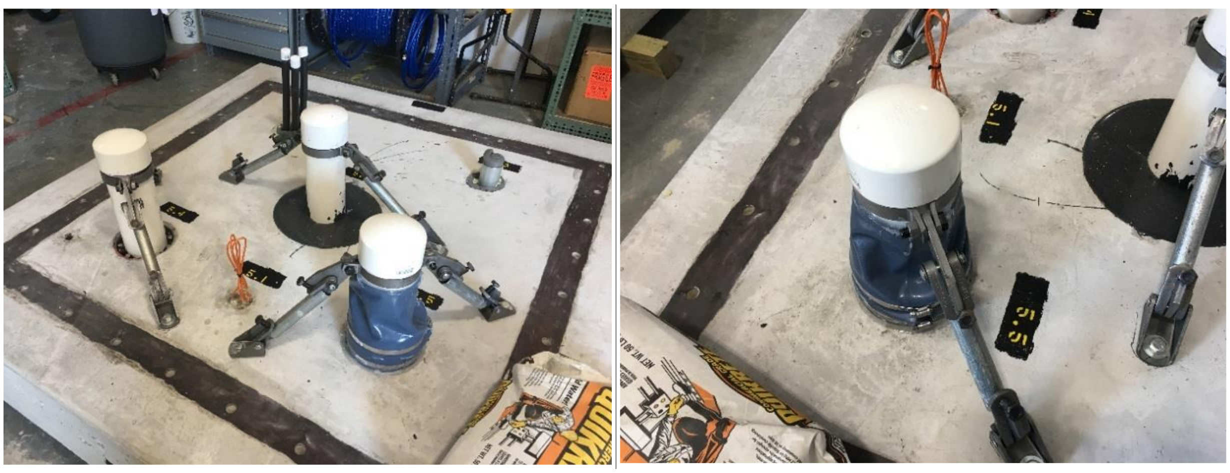

Figure 4-21 Photos of Test Deck 5 with Boot Seal Installation Complete

4.9 Data Acquisition

Data acquisition guidelines outlined in the test protocol (see Sections 3 and 5) were followed during the water pressure tests of the completed test decks.

The test apparatus included a calibrated data acquisition system that recorded the following parameters in 1-second intervals:

- test chamber pressure (pounds per square inch gauge (psig))
- water temperature (degrees Fahrenheit (F))
- water volumetric flow rates from individual seal assemblies (gallons per minute (GPM))

The internal pressure gauge was located near the pressure chamber base, directly above the seal assemblies, to accurately measure the water pressure on the face of each seal assembly.

Although not directly recorded, the water level within the test chamber was actively monitored with a water-level indicator to ensure all seal assemblies remained fully immersed for the duration of a given test.

Flow gauges recorded the leakage rates from individual seal assemblies. The test apparatus design isolated the water leakage collection for each seal assembly. The test apparatus design also allowed for visual observations of any water leakage. This leakage could be observed through transparent hoses attached to the leakage collection systems for each seal assembly. Direct visual observations on the unpressurized side of each seal assembly were not possible during pressure testing.

4.10 Test Procedures

Test procedures came from Section 5 of the draft test protocol. The two main variables for each test were applied water pressure and duration of that applied pressure.

4.10.1 Test Pressure

The test apparatus allowed for test pressures to be controlled precisely and varied for the duration of each test. The test protocol does not outline a defined pressure regime. Instead, it allows for a user-defined pressure regime based on a performance-based approach.

Initially, the chamber was pressurized to 1 psig (7 kilopascals (kPa)) and held there for a 5-minute interval. This initial pressurization was to help ensure watertightness of the test apparatus. After this period, test pressures were progressively increased at the discretion of the test director in approximately 1-psig (7-kPa) increments.

The rate of pressure change was varied between the tests to help to fully exercise the test protocol—the primary objective of the testing phase of this research project. Therefore, tests were conducted with both rapid and slow pressure changes. Test pressures were to be varied or held constant as the result of leakage observations.

The planned maximum test pressure was 20 psig (138 kPa). This is approximately equivalent to a water column (head pressure) of 46 feet (14 meters).

4.10.2 Test Duration

The overall duration of each test was determined by one of two events: (1) reaching the maximum test duration (chosen to be 180 minutes), or (2) experiencing rapid penetration seal dislodgement or nonconformity. In this latter case, the water makeup system could not keep the test chamber filled with water owing to the large water loss through a nonconforming seal assembly located in the test deck. Thus, if a penetration seal dislodged or otherwise failed abruptly, the test would end. The 180-minute maximum test duration was determined to be sufficient time to fully exercise the test protocol within a single pressure test.

5 PROTOCOL EVALUATION—TEST RESULTS

In August 2018, at a Framatome facility in Lynchburg, VA, a series of flood tests were conducted following procedures found in the draft test protocol. Six tests in total were performed on the five constructed test decks. Each test deck was tested once, except Test Deck 2 was tested twice. The following sections summarize the data and observations from each of the six tests.

The following test results were used to assess the procedures found in the test protocol. The test results should not be interpreted as a thorough assessment of the seal materials (e.g., elastomers, low-density foams) or installation designs. For example, low-density foam seals are often a mixture of substances and additives that are proprietary. Properties of these seal materials, such as adhesion and strength, are formula dependent, and product formulas vary greatly among manufacturers. As a result, the data and observations from this section should not be interpreted as qualifying or disqualifying any specific flood penetration seal material or installation design.

5.1 Test 1

Test Deck 1 was the first test deck to be evaluated using the test protocol. This deck primarily comprised low-density foam seals with cable and pipe penetrants (see Section 4.4). Table 5-1 gives an overview of the main results of this first test.

Table 5-1 Test 1 Results Overview

Deck Number	# 1
Approx. Test Duration	61 min
Approx. Max Pressure	3.52 psig (24.3 kPa)
Test Termination Cause	Ejection of seal in Penetration 1.6 (low-density foam)

For the first 25 minutes of the test, no manual attempts were made to increase pressurization, and pressure declined slightly by approximately 0.30 psig. During this initial 25-minute period, the hydrostatic pressure from the water column was the only source of external pressure on the penetration seals. After this initial 25-minute period, the test chamber pressure was manually increased at an approximate rate of 0.5 psig every 2–3 minutes. This relatively slow rate of pressure increase was chosen because of the suspected low-pressure tolerance of the low-density foam seals. Figure 5-1 depicts the test chamber pressure recordings. Pressure was continually increased until reaching a maximum of 3.52 psig at the approximate 1-hour mark. The subsequent ejection of Penetration 1.6 resulted in the large depressurization event depicted at the 62-minute mark in Figure 5-1.

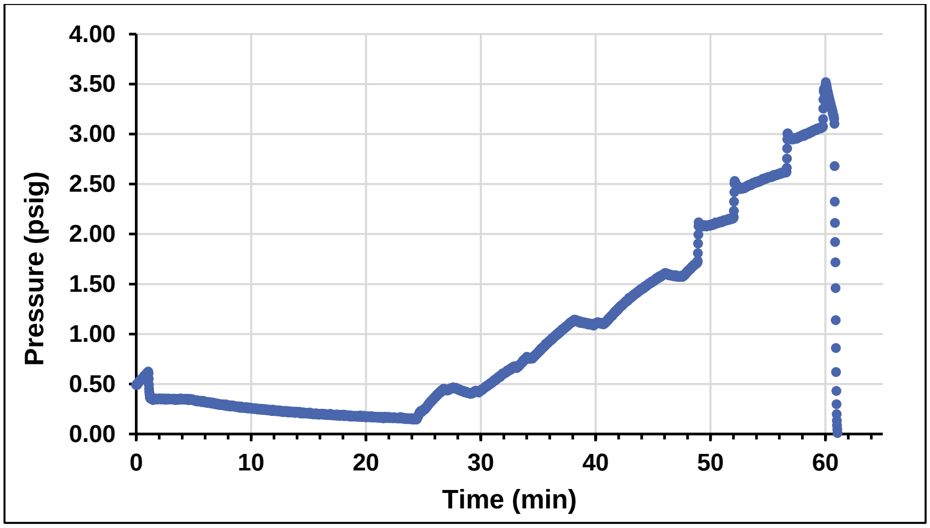

Figure 5-1 Test 1 Pressure vs. Time Graph

Flow rates and visual observations were recorded during Test 1. Table 5-2 provides a timeline of Test 1 with notable visual observations and leakage rates recorded.

Table 5-2 Test 1 Observations

Time (min)	Test Pressure (psig)	Observations
0	0.49	• Pressure mainly hydrostatic from water column. • Minor weeping observed from Penetration 1.1 (less than 1.0 GPM)
10	0.26	• Elevated leakage rates from Penetration 1.1 ceased
25	0.24	• Pressure began to be increased manually within the test chamber
26	0.45	• Elevated leakage rates from Penetration 1.1 were immediately recorded and observed
32	0.64	• Leakage from Penetration 1.1 peaked at 0.27 GPM and began to steadily decrease
38	1.12	• Leakage from Penetration 1.1 negligible
52	2.46	• Leakage from Penetration 1.2 measured at flow meter 6. Rates never exceeded 0.2 GPM
58	2.98	• Leakage from Penetration 1.2 decreased to a negligible quantity
60	3.52 (max pressure)	• Maximum test pressure achieved • Leakage from Penetration 1.6 about 2 GPM

Table 5-2 Test 1 Observations (cont'd.)

Time (min)	Test Pressure (psig)	Observations
61	Rapid decline	• Seal in Penetration 1.6 dislodged, leakage rate measured at over 40 GPM • Leakage from Penetration 1.3 increased to over 2.0 GPM, indicating possible nonconformity • Unable to maintain test chamber pressurization; pressure within the test chamber steadily decreased to 0 psig, and the test was terminated

Flow meters attached to the leakage collection system for each penetration recorded leakage rates. Figure 5-2 and Figure 5-3 depict the flow recordings for Test 1 at different vertical scales. At approximately the 60-minute mark, Figure 5-2 captures the large increase in the flow rate from Penetration 1.6. Figure 5-3 displays the same recorded data as Figure 5-2, but with the vertical axis limited to a maximum of 2 GPM to emphasize flow rate increases from other penetrations. Based on the high flow rates recorded from Penetration 1.3 and surface damage observed on this penetration seal, it is likely that Penetration 1.3 also experienced partial dislodgement immediately after Penetration 1.6 dislodged.

Figure 5-3 also shows small increases in the flow rates from the other four penetrations (1.1, 1.2, 1.4, and 1.5) immediately after Penetration 1.6 dislodged. These small flow rates (less than 0.5 GPM) are most likely overflow from the nearby dislodgement, rather than true leakage from these four penetrations. The large, sudden flow rate from the dislodged Penetration 1.6 may be the source of this discrepancy (the design of the leakage collection system did not completely isolate each penetration in the case of an abrupt seal dislodgement causing a very large flow). This explanation is further supported by the lack of any observable damage to Penetrations 1.1, 1.2, 1.4, and 1.5.

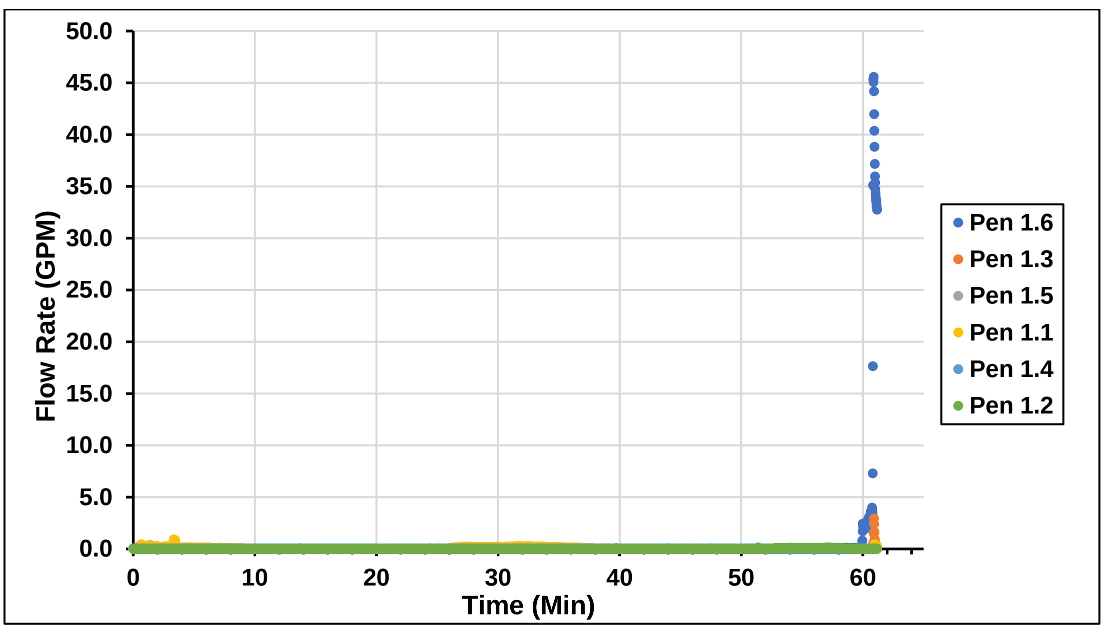

Figure 5-2 Test 1 Flow Rate vs. Time

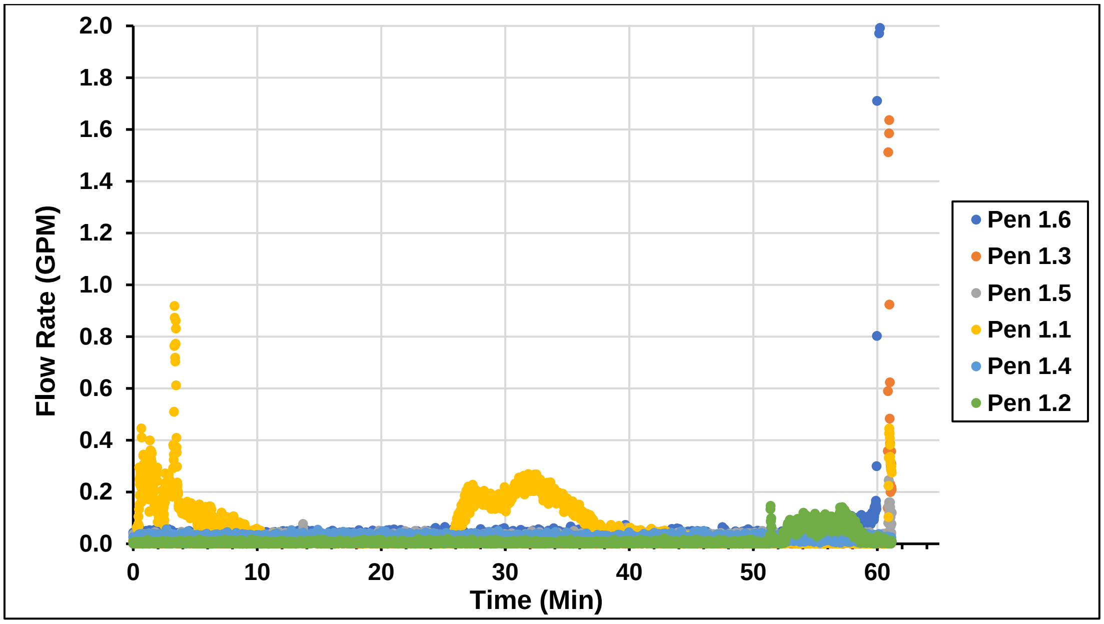

Figure 5-3 Test 1 Flow Rate vs. Time (Truncated Vertical Axis)

5.1.1 Post-test Visual Observations

Following the termination of Test 1, visual inspections were conducted on Test Deck 1 (Figure 5-4). Penetration 1.6 was found to be completely ejected from the test deck and lodged beneath in the leakage collection system. The concrete hole into which Penetration 1.6 had been installed was open and clear of debris. Additionally, the caulk cap of Penetration 1.3 was damaged as evidenced by a large surface crack through the caulk. No damage or other notable discrepancies with the other four penetrations were observed.

Figure 5-4 Empty Penetration 1.6 (Left Photo) and Damaged Penetration 1.3 (Right Photo)

5.2 Test 2

Test 2 was the first test of Deck 2. This deck would be used again in Test 3, making it the only deck tested twice. This deck primarily comprised silicone elastomer seals with cable and pipe penetrants (see Section 4.5). Table 5-3 gives an overview of the main results of Test 2.

Table 5-3 Test 2 Results Overview

Deck Number	# 2
Approx. Test Duration	66 min
Approx. Max Pressure	6.82 psig (47.0 kPa)
Test Termination Cause	Ejection of seal in Penetration 2.2 (sleeved elastomer seal w/cable penetrants)

Test 2 began with incremental test chamber pressure increases every 5–10 minutes. Figure 5-5 depicts test chamber pressure recordings. After approximately 5 minutes, minor leakage (less than 0.5 GPM) from Penetration 2.1 (12-inch silicone elastomer seal with 6-inch pipe penetrant) occurred. This minor leakage would continue to increase for the duration of the test. After 36 minutes and at a test pressure of approximately 3 psig, water leakage from Penetration 2.1 would begin to exceed 1 GPM. When the test pressure reached 3.5 psig, minor leakage (less than 0.1 GPM) occurred from Penetrations 2.2 and 2.6. The maximum test pressure achieved during this test was 6.82 psig at minute 57.9. Less than 2 minutes after reaching this maximum test pressure, the seal in Penetration 2.2 abruptly gave way. Flow rates from this penetration quickly spiked to over 23 GPM before dropping as the test chamber emptied. Flow rates from the perpetually leaking Penetration 2.1 also briefly spiked when Penetration 2.2 gave way. The test chamber immediately depressurized upon the loss of Penetration 2.2. The flow rates from Penetrations 2.1 and 2.2 would continue to decrease as the test chamber emptied, at which time the test was terminated.

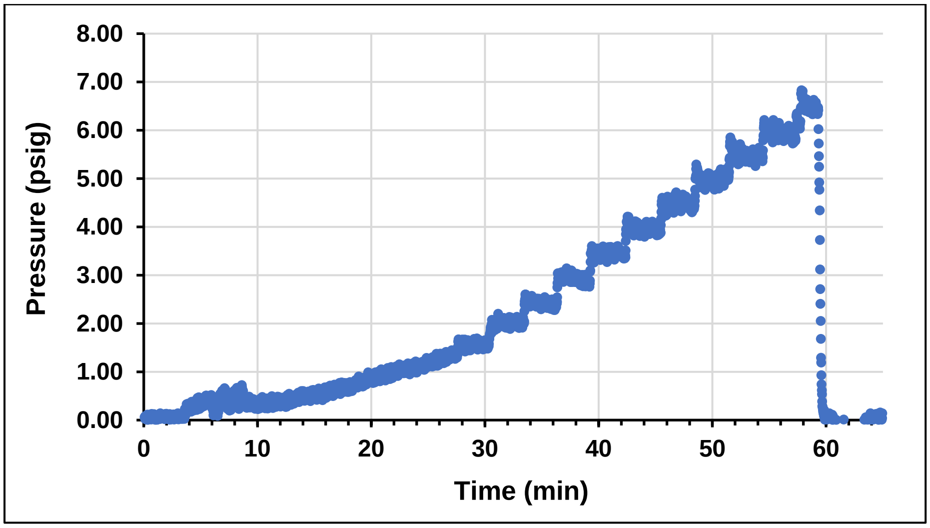

Figure 5-5 Test 2 Pressure vs. Time Graph

Flow meters and test personnel recorded flow rates and visual observations during Test 2. Table 5-4 provides a timeline of Test 2 with notable visual observations and leakage rates recorded.

Table 5-4 Test 2 Observations

Time (min)	Test Pressure (psig)	Observations
5.0	0.37	• Minor leakage recorded from Penetration 2.1 (less than 0.5 GPM)
36.5	2.93	• Leakage recorded from Penetration 2.1 exceeds 1 GPM
40.0	3.50	• Minor leakage observed from Penetrations 2.2 and 2.6 (less than 0.5 GPM)
45.7	4.44	• Leakage recorded from Penetration 2.1 exceeds 2 GPM
51.6	5.70	• Leakage recorded from Penetration 2.1 exceeds 3 GPM
57.9	6.82 (max pressure)	• Maximum test pressure achieved • Leakage recorded from Penetration 2.1 was 3.93 GPM
59.4	4.77	• Seal in Penetration 2.2 dislodged, leakage rate measured over 20 GPM • Leakage recorded from Penetration 2.1 increased over 11 GPM • Unable to maintain test chamber pressurization, pressure within the test chamber steadily decreased to 0 psig
66.0	0	• Unpressurized test chamber emptied of water and the test was terminated

Flow meters attached to the leakage collection system for each penetration measured and recorded leakage rates. Figure 5-6 and Figure 5-7 depict the flow recordings for Test 2 at different vertical scales. At approximately the 59-minute mark, Figure 5-6 captures the large increase in the flow rate from Penetration 2.2. Figure 5-7 displays the same recorded data as Figure 5-6, but with the vertical axis limited to a maximum of 7 GPM to illustrate the flow rate increases from other penetrations. The sudden pressure change that occurred after Penetration 2.2 dislodged may be the source of the minor spike in the flow rate from Penetration 2.1. After this nonconforming event, flow rates continued to be measured from Penetrations 2.2 and 2.1 for a number of minutes, even with the test chamber depressurized. These flow rates would eventually decrease to zero as the test chamber emptied of water.

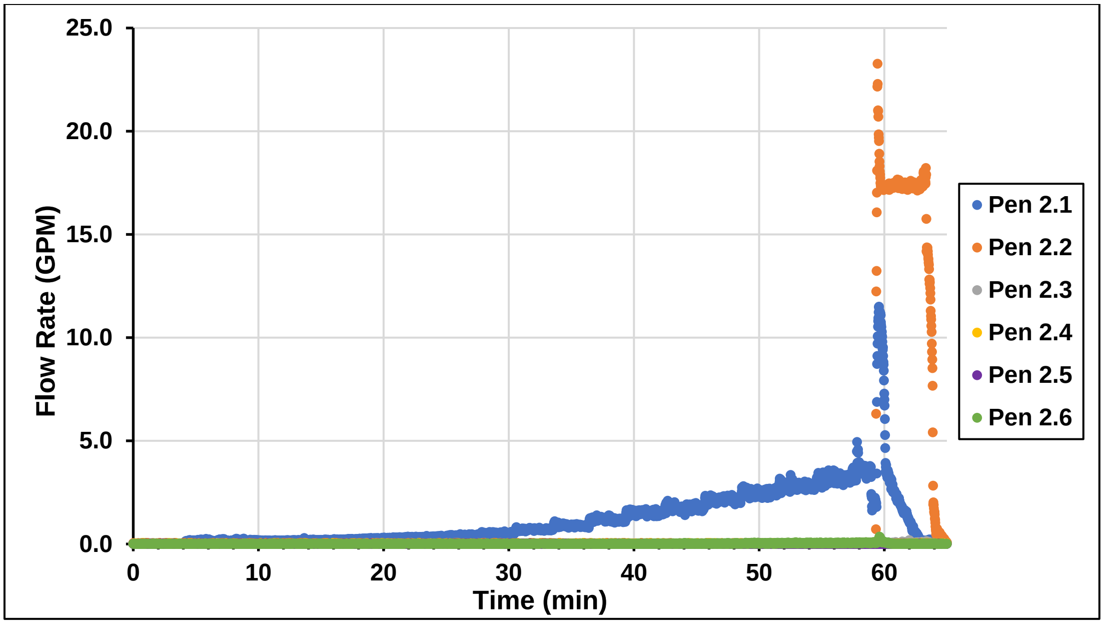

Figure 5-6 Test 2 Flow Rate vs. Time

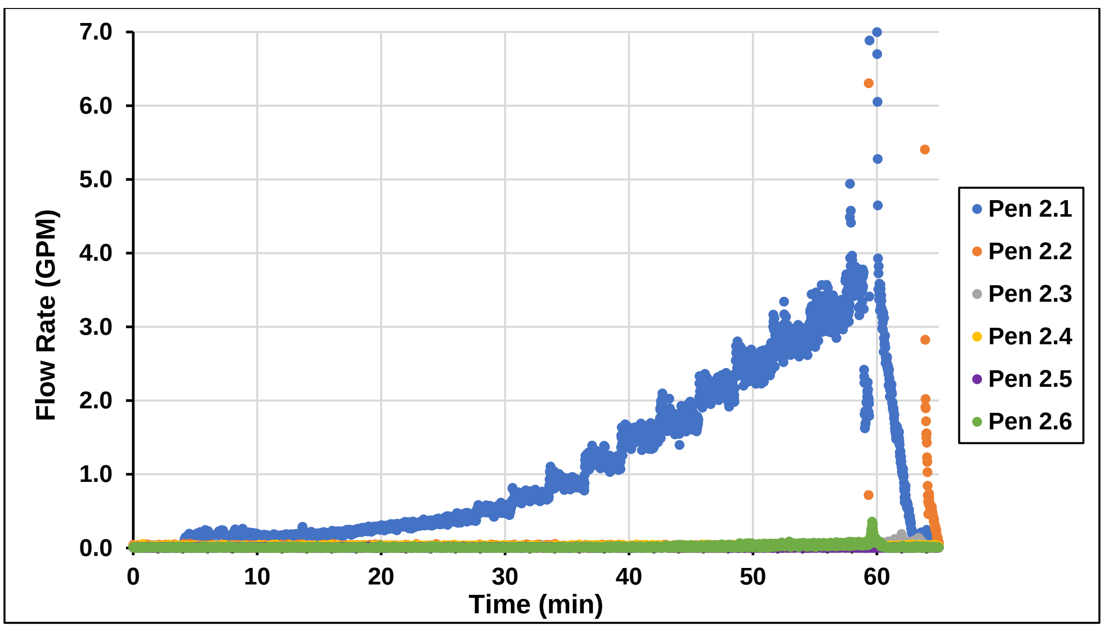

Figure 5-7 Test 2 Flow Rate vs. Time (Truncated Vertical Axis)

5.2.1 Post-test Visual Observations

Following the termination of Test 2, visual inspections were conducted on Test Deck 2 (Figure 5-8). Penetration 2.2 was found to be completely dislodged from its sleeve within the test deck and pushed down into the leakage collection system. No damage or other notable discrepancies with the other five penetrations were observed. The lack of visible damage to Penetration 2.1 indicates that, although it experienced significant leakage during the test, it was not the source of the rapid depressurization within the water chamber, resulting in test termination.

Figure 5-8 Top-Down View (Left Photo) of Penetration 2.2 Dislodged with its White Cable Cap Visible and Penetration 2.2 Removed (Right Photo) from the Test Deck (its White Cable Cap Not Visible)

5.3 Test 3

Test 3 was the second test of Deck 2 (repaired after Test 2). The dislodged Penetration 2.2 was permanently plugged to prevent any further leakage. The leaking Penetration 2.1 was repaired with silicone caulk, which was applied between the elastomer seal and penetrating PVC pipe. The annulus between these two materials was the suspected source of the water leak during Test 2. Table 5-5 gives an overview of the main results of Test 3.

Table 5-5 Test 3 Results Overview

Deck Number	# 2
Approx. Test Duration	42 min
Approx. Max Pressure	12.07 psig (83.22 kPa)
Test Termination Cause	Ejection of seal in Penetration 2.6 (4-inch, sleeved low-density foam seal w/ restrained cable penetrants)

After the repairs to Test Deck 2 were allowed to cure, the test apparatus was reinstalled, and Test 3 was initiated. The test chamber was pressurized at a greater rate than that of Test 2 (see Figure 5-9). After approximately 5 minutes, the test chamber pressure exceeded 5 psig with no observable leakage from the penetrations. After 8 minutes, the rate of pressure increase was reduced to approximately 0.5 psig increments every 2–3 minutes. After 11 minutes, the test chamber pressure exceeded the maximum test pressure achieved in Test 2 (6.82 psig). After 21 minutes and at an approximate pressure of 8.5 psig, minor leakage (less than 0.4 GPM) was recorded from Penetration 2.6 (a 4-inch sleeved, low-density foam seal with restrained cable bundle penetrant). This minor leakage abruptly ceased before increasing again at the 24-minute mark. Leakage from Penetration 2.6 would steadily increase until the test terminated. A maximum test pressure of 12.07 psig was achieved at the 39.7-minute mark. Less than 30 seconds later, the seal in Penetration 2.6 was ejected from the test deck. Following the dislodgement of Penetration 2.6, the test chamber rapidly became unpressurized. With a total loss of pressurization and the inability to replace the lost water, the test was abruptly terminated.

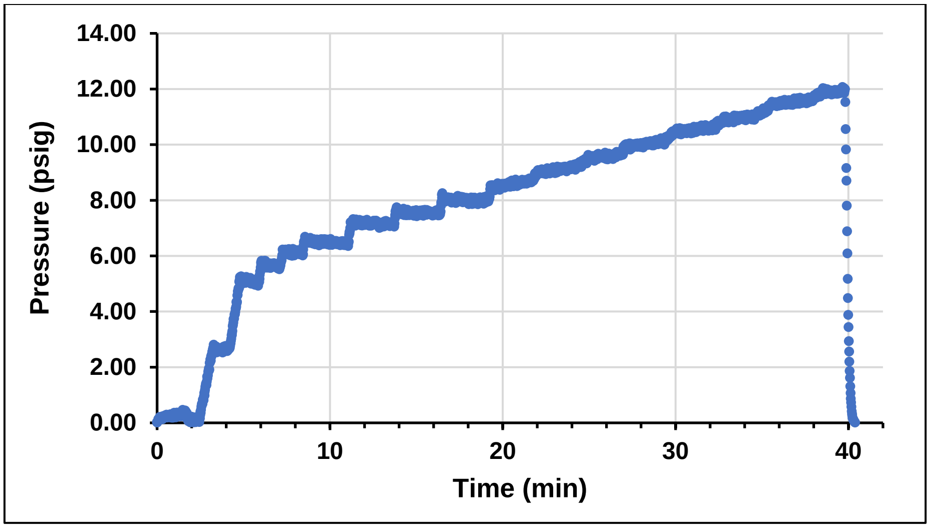

Figure 5-9 Test 3 Pressure vs. Time Graph

Flow meters and test personnel recorded flow rates during Test 3. Table 5-6 provides a timeline of Test 3 with notable visual observations and leakage rates recorded during this test.

Table 5-6 Test 3 Observations

Time (min)	Test Pressure (psig)	Observations
4.0	2.76	• Test pressure rapidly increased by 1 psig per minute
8.0	6.02	• Test pressure changes reduced to 0.5 psig increments every 2–3 minutes
11.1	6.85	• Maximum test pressure from Test 2 exceeded (6.82 psig)
20.8	8.66	• Minor leakage (< 0.4 GPM) recorded from Penetration 2.6
25.0	9.63	• Leakage from Penetration 2.6 exceeds 0.1 GPM and continues to increase for the duration of the test
39.7	12.07 (max pressure)	• Maximum test pressure achieved • Leakage from Penetration 2.6 exceeds 0.33 GPM • No leakage observed or recorded for other penetrations
39.8	10.56	• Nonconformity with seal in Penetration 2.6 with leakage exceeding 14.1 GPM
39.9	8.71	• Maximum flow rate (72.40 GPM) through Penetration 2.6 • Elevated flow rates recorded but not observed for other penetrations (addressed in discussion below)
~40	0	• Test chamber completely unpressurized • Test terminated

Flow meters attached to the leakage collection system for each penetration measured and recorded leakage rates. Figure 5-10 and Figure 5-11 depict the flow recordings for Test 3 at different vertical scales. At approximately the 40-minute mark, Figure 5-10 captures the large increase in the flow rate from Penetration 2.6. Figure 5-11 displays the same recorded data as Figure 5-10, but with the vertical axis limited to a maximum of 2 GPM, which better highlights the flow rates from Penetration 2.6 before its ejection.

Figure 5-11 also shows small increases in the flow rates from the two other penetrations (2.1 and 2.2) immediately after Penetration 2.6 was dislodged. These small flow rates (less than 2 GPM) are most likely due to the large, sudden overflow (spray) from the dislodged Penetration 2.6 and from the design of the apparatus leakage collection system, rather than true leakage from these two penetrations. This explanation is further supported by the lack of any observable post-test damage to Penetrations 2.1 and 2.2.

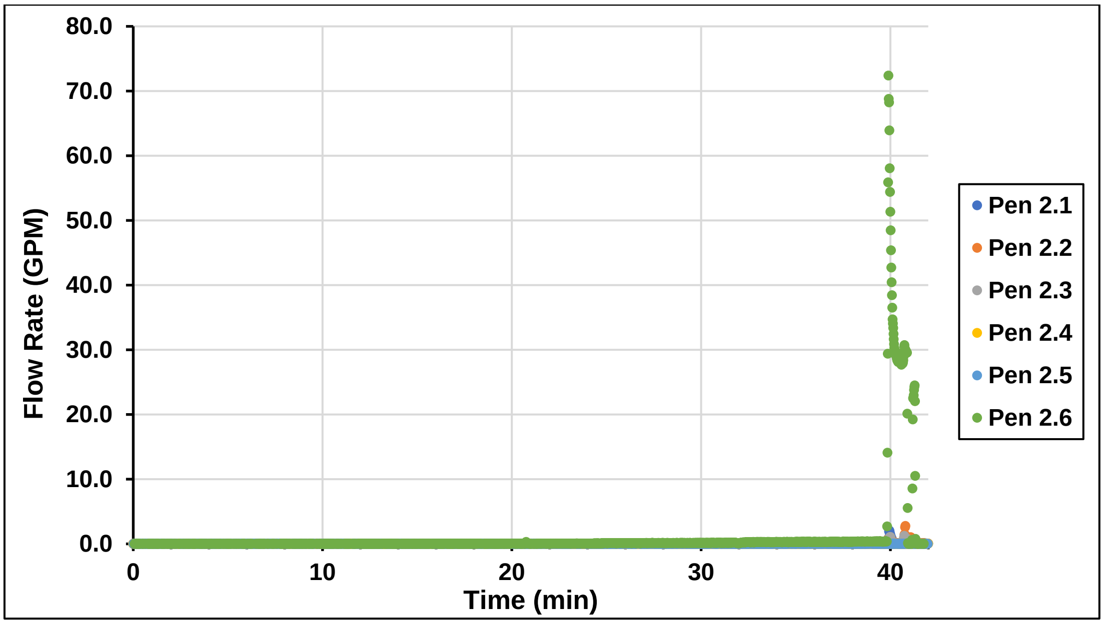

Figure 5-10 Test 3 Flow Rate vs. Time

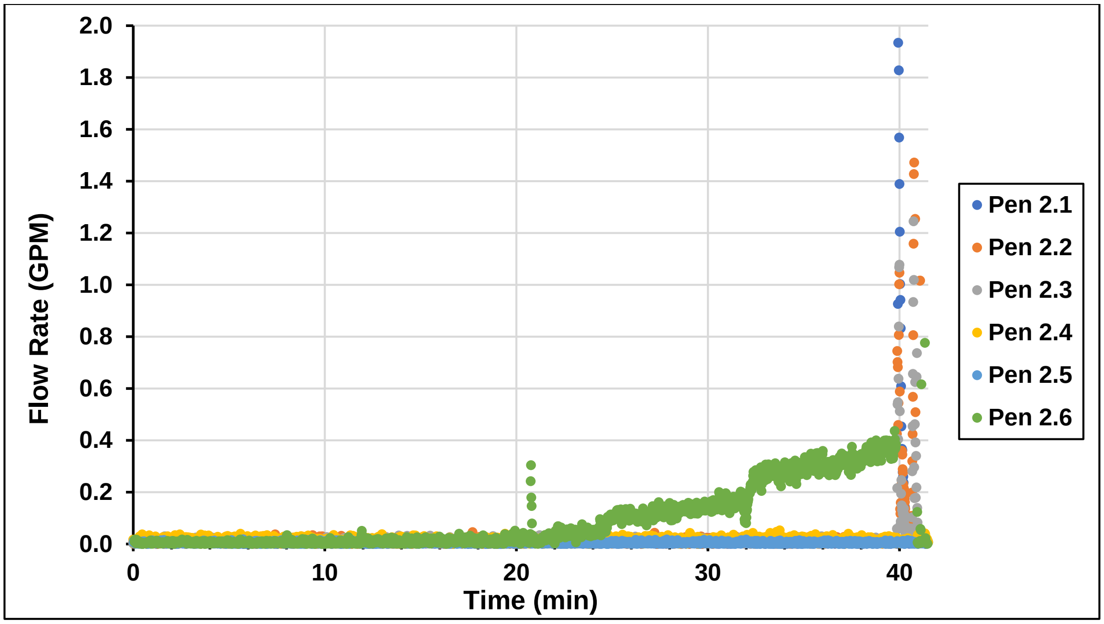

Figure 5-11 Test 3 Flow Rate vs. Time (Truncated Vertical Axis)

5.3.1 Post-test Visual Observations

Following the termination of the pressure test, visual inspections were conducted on Test Deck 2 (Figure 5-12). The yellow object in the left photograph in Figure 5-12 is the permanent plug for Penetration 2.2. Penetration 2.6 was found to be completely dislodged from its sleeve within the test deck and pushed down into the leakage collection system. Figure 5-13 is a photograph of the ejected seal from Penetration 2.6. No damage or other notable discrepancies with the other five penetrations were observed.

Figure 5-12 Test Deck 2 Post-Test (Left Photo) and Empty Sleeve (Right Photo) for Ejected Penetration 2.6

Figure 5-13 Ejected Seal and Penetrant from Penetration 2.6

5.4 Test 4

Test 4 evaluated the flood penetration seals installed in Test Deck 5. This was the only deck that included modular and boot seals. This test would achieve the highest test chamber pressure of the six flood tests. Table 5-7 gives an overview of the main results of Test 4.

Table 5-7 Test 4 Results Overview

Deck Number	# 5
Approx. Test Duration	60 min
Approx. Max Pressure	19.02 psig (131.1 kPa)
Test Termination Cause	Complete, abrupt dislodgement of seal in Penetration 5.2 (12-inch, unsleeved silicone elastomer with a 4-inch pipe penetrant)

Test 4 began by pressurizing the test chamber in 1-psig increments every 3 minutes. This rate of pressurization was held approximately constant during the duration of this test as depicted in Figure 5-14. A minor amount of leakage from Penetration 5.2 was observed at the 15-minute mark. Apart from this intermittent dripping, no measurable leakage from any penetrations was observed or recorded until approximately the 58th minute of the test. A maximum pressure of 19.02 psig was achieved at the 58-minute mark. Less than a minute later, the seal in Penetration 5.2 was abruptly dislodged. Flow rates through this nonconforming penetration briefly exceeded 60 GPM before quickly decreasing to zero as the test chamber emptied, causing the termination of Test 4.

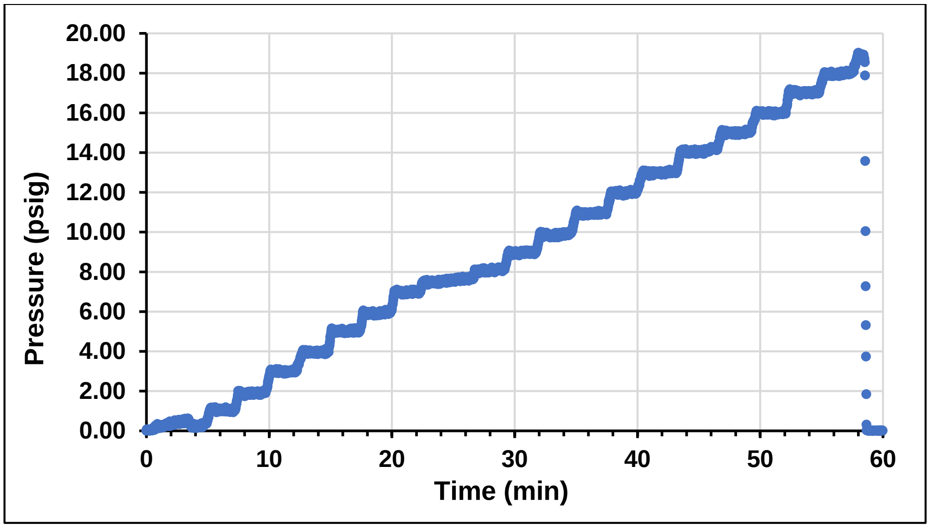

Figure 5-14 Test 4 Pressure vs. Time Graph

Flow meters and test personnel recorded flow rates during Test 4. Table 5-8 provides a timeline of Test 4 with notable visual observations and leakage rates recorded.

Table 5-8 Test 4 Observations

Time (min)	Test Pressure (psig)	Observations
5	0.67	• Test pressure increased in 1 psig increments every 3 minutes
14.8	4.00	• Minor dripping observed from Penetration 5.2
58.0	19.02 (max pressure)	• Maximum test pressure achieved • No leakage recorded from any penetration
58.5	18.55	• Abrupt dislodgement of seal in Penetration 5.2 with flows quickly exceeding 60 GPM • Minor water flows recorded through other penetrations (addressed below)
~60	0	• Test chamber completely depressurized • Test terminated

Flow meters attached to the leakage collection system for each penetration measured and recorded leakage rates. Figure 5-15 and Figure 5-16 depict the flow recordings for Test 4 at different vertical scales. At approximately the 59-minute mark, Figure 5-15 captures the large increase in the flow rate from Penetration 5.2. Figure 5-16 displays the same recorded data as Figure 5-15 but with the vertical axis limited to a maximum of 2 GPM.

Figure 5-15 and Figure 5-16 also show small increases in the flow rates from the remaining penetrations immediately after Penetration 5.2 dislodged. These other flow rates (all less than

8 GPM) are most likely due to the large, sudden overflow from the dislodged Penetration 5.2 and from the design of the apparatus leakage collection system, rather than true leakage from these remaining penetrations. This explanation is further supported by the lack of any observable post-test damage to these penetrations.

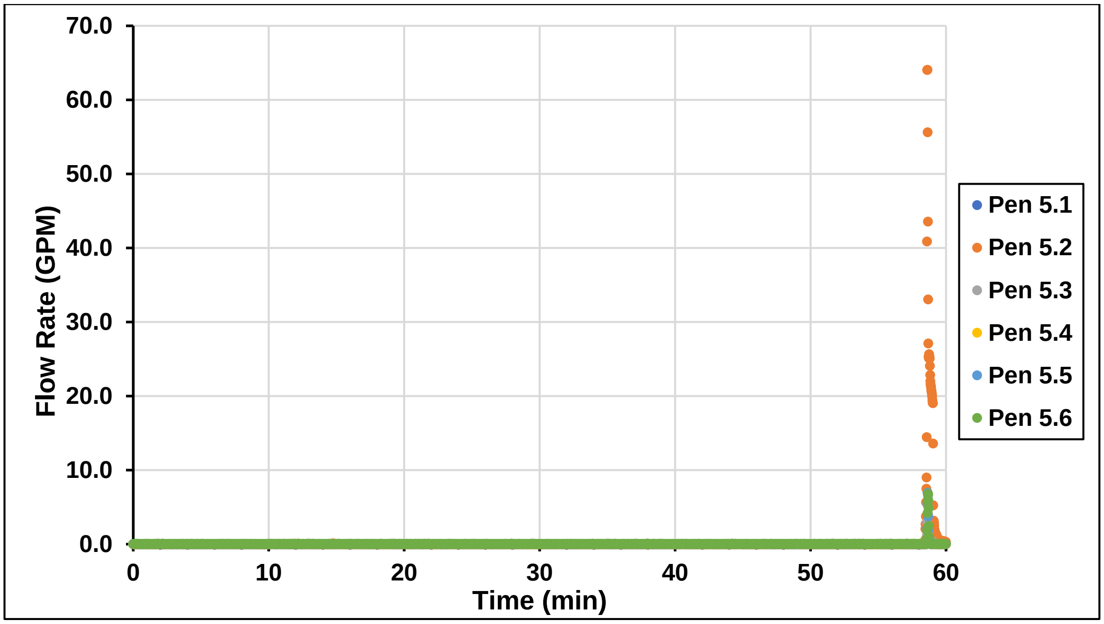

Figure 5-15 Test 4 Flow Rate vs. Time

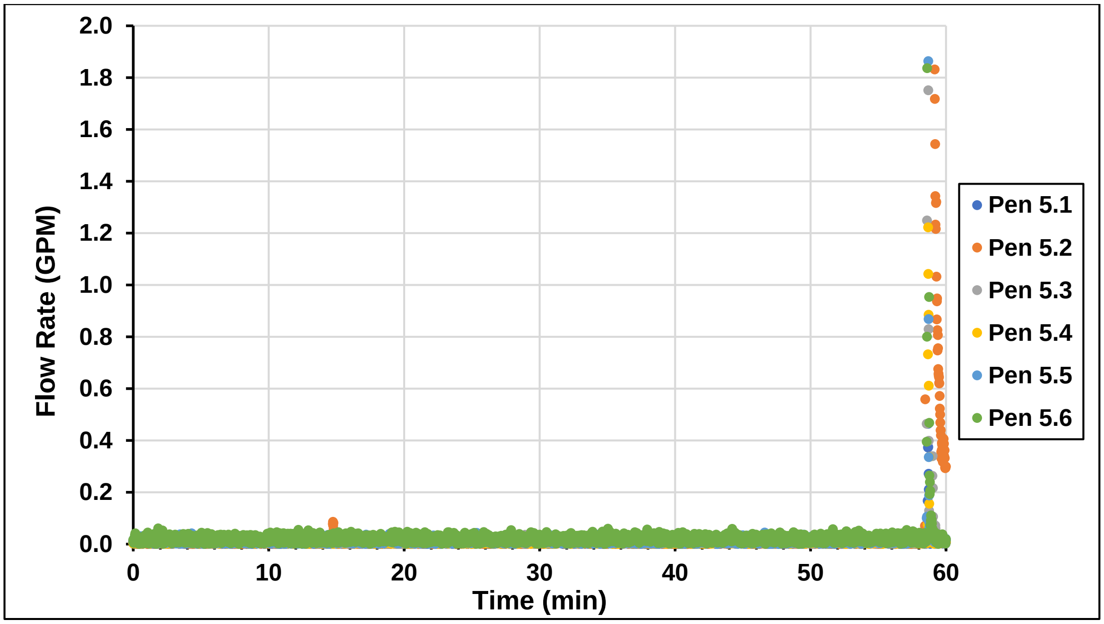

Figure 5-16 Test 4 Flow Rate vs. Time (Truncated Vertical Axis)

5.4.1 Post-test Visual Observations

Following the termination of the pressure test, visual inspections were performed on Test Deck 5 (Figure 5-17). Penetration 5.2 was found to be completely dislodged from its installed position and pushed down into the leakage collection system. No damage or other notable discrepancies with the other five penetrations were observed.

Figure 5-17 Dislodged Penetration 5.2

5.5 Test 5

Test 5 evaluated the flood penetration seals installed in Test Deck 4. Table 5-9 gives an overview of the main results of Test 5.

Table 5-9 Test 5 Results Overview

Deck Number	# 4
Approx. Test Duration	35 min
Approx. Max Pressure	11.12 psig (76.67 kPa)
Test Termination Cause	Dislodged seal in Penetration 4.4 (6-inch, sleeved low-density foam seal)

Test 5 began by pressurizing the test chamber in 1-psig increments every 2–3 minutes. This rate of pressurization was held approximately constant during the duration of this test, as depicted by Figure 5-18. Minor leakage from Penetration 4.1 was observed immediately upon filling the test chamber with water. After reaching 3 psig, minor leakage was also observed from Penetration 4.3. At a test pressure of 5 psig, both penetrations were leaking at an approximate rate of 0.2 GPM. After reaching 7 psig, Penetration 4.3 ceased leaking while Penetration 4.1 continued to leak at an approximate rate of 0.3 GPM. At 8 psig, minor leakage from Penetration 4.6 was observed. As pressure was increased to 11 psig, the leakage from Penetration 4.1 increased to 0.7 GPM. A maximum pressure of 11.12 psig was achieved after 33 minutes. Less than a minute later, Penetration 4.4 abruptly dislodged. Flow rates through this dislodged penetration briefly exceeded 60 GPM before quickly decreasing to zero as the test chamber emptied. After the test chamber rapidly emptied of water, and with re-pressurization impossible, Test 5 was terminated.

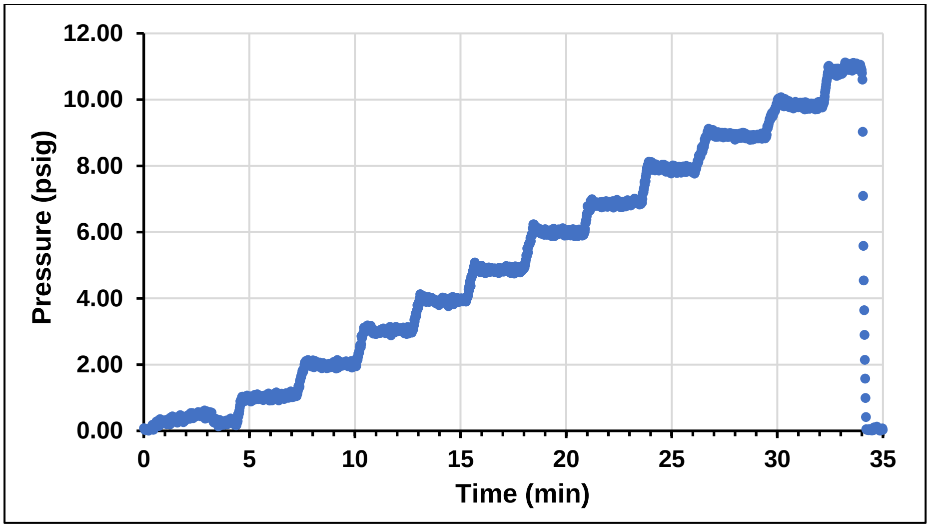

Figure 5-18 Test 5 Pressure vs. Time Graph

Flow meters and test personnel recorded flow rates during Test 5. Table 5-10 provides a timeline of Test 5 with notable visual observations and leakage rates recorded during this test.

Table 5-10 Test 5 Observations

Time (min)	Test Pressure (psig)	Observations
0	0.07	• Minor leakage (< 0.1 GPM) from Penetration 4.1
11.1	3.00	• Minor leakage (< 0.1 GPM) from Penetration 4.3 • Minor leakage (< 0.1 GPM) from Penetration 4.1
15.7	4.96	• Minor leakage (~0.21 GPM) from Penetration 4.3 • Minor leakage (~0.18 GPM) from Penetration 4.1
23.3	7.01	• Minor leakage from Penetration 4.3 ceased • Minor leakage (~0.28 GPM) from Penetration 4.1
24.2	8.00	• Minor leakage (~0.45 GPM) from Penetration 4.1 • Minor leakage (< 0.1 GPM) from Penetration 4.6 observed
33.2	11.12 (max pressure)	• Maximum test pressure achieved • Minor leakage (~0.58 GPM) from Penetration 4.1 • Minor leakage (< 0.1 GPM) from Penetration 4.4 observed
34.4	7.09	• Seal in Penetration 4.4 dislodged • Leakage from Penetration 4.1 was approx. 0.64 GPM when seal in Penetration 4.4 dislodged
~35	0	• Test terminated

Flow meters attached to the leakage collection system for each penetration measured and recorded leakage rates. Figure 5-19 and Figure 5-20 depict the flow recordings for Test 5 at different vertical scales. At approximately the 34-minute mark, Figure 5-19 captures the large increase in the flow rate from Penetration 4.4. Figure 5-20 displays the same recorded data as Figure 5-19 but with the vertical axis limited to a maximum of 2 GPM.

Figure 5-19 and Figure 5-20 also show small increases in the flow rates from the remaining penetrations immediately after the seal in Penetration 4.4 dislodged. These other flow rates (all less than 5 GPM) are most likely due to the large, sudden overflow from the dislodged Penetration 4.4 and from the design of the apparatus leakage collection system, rather than true leakage from these remaining penetrations. This explanation is further supported by the lack of any observable post-test damage to these penetrations.

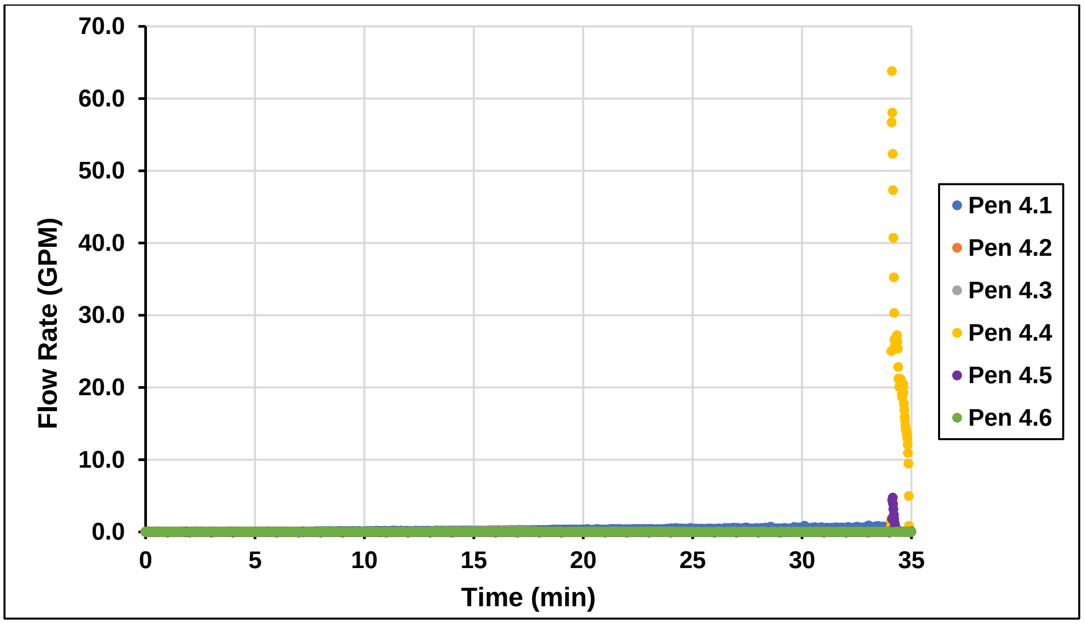

Figure 5-19 Test 5 Flow Rate vs. Time

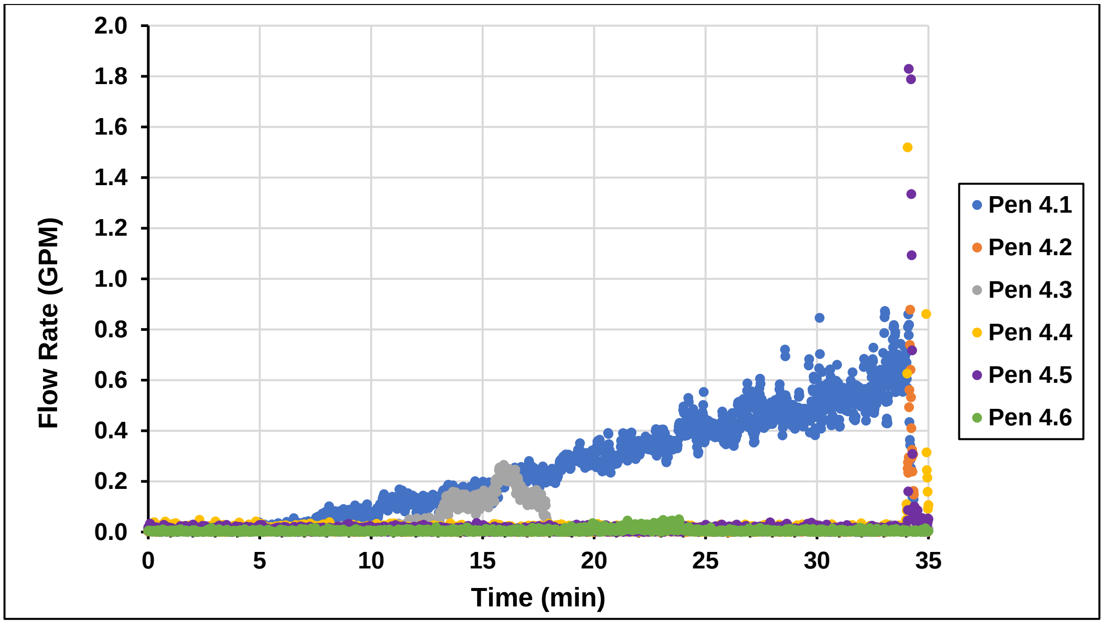

Figure 5-20 Test 5 Flow Rate vs. Time (Truncated Vertical Axis)

5.5.1 Post-test Visual Observations

Following the termination of the pressure test, visual inspections were conducted on Test Deck 4. The seal in Penetration 4.4 was found to be partially dislodged from the test deck. No damage or other notable discrepancies with the other five penetrations were observed.

5.6 Test 6

Test 6 evaluated the flood penetration seals installed in Test Deck 3. This was the final and shortest pressure test in this test series. Table 5-11 gives an overview of the main results of Test 6.

Table 5-11 Test 6 Results Overview

Deck Number	# 3
Approx. Test Duration	13 min
Approx. Max Pressure	8.29 psig (57.2 kPa)
Test Termination Cause	Dislodged seal in Penetration 3.3 (6-inch sleeved silicone elastomer with cable penetrants)

The test chamber pressure remained unchanged for the first 5 minutes of the test. After this initial period, the test chamber pressure was rapidly increased to approximately 1 psig per minute (Figure 5-21). Minor leakage from Penetration 3.5 was observed immediately after filling the test chamber with water. After the pressure was raised to 3 psig, minor leakage was also observed from Penetrations 3.1 and 3.4. Just after minute 8 and at approximately 5 psig, leakage from Penetration 3.3 exceeded 1 GPM. This penetration would continue to leak above this elevated level until the end of the test. At 8 psig, minor leakage (less than 0.1 GPM) was additionally observed from Penetration 3.5. At minute 11.8, a maximum test pressure of 8.29 psig was achieved. At minute 11.9, the seal in Penetration 3.3 dislodged. Its flow rate

briefly reached 40 GPM before steadily decreasing as the test chamber emptied, and the test was terminated after approximately 13 minutes.

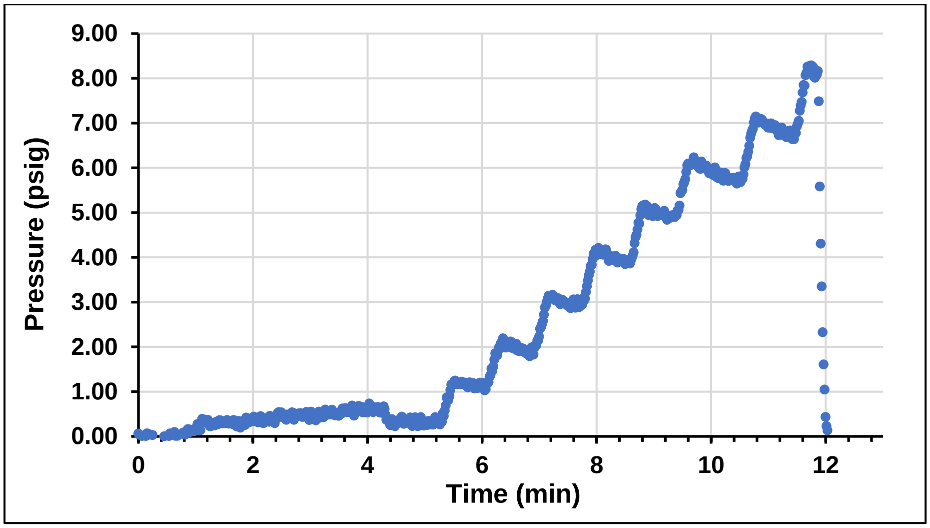

Figure 5-21 Test 6 Pressure vs. Time Graph

Flow meters and test personnel recorded flow rates and visual observations during Test 6. Table 5-12 provides a timeline of Test 6 with notable visual observations and leakage rates recorded during this test.

Table 5-12 Test 6 Observations

Time (min)	Test Pressure (psig)	Observations
0	0.06	• Minor leakage (< 0.1 GPM) observed from Penetration 3.5 after the test chamber was filled with water
5.0	0.36	• Test pressure began to be increased by 1 psig per minute
7.7	3.00	• Minor leakage (< 0.1 GPM) from Penetration 3.1 • Minor leakage (< 0.1 GPM) from Penetration 3.4
8.9	4.94	• Leakage from Penetration 3.3 exceeds 1.0 GPM
11.8	8.29 (max pressure)	• Maximum test pressure achieved • Leakage from Penetration 3.3 exceeds 1.7 GPM
11.9	4.31	• The seal in Penetration 3.3 dislodged with flow rates increasing to almost 40 GPM
~13	0	• Test terminated

Flow meters attached to the leakage collection system for each penetration measured and recorded leakage rates. Figure 5-22 and Figure 5-23 depict the flow recordings for Test 6 at

different vertical scales. At approximately the 12-minute mark, Figure 5-22 captures the large increase in the flow rate from Penetration 3.3. Figure 5-23 displays the same recorded data as Figure 5-22 but with the vertical axis limited to a maximum of 3.5 GPM.

Figure 5-22 and Figure 5-23 also show small increases in the flow rates from the remaining penetrations immediately after Penetration 3.3 dislodged. These other flow rates (all less than 5 GPM) are most likely due to the large, sudden overflow from the dislodged seal in Penetration 3.3 and from the design of the apparatus leakage collection system, rather than true leakage from these remaining penetrations. The final paragraph for Test 1 provides a more in-depth explanation.

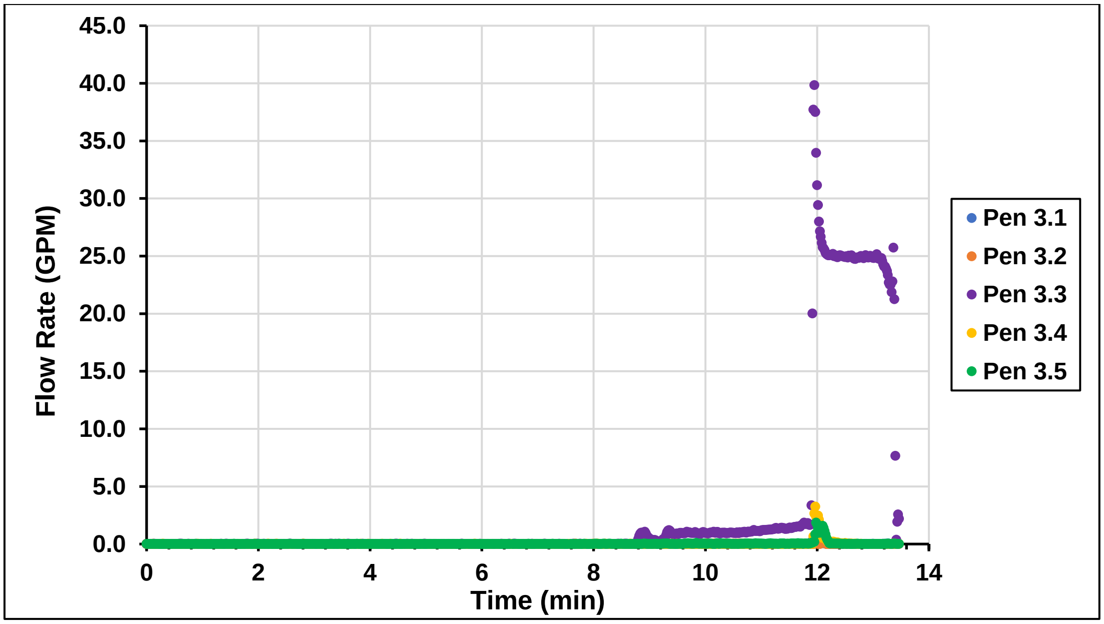

Figure 5-22 Test 6 Flow Rate vs. Time

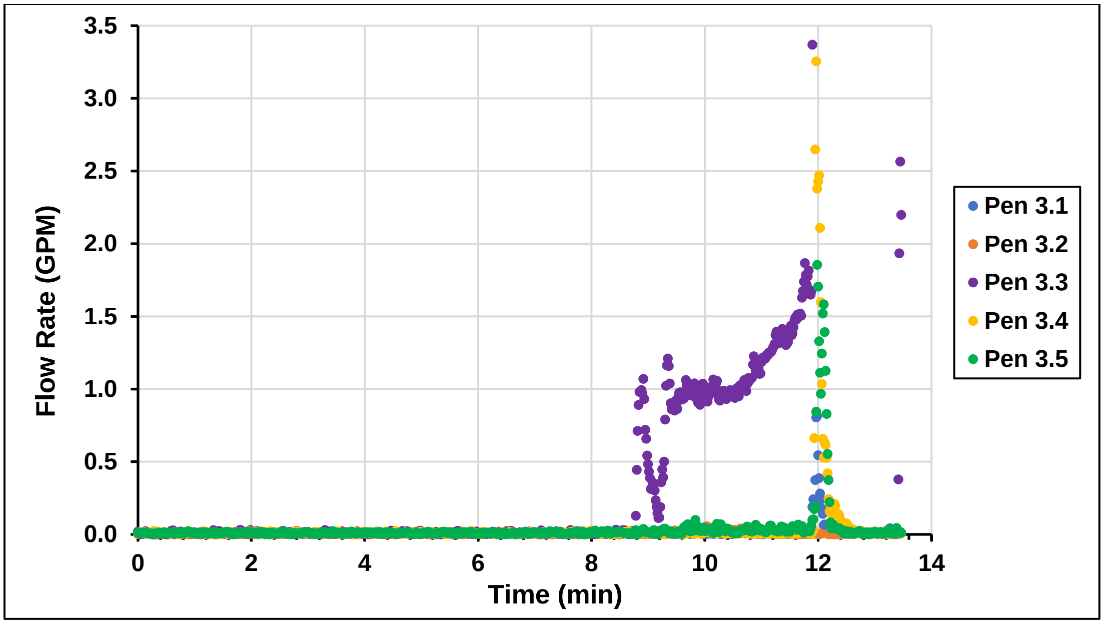

Figure 5-23 Test 6 Flow Rate vs. Time (Truncated Vertical Axis)

5.6.1 Post-test Visual Observations

Following the termination of the test, visual inspections were conducted on Test Deck 3 (Figure 5-24). The seal in Penetration 3.3 was found to be completely dislodged from its installed position and pushed down into the leakage collection system. No damage or other notable discrepancies with the other five penetrations were observed.

Figure 5-24 Empty Steel Sleeve for Ejected Penetration 3.3 (Left Photo) and Ejected Seal Material and Penetrants for Penetration 3.3 (Right Photo)

6 TEST SUMMARY AND PROTOCOL AMENDMENTS

The objective of the test series was to exercise the draft test protocol and assess its ability to generate performance data of flood penetration seals. Data and observations from this test sequence should not be interpreted as qualifying or disqualifying any specific flood penetration seal or installation design. Such determinations would require a more rigorous testing program.

The test series was successful in its objective to assess the draft test protocol. The test series demonstrated that the procedures outlined by the protocol were sufficient with regard to measuring and collecting performance data for candidate seal assemblies. Specified parameters such as volumetric leakage rates, applied pressure rates, and water temperatures were all actively measured and recorded. Furthermore, the test protocol's application to a variety of pressure regimes was successful. Figure 6-1 illustrates the pressure versus time recordings for all six tests. Large, sudden increases in applied pressure (Test 6) as well as short, incremental increases (Test 1) were implemented using the test protocol.

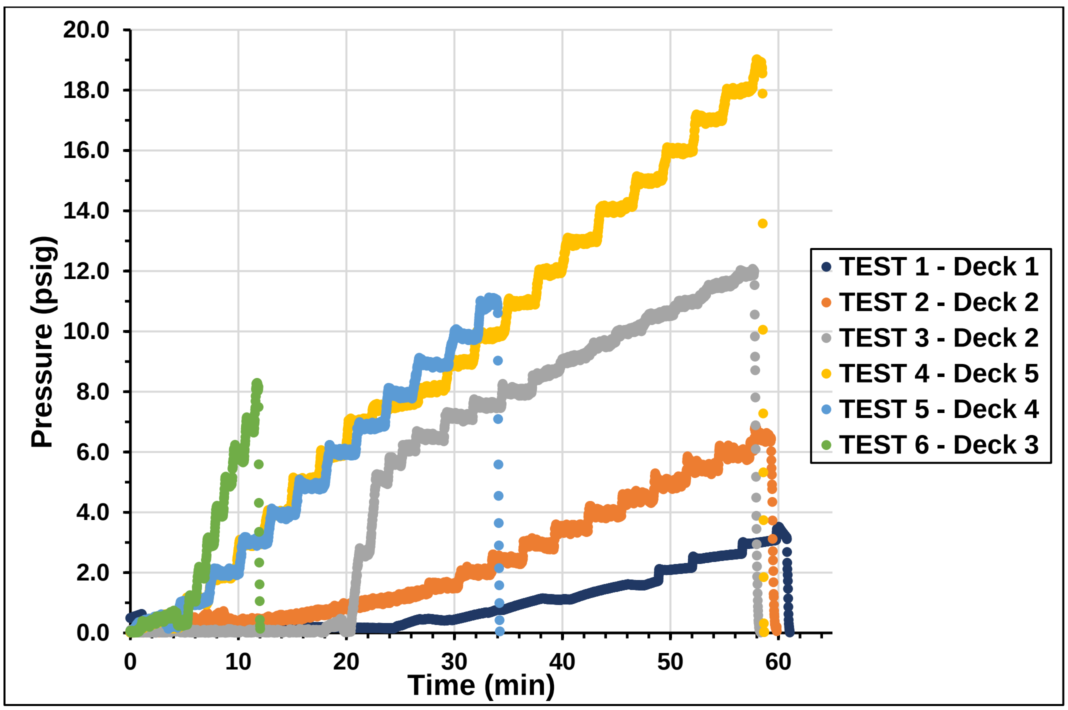

Figure 6-1 Pressure vs. Time Recordings for the Six Tests

6.1 General Observations

Six tests were conducted using Framatome's test apparatus to evaluate the procedures found within the test protocol. This brief testing regime was not exhaustive of all possible experimental variables governing flood penetration seal design and construction. The observations listed in this section should be interpreted with this limitation in mind.

6.1.1 Test Termination Cause

An abrupt and complete dislodgement of a seal assembly ended each test. These seal assembly failures were usually rapid and irreversible. Once a seal assembly was dislodged, pressure within the test chamber could not be maintained, and the makeup water system could not adequately replace the water lost through the dislodged penetration seal. No test was terminated due to reaching the maximum test duration (3 hours).

Despite the limited testing, it appears that seal dislodgement was influenced by the type of penetrant and sleeve material (steel versus PVC) used in its design. As evidenced in Tests 2 and 4, the lack of seal material adherence to PVC was a likely cause of these failures. PVC is not a typical material found at most NPPs. As acknowledged in Section 4, the testing objective was not to obtain actionable data but instead to exercise and then assess the test protocol, thus gaining some cost efficiencies during penetrant material procurement.

The exact failure mechanism that caused these dislodgements is unknown. More testing and research could be undertaken to investigate exactly how these seal assemblies fail. In future testing, video recordings may be useful for evaluating how these seal assemblies fail within the test apparatus. The investigation of these failure mechanisms was beyond the scope of this exploratory research project.

6.1.2 Data Measurement Observations

Pressure, flow rate, and water temperature measurements were continuously recorded in 1-second intervals during each test. These relatively small time-step increments allowed for more precise data measurements to be recorded during rapid changes in testing conditions (e.g., abrupt penetration seal dislodgements). Larger time recording intervals could have rendered data measurements incomplete during such rapid changes.

Water flow data for each seal assembly were successfully recorded during the test series. The testing of multiple seal assemblies during a given test added additional complexity for such recordings. For the chosen test apparatus, the abrupt dislodgements of certain seal assemblies and the large water outflow briefly distorted the flow recordings for intact seal assemblies. Although these distortions were minor and identifiable, care should be taken in future test apparatus designs to eliminate or reduce such occurrences, if feasible. This issue could be eliminated completely by only testing one seal assembly at a time, instead of the multi-assembly test decks used in this project.

6.2 Protocol Amendments

Researchers added some improvements and further insights to the protocol to address shortcomings identified from this test series. Table 6-1 highlights sections of the test protocol that have been substantially updated or otherwise amended. **Bolded** text indicates amendments.

Table 6-1 Test Protocol Amendments Post Test

Section	Amendment	Justification
3.8	"Given that the potential for leakage through the various seal assemblies being tested exists, the test apparatus **may** have the capability to provide	This clarifying text was added to this section as a result of lessons learned from the test series. Substantial leakage from the penetration seals may require

Table 6-1 Test Protocol Amendments Post Test (cont'd.)

Section	Amendment	Justification
	makeup water to the pressure chamber **throughout the specified duration of the test."**	actively adding makeup water to avoid premature termination of a given water pressure test.
3.9	"Appendix A to this test protocol includes a diagrammatic sketch of a typical configuration for a test chamber and its associated test and support equipment. **This sketch is for reference only and is not intended to reflect the only potential configuration for a test apparatus."**	This text was added to explain that the provided test apparatus sketch/diagram within the test protocol is for reference only and should not be considered mandatory or otherwise required for testing purposes. The design and selection of a testing apparatus are up to the end user.
4.4	"Each penetrating item containing hollow spaces, such as pipes and conduit, through which water can leave the chamber should be sealed to prevent any water leakage through the penetrant. **If a penetrant is subject to leakage under actual (installed) conditions and requires an internal seal assembly, this should be considered in the testing for the subject seal assembly configuration."**	This text in the protocol was amended for clarification purposes and to remove previous unclear, restrictive language.
4.6	**"For penetrating items like cables, bracing on either side of the pressure chamber may be necessary to provide better realism."**	Shortened cable penetrant samples were ejected largely due to lack of bracing. In real world conditions, these cables would be substantially longer and would not necessarily have or need such bracing.
4.7	"…**Other materials such as chemicals and coatings, including releasing agents on the forms used when constructing the penetrations in the test deck, should not be used to prepare the penetration unless the manufacturer has verified that such use, as applicable, would have no impact on the performance of the sample seal assembly or materials to be tested.**"	Lessons learned during the penetration seal installations demonstrated the need for additional language within the test protocol on the use of these special coatings.
6.1.7.1	**"The rationale for the 'pressure versus time' curve used, including the maximum test pressure."**	The previous version only included a maximum test pressure rationale. However, time-dependent pressure testing may be performed to mimic real-life flooding conditions.

Despite not being explicitly recommended by the test protocol, a detailed test plan proved to be essential for a successful test program. Lessons learned from the test series further indicated the importance of pretest checklists to verify and ensure the operational readiness of all test apparatus and data acquisition equipment. Such steps can help ensure that subsequent testing can be fully successful.

Although not a primary testing objective, each test provided new indications of how flood penetration seals leak, why flood penetration seals likely fail, and when such leakage likely occurs. It is recognized that these indications stem from a limited test series. More testing would be needed to fully characterize penetration seal behavior under flooding conditions. Consequently, one such indication gained from this test series was the tendency for a penetration seal to dislodge abruptly often with little prior indication. These sudden dislodgements were particularly evident with Tests 3, 4, and 5. The use of compressed air to pressurize the test chamber and the sudden pressure rate changes may have played a role in these abrupt dislodgements. When the test chamber containment dislodged, the compressed air released its energy in a dynamic manner. In addition, it appears that seal dislodgement was influenced by the type of penetrant and sleeve material (steel versus PVC) used in its design. As evidenced in Tests 2 and 4, the lack of seal material adherence to PVC was a likely cause of these failures. PVC is not a typical material found at most NPPs.

Another observation was the impact of bracing penetrants on the pressurized side of the test. Cable penetrants that were not fixed in place might have remained in place longer if they had been clamped to the concrete test deck (e.g., with metal brackets). Such bracing might have prevented their ejection and allowed testing to continue for a longer period.

In addition to the revised test protocol, this testing knowledge will be useful for subsequent research activities pertaining to flood penetration seals.

7 CONCLUSIONS

The application of the test protocol to a series of pressure tests demonstrated that the performance of flood penetrations seals could be measured successfully in a laboratory setting. Through direct observation and data recordings, flood penetration seal performance was assessed and used to improve the methodology found within the test protocol. The revised test protocol included in Appendix A should be considered as a demonstrative research product. Future research can build on this exploratory project using the observations and lessons learned.

The initial steps taken by this research effort can provide useful insights and a basis for future efforts to quantify the performance of these flood barriers. For example, the test protocol developed could be used as a starting point or framework for the future development of an industry consensus standard by appropriate standard-making organizations.

As for next steps, the testing of aged penetrations in their actual installed arrangements could provide more insights into their actual performance under flood conditions. Combined with a thorough uncertainty analysis, these tests could provide the most accurate data on component fragilities for any subsequent PRAs. Beyond just flood performance, the harvesting of aged penetrations from decommissioned sites could shed light on their material properties and the effects of environmental factors. Similarly, future testing work could examine other evaluation parameters, including simulated material aging, vibration, or debris loading.

This exploratory research project has demonstrated to NRC staff how flood penetration seals perform under simulated flooding conditions, and the project has provided a new understanding of how such laboratory testing could be performed. This foundational knowledge will be useful as the NRC staff continues its probabilistic assessment of flood hazards and plant response.

8 REFERENCES

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APPENDIX A
TEST PROTOCOL

This test protocol is to be viewed as an informed research product of a multiyear development and testing effort in an area that does not have any formal recognized testing standard. Its wording and overall language are the aggregation of the best lessons learned from the protocol's development and laboratory prototype testing experience. The development of this project also included multiple interactions with stakeholders in the public meeting and comment process. The language of the test protocol is not to be interpreted as enforceable regulatory guidance or requirements. To ensure this, the test protocol will only use the word "should" throughout, with the understanding that, if the protocol were to evolve into a "Recognized Standard," the standard development process would determine which requirements were mandatory (i.e., shall) and which were only recommended (i.e., should).

A.1 <u>Test Protocol</u>

1. Scope

1.1[1] The test protocol is formulated so it could be applicable to through-penetration seal assemblies of various materials and construction that are intended for use in flood-rated barriers (e.g., internal and external walls, floors, ceilings) installed in nuclear power plants (NPPs).

1.2 This protocol is the result of a flooding research program by the U.S. Nuclear Regulatory Commission (NRC), which developed it to inform at least two sets of distinct groups and functions:

> 1.2.1 manufacturers, to develop performance parameters and limitations associated with their specific type(s) of seal assemblies/materials
>
> 1.2.2 NPPs and regulators, to obtain insights on the type of testing that could be conducted for measuring performance data for flood penetration seal assemblies and materials used in specific configurations and with specific flood exposure parameters

1.3 The NRC does not intend this test protocol to establish "pass/fail" criteria. The test protocol represents a performance-based approach to evaluate the flood mitigation characteristics associated with specific penetration seal assemblies and materials when exposed to specified flood event parameters, including water pressure(s) and duration.

1.4 The method of testing through-penetration seal assemblies consists of direct exposure of test samples to a specified water pressure. The manufacturer or end user will specify the magnitude of the water (head) pressure to which the individual seal assemblies are tested. The performance evaluation of each through-penetration flood seal assembly will be based on the following:

> 1.4.1 ability to restrict water transmission (leakage) through the assembly

---

1 Additional, related explanatory material that can be found in Appendix B.

1.4.2 overall flood-mitigation performance over the required exposure duration

1.4.3 compatibility of the assembly to the proposed environment, which can include aging characteristics of assembly materials, noting that all "aging" should occur before any flood-resistance testing

1.5 This test protocol includes exposure to water (head) pressure for a specified duration to replicate flooding conditions to which the assembly(ies) may be exposed during an anticipated flood event. This flood testing is to determine the ability of the seal configuration, material, or device to resist the passage of water under the designated pressures and duration.

1.6* This test protocol is used to quantify the performance of flood seals when exposed to water pressure. It is not intended to quantify the performance of flood seals when subjected to other forces, such as the failure of cable or pipe support systems or the impact from falling or floating debris.

1.7 The intent for this test protocol is to develop data and identify parameters related to the flood-mitigation performance of penetration seal assemblies of all types (e.g., materials, configurations) that are likely used in flood-rated barriers.

1.8 The (head) pressure values stated in pounds per square inch (psi) and volumetric flow (leakage) rates stated in gallons per minute (GPM) should be considered as standard units. Values used in expressing test pressure represent the increased pressure difference above standard, ambient atmospheric pressure, to which a candidate seal assembly is exposed during a test cycle. Any values given in parentheses are mathematical conversions to international (metric) units.

1.9 This test protocol is developed to quantify and describe the response of penetration seal assemblies, products, and materials that are exposed to water pressure under controlled conditions but does not by itself incorporate all variables or factors that could influence the ultimate performance of a seal assembly when exposed to actual flood conditions.

1.10 It is not the intent of this test protocol to determine the performance capabilities of a flood seal subsequent to being exposed to a flooding event. It is the responsibility of the user of this test protocol, or the data resulting from testing performed in accordance with this test protocol, to evaluate the condition of any flood seal, including the potential for degradation, whether visible or not, after exposure to an actual flooding event.

1.11 All penetration seal assemblies and penetrants should be installed in the test apparatus in the specific configuration(s) that is reflective of their intended as-built (or planned) configuration(s) in NPPs.

1.12 It is the intent of this test protocol that all testing will be performed using fresh water. If the penetrations being tested are to be qualified for exposure to seawater environments, a conversion (reduction) factor of 0.975 should be applied to the recorded test (head) pressures to account for the difference in the average density (weight) of seawater as compared to fresh water (0.445 psi per foot of seawater versus 0.433 psi per foot of fresh water). The manufacturer should specify any potential compatibility limitations associated with exposure of the seal assembly and materials to seawater.

2. General

2.1 Units of Measurement

2.1.1 Values listed without the use of parentheses are the assumed units for this test protocol. Values in parentheses are for use when the metric system of units is desired.

2.2 Glossary

2.2.1 Ambient Temperature: The average air temperature surrounding the test apparatus.

2.2.2 Fire-Rated Penetration Seal: A fire-resistant seal assembly or material designed to maintain the fire-resistive integrity of the barrier in which it is installed.

2.2.3 Flood-Rated Penetration Seal: A flood-resistant seal assembly or material designed to maintain the flood rating of the barrier in which it is installed. Barrier penetrations to be protected may consist of either through-penetrations or membrane penetrations.

2.2.3.1 Through-barrier penetration: A penetration that extends completely through the flood barrier.

2.2.3.2 Membrane penetration: A penetration that passes through part of the barrier but not the entire barrier. Some examples are outlet boxes, drains, or conduits that lead from a back-box to the space above the ceiling. Flood seal assemblies for membrane penetrations will be tested in the same manner as that used for through-penetrations.

2.2.4 Flood Penetration Seal Configuration: The physical arrangement of both the penetration itself and the materials and components within the barrier penetration, including both the flood seal and penetrants.

2.2.5 Independent Testing Laboratory: A laboratory that has been determined to have the capabilities and qualifications to properly perform the testing outlined in this test protocol and that has no financial or technical conflict of interest associated with any of the sample flood penetration seal assemblies or materials being tested.

2.2.6 Internal Conduit Seal: A material, combination of materials, or premanufactured device installed inside a conduit. Internal conduit seals are typically installed at the first access point in the conduit from the barrier being penetrated. Access points include pull boxes, junction boxes, or an open-end if the conduit terminates in space.

2.2.7 Leakage: The passage of water through or between the flood seal assembly and the surface interface with the penetrated barrier or penetrating item (e.g., pipe, conduit).

2.2.8 Leakage Rate: The volumetric rate at which water is measured as leaking through or around the sample flood seal assembly or material, measured in GPM units or, alternatively, liters per minute.

2.2.9 Sample Test Deck: The test assembly with through-penetration flood seal assembly(ies) or material(s) installed within the sample penetration(s), including penetrants that each seal assembly is designed to support. The size and configuration of the penetration(s) in the test sample should be dependent upon the specific seal assembly to be tested and qualified; as installed in accordance with their individual manufacturer's specifications.

2.2.9.1 Discussion: Penetrating items may include, but not be limited to, pipes, conduits, cables, or cable trays.

2.2.10 Test Apparatus: The equipment to which a sample test deck is mounted or installed. The test apparatus is designed to subject a sample penetration seal assembly(ies) to water pressure at a specific pressure and duration. The tested pressure represents the difference in pressure (Δp), as measured between the ambient environment and the exposed side of the tested seal assembly, which is to be expressed in psi or, alternatively, in metric units of kilopascals.

3. Test Equipment

3.1 The test apparatus should include a pressure chamber that will consist of a sealed vessel capable of producing the simulated water pressures associated with an expected flooding event that the sample seal assembly(ies) is (are) expected to withstand. The pressure chamber should be open on the side on which the sample test deck is to be installed. The pressure chamber should be provided with a mounting flange and gasket, or similar arrangement, to provide a watertight seal with the sample test deck.

3.2 The pressure chamber may be designed for operation with the sample test deck in either a vertical or horizontal configuration. [Note: For consistency and ease of (head) pressure measurement at the level of each penetration, the horizontal mounting is typically preferred.] The area (size) of the open side of the pressure chamber should, at a minimum, be sufficient to accommodate the largest penetration for which a seal assembly is to be tested.

3.3 The pressure chamber should be provided with a water fill connection that is designed to ensure that all flood seal assemblies installed in the test sample are fully immersed in water throughout the test duration. This includes the capability for makeup water to enter the chamber during testing to compensate for water that may be lost due to leakage through or around a seal assembly. If the pressure chamber is not designed to be completely flooded with water throughout the test, a water level indicator should be included in the pressure chamber design.

3.4 The design of the test apparatus should include the capability to deliver and maintain a specified water pressure, whether static or variable, on the exposed side of the test sample throughout the specified test duration. The test apparatus should have the capability to increase the water pressure within the pressure chamber from ambient (static head pressure from the water in the chamber) to the maximum test pressure as required to mimic the expected flood event for which the sample is being evaluated or qualified.

3.5 The pressure chamber should be provided with an attached pressure gauge to indicate internal water pressure, along with an internal pressure-sensing device that is connected to a data acquisition system that will automatically record the internal pressure within the pressure chamber throughout the test duration. Both the external pressure gauge and internal sensor should be located as close to the level of the penetrations as possible.

3.6 If air pressure is used to produce the test pressures and will partially fill the pressure chamber, two external pressure gauges should be used; one that is located within the water space at (or near) the level of the penetrations and one that is located within the air space of the chamber. This configuration will also require that a water-level sensor be installed within the pressure chamber to ensure an adequate water level is maintained.

3.7 The test apparatus should include the capability to capture and record any leakage through the individual penetration seal assembly(ies) on the nonexposed side of the test sample. The data acquisition system should have the capability to record the volumetric leakage rate through any individual seal assembly throughout the duration of the test.

3.8 Given the potential for leakage through the various seal assemblies being tested, the test apparatus may have the capability to provide makeup water to the pressure chamber throughout the specified duration of the test.

3.9 Appendix A to this test protocol includes a diagrammatic sketch of a typical configuration for a test chamber and its associated test and support equipment. This sketch is for reference only and is not intended to reflect the only potential configuration for a test apparatus.

4. Test Sample

4.1 The individual penetration seal assembly(ies) is (are) to be installed in the sample test deck, which is to be installed against, and affixed to, the pressure chamber. The sample test deck should be designed to allow for a watertight seal to be maintained at the interface with the pressure chamber.

4.2 The design of the sample test deck should ensure that all installed penetrations are located within the opening of the pressure chamber, while allowing sufficient additional space around the perimeter of the pressure chamber opening to facilitate attachment to the pressure chamber mounting flange (or other attachment arrangement), along with ensuring proper strength of the sample test deck to withstand the anticipated pressure load.

4.3 The specific material design and specifications for the sample test deck should be based on the design of the flood barrier, including its intended maximum flood resistance

rating, that the seal assembly(ies) is (are) designed to support. If penetrations through a flood barrier are to be “sleeved,” then the design of the test sample needs to include the installation of sleeves when being constructed. Proper monitoring and inspection during the performance of the flood testing are necessary to ensure that an improperly constructed sample test deck, which results in leakage between a sleeved penetration and the sample test deck material or other leakage paths, such as cracks, does not result in the inadvertent assignment of additional leakage volume (rate) to a seal assembly.

4.4 Each penetrating item containing hollow spaces, such as pipes and conduits, through which water can leave the chamber should be sealed to prevent any water leakage through the penetrant. If a penetrant is subject to leakage under actual (installed) conditions and requires an internal seal assembly, this should be considered in the testing for the subject seal assembly configuration.

4.5 Construction of a new flood penetration seal assembly should be representative of an “as-built” configuration, including, for example, all pipes, conduits, cables (percent fill), and required supports, and be in accordance with the applicable manufacturer’s specifications and instructions.

4.6 Any through-penetrating items should be installed so that they extend beyond the surface of sample test deck as necessary to protect against internal leakage and to prevent undue stresses on the seal assembly and material. For penetrating items like cables, bracing on either side of the pressure chamber may be necessary to provide better realism. If penetrating items are designed to be provided with bracing during field installation, the penetrants need to be extended to a sufficient length on either side of the test sample to accommodate any required bracing. Install membrane penetrating items to match the field installation configuration.

4.7 The sample test deck should be constructed to mimic the field installation for both the barrier (e.g., internal and external wall, floor, ceiling) materials and those of the penetration seal assembly. New seals should be installed in accordance with the manufacturer’s recommendations. Sufficient cure time should be ensured for all materials to achieve their design strength before beginning testing, in accordance with the manufacturer’s instructions for the seal materials and with standard construction practices for the barrier materials if, for example, concrete or mortar is used. Other materials such as chemicals and coatings, including releasing agents on the forms used when constructing the penetrations in the test deck, should not be used to prepare the penetration unless the manufacturer has verified that such use, as applicable, would have no impact on the performance of the sample seal assembly or materials to be tested. For sealing compounds, other parameters to consider include density before and after curing, volume of compound used in each layer, cure time for each layer, mixing technique, and damming characteristics.

4.8 The test sample, including all installed penetration seal assemblies or materials, should be conditioned to provide a moisture content that is representative of that anticipated for the end use application. For the purposes of standardization, this condition is considered to be achieved when the seal assembly materials have a moisture content corresponding to drying to equilibrium with air in the range of 50 percent to 75 percent relative humidity at 73 (+/- 5) degrees Fahrenheit (F) (23 (+/- 3) degrees Celsius (C)). If, however, due to the nature of the material(s) or their

construction configuration, this cannot be achieved, then these conditions may be waived, except as to the attainment of the required strength as outlined in Section 4.7.

5. Conduct of Flood Testing

5.1 Flood testing should be performed under a qualified quality assurance program.

5.2 Test conditions should replicate the end use application. Flood tests should be performed within an environmentally controlled area to minimize any variables associated with changes in ambient conditions that might affect the test results. Ambient temperature and pressure within the test facility should be recorded at the start of each test cycle and monitored throughout the duration of the test. It is recommended that the ambient temperatures surrounding the test equipment be maintained between 50 degrees F (10 degrees C) and 90 degrees F (32 degrees C). If it is anticipated that a penetration seal assembly will be exposed to freezing or excessively warm temperatures that the manufacturer has indicated may have a detrimental impact on seal performance, additional testing or evaluation may be necessary to quantify any performance reduction.

5.3 Before the test begins, the specific design or configuration of the test sample, including each seal assembly installed, should be recorded, including, but not limited to, the following information:

5.3.1 sample test deck (material) description and dimensions

5.3.2 seal assembly or material manufacturer(s)

5.3.3 seal assembly or material description(s)

5.3.4 penetration size (dimensions or diameter)

5.3.5 penetrant(s) description, including fill density,[2] as appropriate, noting that, for seals tested without any penetrating items, the fill density should be recorded as “zero”

5.4 Flood testing should not begin until the sample test deck has developed sufficient strength, as appropriate for its construction material(s) and standard industry practice, to retain securely in position the materials and devices that are used to seal the penetrations.

5.5 Unless the test apparatus is specifically designed to use air pressure within the test chamber to regulate the test pressure, testers should ensure all air is vented from the pressure chamber before beginning the flood testing.

5.6 Maximum test pressure within the pressure chamber, and the rate at which it is achieved, should be based on the parameters needed to mimic a specific flood event or those specified by the manufacturer.

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[2] Fill density is the percentage of the available penetration opening area that is occupied by a penetrating item. For example, a 2-inch diameter pipe installed through a 4-inch diameter penetration would represent a fill density slightly in excess of 25 percent.

5.7 Visual inspections of the sample test deck should be performed throughout the test cycle, including after reaching the maximum test pressure, to determine whether any leakage is visible at the interface between the pressure chamber and the sample test deck or from any location other than “through” the sample seal assembly being tested.

5.8 The installed data acquisition system should record the water pressure to which the sample seal assemblies are exposed, including the rate at which the pressure may be applied over the duration of the test.

5.9 The installed data acquisition system should record the volumetric leakage rate through any individual penetration seal assembly throughout the duration of the test.

5.10 The end user should specify the duration of each test, whether by a manufacturer to qualify a specific penetration for exposure to a maximum pressure or duration, or to develop performance data for specific assemblies and materials. The data acquisition system should record the duration of each test.

6. Report

6.1 A detailed report of the performance of each flood penetration seal assembly installed in the sample test deck should be provided. Such a report should, at a minimum, include the following information:

6.1.1 a description of the test apparatus, including photos or schematic diagrams, used in performing the flood testing

6.1.2 a detailed description of the sample test deck, including the following:

6.1.2.1 materials of construction and a drawing that depicts geometry and dimensions, along with locations of penetrations within the sample test deck

6.1.2.2 installed seal assemblies, including manufacturer, type of assembly or material, configuration (or link to specific penetration listed in 6.1.2.1), penetrating items and any applicable fill density, including drawings or pictures depicting the installed configuration of each seal assembly, along with photographs during and following each test, as appropriate

6.1.2.3 orientation of the sample test deck used during testing

6.1.3 the relative humidity of the ambient environment during curing and testing of the test sample and the installed seal assemblies and materials, if applicable

6.1.4 a summary of test results or printout from the data acquisition system, which, at a minimum, should include pressure and leakage data as a function of test time (duration) for each seal assembly

6.1.5 testing equipment calibration records

6.1.6 any observations and significant details about the test, including any issues associated with the sample test deck and each penetration seal assembly tested;

documentation of any leakage from either the pressure chamber or deck interface or penetration assembly; and any information such as test apparatus faults, anomalies, or failures

6.1.7 a general summary that, as a minimum, outlines the following:

6.1.7.1 the rationale for the "pressure versus time" curve used, including the maximum test pressure

6.1.7.2 the final test duration recorded for all seal assemblies, noting that the overall test duration may vary for each test, since the desired duration will be a function of the anticipated exposure associated with a specific flood event for a specific geographic location

6.1.7.3 the final performance of all seal assemblies for the test period, including an assessment of any leakage recorded through a seal assembly and any changes in the rate of leakage observed throughout the test duration

6.1.7.4 a statement on the flood resistance performance of each seal assembly, inclusive of any leakage rate(s) associated with the assembly.[3]

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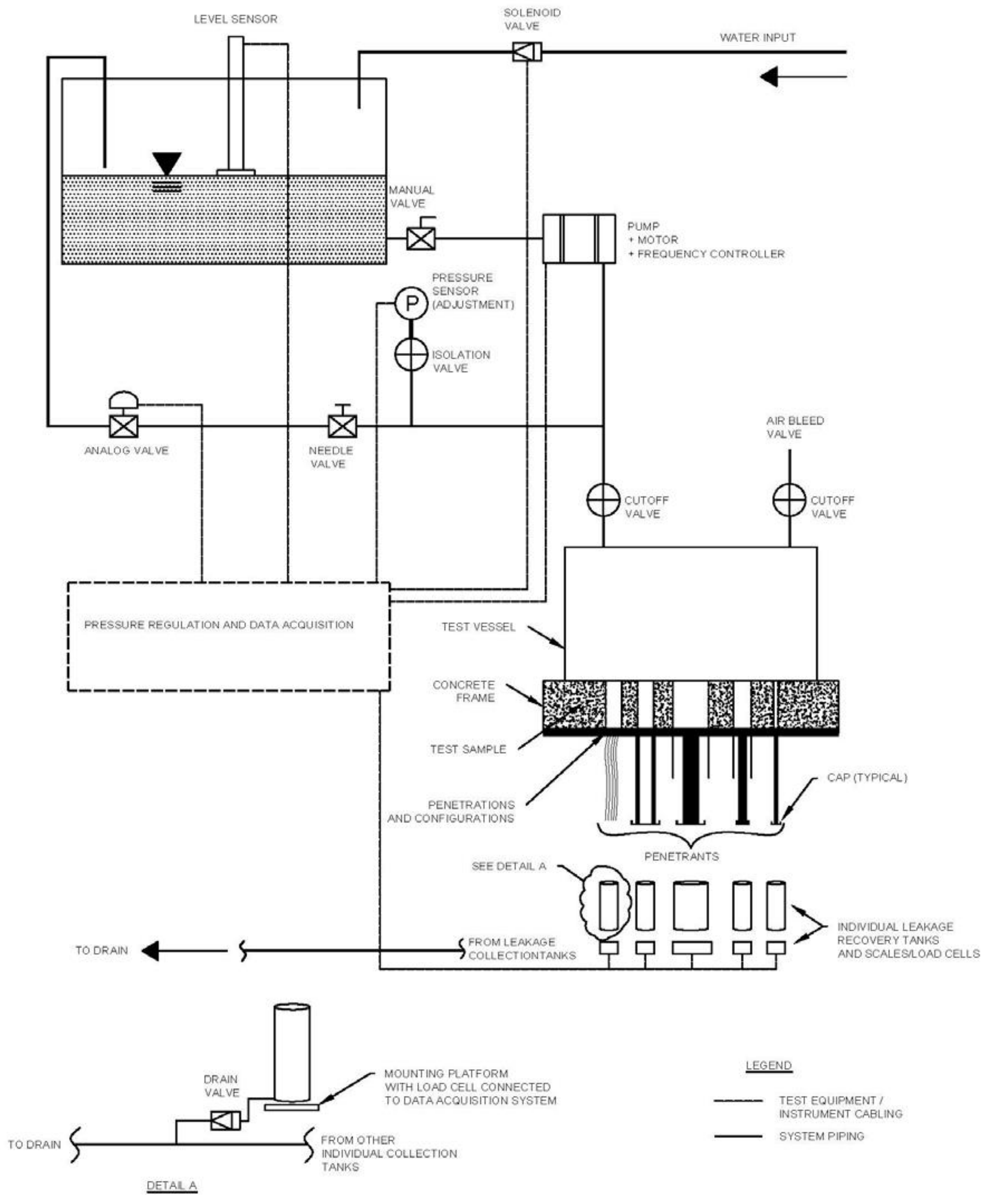
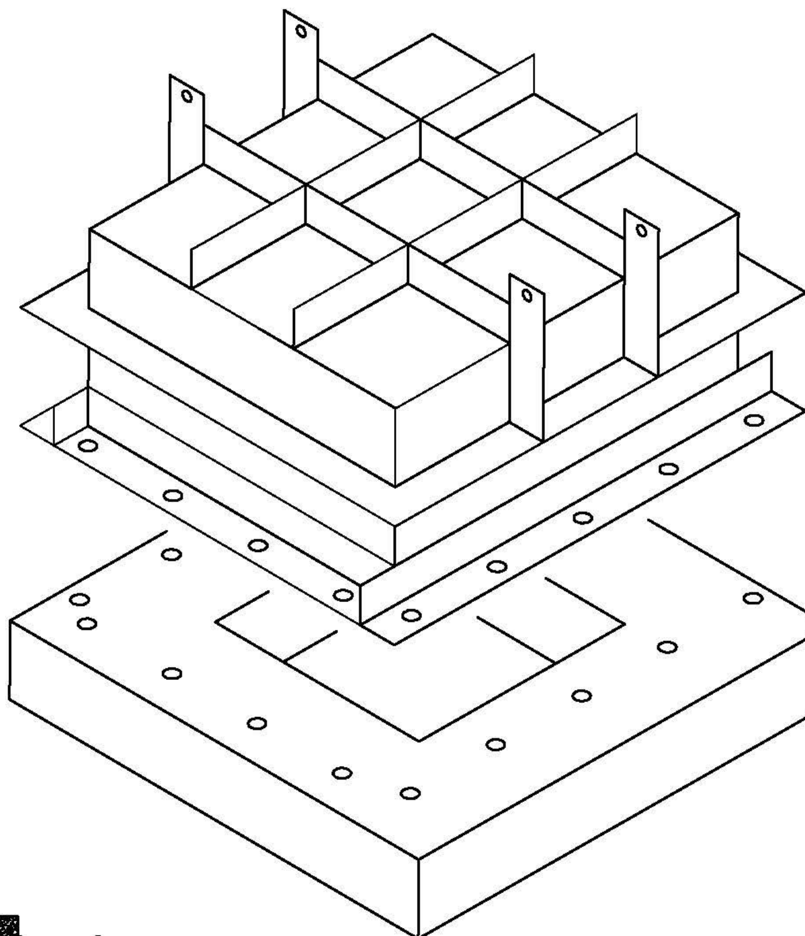
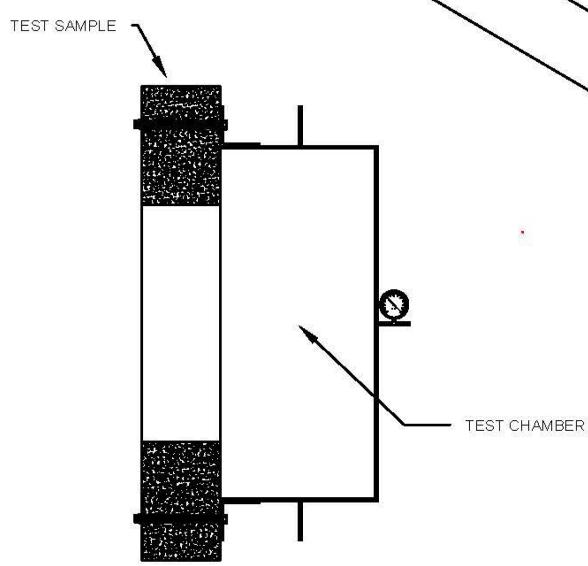
[3] Where flood penetration seals are to be exposed to seawater, the maximum pressure rating developed during the testing using this methodology should be reduced by a factor of 0.975 to account for the difference in densities (weight) between seawater and fresh water.

PROTOCOL APPENDIX A
Test Equipment General Arrangement Schematic[4]
(Sample)



4 The sample test deck depicted in this example consists of concrete. Actual test decks should consist of any material that is representative of the wall, the floor, or the ceiling where the penetration seal assembly is to be installed.





The test chamber should be designed to have sufficient flexibility and capabilities to accommodate a wide range of potential installation scenarios, including the ability to withstand the maximum flood pressures anticipated at any NPP.

APPENDIX B
GENERAL DISCUSSION OF THE NRC FLOOD PENETRATION SEAL TEST PROTOCOL

B.1 Introduction

The March 2011 disaster that occurred at the Fukushima Dai-ichi nuclear plant in Japan highlighted the potential damage that can be caused as the result of a significant flooding event. Many of the commercial nuclear power plants (NPPs) in the United States are known to be located in areas that are subject to potential flooding events of varying degrees of severity. Subsequent to the Fukushima nuclear incident, the U.S. Nuclear Regulatory Commission (NRC) issued a request to all operating NPPs in the United States for information under Title 10 of the *Code of Federal Regulations* (10 CFR) 50.54(f) on the design-basis flood estimates used at NPPs. Additionally, the NRC staff performed a number of site surveys at NPPs that focused on flood mitigation. Licensees reevaluated flood hazards in their design basis as part of the post-Fukushima actions.

The results of internal NRC research on flood protection at NPPs identified the lack of standardized test procedures or methodologies used by licensees to verify or quantify the level of performance associated with specific flood seal assemblies installed in the penetrations through flood-rated barriers. The NRC staff held that a standard set of procedures or protocols to evaluate the performance of the various flood penetration seals and configurations could help verify whether or not a specific penetration seal assembly could adequately support the flood mitigation requirements at the various NPPs.

In fall 2015, the NRC initiated a research program to identify the types of penetration seal assemblies and materials being used by NPPs in maintaining the integrity of their flood-rated barriers and to demonstrate the development of a testing protocol. This test protocol is not intended to be an NRC-approved standard test method, although results from this research effort (including the final test protocol) could be used as a starting point or initial framework for the future development of an industry consensus standard.

B.2 Applicability

This testing protocol is not an NRC-approved standard test method. Rather, it is the research product of an exploratory project that was intended to provide the NRC staff with knowledge and experience on how flood penetration seal testing could be performed. As part of this exercise, this test protocol was developed to apply to any type of penetration seal assembly or material that is intended for installation in a flood-rated barrier. These flood seal assemblies or materials are normally intended for use in openings in flood-rated barriers (e.g., internal and external walls, floors, ceilings), whether these openings represent through-penetrations of the entire barrier or are penetrations through only one portion of a membrane-type barrier.

B.3 Criteria

As a demonstrative research product, this flood test protocol may help inform the evaluation of the flood-mitigation performance of penetration seals that are designed to protect openings in barriers (e.g., internal and external walls, floors, ceilings) that have been otherwise credited as

having a flood resistance rating in support of a flood-mitigation program at a commercial NPP. The research objective for this test protocol was to demonstrate a potential method for quantifying the flood performance of penetration seal assemblies. As a result, this test protocol does not specify minimum performance criteria, such as exposure pressure or duration, to which the seal assemblies must be exposed.

It is understood that different assemblies and materials will have varying properties that may make them susceptible to leakage when exposed to varying levels of pressure exerted on one side of the penetration assembly. Different assemblies and materials may have greater pressure resistance when installed in penetrations involving specific types of penetrants or may be limited in the size of a penetration that they may be able to support.

This test protocol was not developed to demonstrate or address any other potential mechanisms that might result in damage to, or leakage through, penetration seal assemblies beyond exposure to specified water pressures for a specified duration. This includes mechanisms such as impact from float debris, vibration due to seismic activity or attached machinery, or aging. Although some seal assemblies could be exposed to "impact" damage from floating debris and seismic activity, too many variables are associated with such an event to develop a realistic simulation for inclusion in a "standardized" testing protocol. Where such events need to be evaluated, those evaluations should be separate from this test protocol, and the following are provided as recommendations to support those evaluations:

Impact Damage: It will be necessary to either develop a "scenario-specific" test, including the test apparatus, to obtain impact performance data or to provide a protective barrier around the installed penetration(s) to mitigate any potential impact damage.

Vibration: Similar to fire-rated penetration seals, if the manufacturer does not indicate that a seal assembly or material has the ability to accommodate vibration or other movement of a penetrating item, within specified limits, the penetrating item could be braced to the penetrated barrier such that no movement between the penetrating item and the barrier occurs.

Aging: This protocol does not include the potential impacts on seal assembly due to "aging" effects. If this is an issue of interest, a candidate seal assembly could be subjected to any artificial aging standardized techniques separately, before testing the assembly for flood resistance.

B.4 Test Samples

For the testing phase of this research project, the piping, cables, conduits, and other penetrating items anticipated for flood-rated barriers were chosen to be adequately representative of the field configurations for the given seal assembly.

The scope of this exploratory research project limited the size, configuration, and number of test samples that could be tested. Although it was intended that the test samples include penetrations and penetrants (including supporting structures) that were representative of actual field installations, the tested configurations may not have been fully representative of "worst

case” field conditions due to the constraints and limitations associated with performing tests of this nature. For example, testing of penetration seal assemblies intended for installation in vertical walls with a test sample mounted in a horizontal configuration may not have reflected the potential movement of, or stresses on, the penetrants that might be expected during exposure to a flood event.

NRC FORM 335 (12-2010) NRCMD 3.7

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Walkdowns of design-basis flood protection features conducted by U.S. nuclear power plant licensees in the aftermath of the Fukushima Dai-ichi accident found numerous examples of degraded or nonconforming flood protection features, the majority of which were penetration seals. The assessment of flood penetration seals during the walkdowns was mainly through visual inspection, which highlighted the lack of a nationally recognized standard or protocol for evaluating flood penetration seal performance. In response, the staff of the U.S. Nuclear Regulatory Commission’s Office of Nuclear Regulatory Research conducted a research project to investigate how flood penetration seal performance might be evaluated. The research comprised three phases: (1) profiling the flood penetration seals currently used in U.S. NPPs, (2) developing a draft ex situ performance testing protocol, and (3) performing limited testing of several seal types and applications to evaluate and refine the testing protocol. The performance testing protocol developed in this project provides the NRC staff and other interested parties with information on how to evaluate flood penetration seal performance in a laboratory setting. The limited performance testing conducted also provides insights into the general performance of various flood penetration seal designs under anticipated flooding conditions.

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