U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG/CR-7279
INL/EXT-19-56427

Research to Develop Flood Barrier Testing Strategies for Nuclear Power Plants

Office of Nuclear Regulatory Research

AVAILABILITY OF REFERENCE MATERIALS IN NRC PUBLICATIONS

NRC Reference Material

As of November 1999, you may electronically access NUREG-series publications and other NRC records at the NRC's Library at www.nrc.gov/reading-rm.html. Publicly released records include, to name a few, NUREG-series publications; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigative reports; licensee event reports; and Commission papers and their attachments.

NRC publications in the NUREG series, NRC regulations, and Title 10, "Energy," in the *Code of Federal Regulations* may also be purchased from one of these two sources:

1. **The Superintendent of Documents**
   U.S. Government Publishing Office
   Washington, DC 20402-0001
   Internet: www.bookstore.gpo.gov
   Telephone: (202) 512-1800
   Fax: (202) 512-2104

2. **The National Technical Information Service**
   5301 Shawnee Road
   Alexandria, VA 22312-0002
   Internet: www.ntis.gov
   1-800-553-6847 or, locally, (703) 605-6000

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

Address: **U.S. Nuclear Regulatory Commission**
Office of Administration
Digital Communications and Administrative Services Branch
Washington, DC 20555-0001
E-mail: distribution.resource@nrc.gov
Facsimile: (301) 415-2289

Some publications in the NUREG series that are posted at the NRC's Web site address www.nrc.gov/reading-rm/doc-collections/nuregs are updated periodically and may differ from the last printed version. Although references to material found on a Web site bear the date the material was accessed, the material available on the date cited may subsequently be removed from the site.

Non-NRC Reference Material

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at—

The NRC Technical Library
Two White Flint North
11545 Rockville Pike
Rockville, MD 20852-2738

These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute
11 West 42nd Street
New York, NY 10036-8002
Internet: www.ansi.org
(212) 642-4900

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG/CR-7279
INL/EXT-19-56427

Research to Develop Flood Barrier Testing Strategies for Nuclear Power Plants

Manuscript Completed: March 2021
Date Published: February 2022

Prepared by:
Z. Ma[1]
S. Zhang[1]
C. Pope[2]
C. Smith[1]

[1]Idaho National Laboratory
P.O. Box 1625
Idaho Falls, ID 83415

[2]Idaho State University
921 South 8th Avenue
Pocatello, Idaho 83209

T. Aird, NRC Project Manager

Office of Nuclear Regulatory Research

ABSTRACT

This report presents results of research performed by Idaho National Laboratory (INL) for the Nuclear Regulatory Commission (NRC) to identify and develop strategies for testing nuclear power plant (NPP) flood barriers. This research project began with a literature review that documented the results of previous NRC-funded research, work performed by other government agencies, reports generated by industry organizations, NRC licensee submittals, information from testing facilities, and information from commercial firms engaged in NPP decommissioning. This literature review was then used to develop a simplified flood protection categorization scheme and related glossaries. Using this categorization scheme and glossaries, a survey of currently used flood barriers was conducted, focusing on both permanent and temporary flood barriers. External flood barriers such as levees and berms were outside the scope of this survey. This research project also assessed the current state of NPP decommissioning for potential flood barrier harvesting opportunities, surveyed capabilities of domestic and international flood testing facilities, and explored technical challenges to harvesting and testing of flood barriers. Other factors that should be considered in developing flood barrier testing strategies were also explored and are documented in this report (e.g., selection of flood barriers for testing, codes and standards for flood barrier testing, potential alternatives to harvesting such as in-situ testing, testing performance criteria, and testing parameters).

TABLE OF CONTENTS

ABSTRACT ... **iii**

LIST OF FIGURES ... **vii**

LIST OF TABLES ... **ix**

ACKNOWLEDGMENTS ... **xi**

ABBREVIATIONS AND ACRONYMS ... **xiii**

1 INTRODUCTION ... **1-1**

1.1 Background ... 1-1
1.2 Objective ... 1-2
1.3 Research Approach and Scope ... 1-3
1.4 Outline ... 1-3

2 FLOOD BARRIER CATEGORIZATION AND TERMINOLOGY ... **2-1**

2.1 Categorization ... 2-1
2.2 Glossary ... 2-3

3 LITERATURE REVIEW ... **3-1**

3.1 U.S. Nuclear Regulatory Commission ... 3-1
3.1.1 Regulatory Guide 1.102 ... 3-1
3.1.2 Interim Staff Guidance JLD-ISG-2012-05 ... 3-1
3.1.3 NUREG-2240 ... 3-1
3.1.4 Materials Related to Fire Barriers or Fire Tests ... 3-2
3.2 Nuclear Energy Institute ... 3-2
3.3 Electric Power Research Institute ... 3-3
3.3.1 EPRI 30020054230F ... 3-3
3.3.2 EPRI Presentation on External Flood Seal Risk-Ranking Process ... 3-3
3.4 U.S. Army Corps of Engineers Engineer Research and Development Center ... 3-3
3.4.1 ERDC/CHL TR-15-3 ... 3-3
3.4.2 ERDC TR-07-3 ... 3-4
3.5 Nuclear Energy Agency ... 3-4
3.6 Center for Nuclear Waste Regulatory Analyses ... 3-4
3.7 Nuclear Plant Flooding Walkdown Reports ... 3-4
3.8 FM Approvals ... 3-5
3.9 Materials from Miscellaneous Sources ... 3-6

4 FLOOD BARRIER OVERVIEW ... **4-1**

4.1 On-Site Permanent Flood Barriers ... 4-1
4.1.1 Penetration Seals ... 4-1
4.1.2 Doors 4-5
4.2 On-Site Temporary Flood Barriers ... 4-6

4.2.1 Disposable 4-7
4.2.2 Reusable 4-7

5 POTENTIAL FLOOD BARRIER TESTING FACILITIES 5-1

5.1 Operating Nuclear Power Reactors 5-1
5.2 Decommissioning Nuclear Power Reactors 5-1
5.3 Decommissioning Plant Site Visit 5-5
5.4 U.S. Flood Testing Facilities 5-8
5.4.1 Idaho State University Flood Testing Facility 5-8
5.4.2 Framatome Testing Facility 5-13
5.4.3 Oregon State University Hinsdale Wave Research Laboratory 5-14
5.4.4 USACE ERDC Coastal and Hydraulics Laboratory 5-16
5.5 International Flood Testing Facilities 5-20
5.5.1 China Institute of Water Resources and Hydropower Research 5-20
5.5.2 Electricité De France 5-21
5.5.3 Central Research Institute of Electric Power Industry (Japan) 5-22

6 DEVELOPING FLOOD BARRIER TESTING STRATEGIES 6-1

6.1 Testing Strategies 6-1
6.1.1 Selection of Flood Barriers for Testing 6-1
6.1.2 Type of Flood Barriers for Testing 6-1
6.1.3 Codes and Standards for Flood Barrier Tests 6-2
6.1.4 Protocols and Plans for Flood Barrier Tests 6-2
6.2 Previous Test Examples 6-4
6.2.1 Previous Test 1 6-4
6.2.2 Previous Test 2 6-5
6.2.3 Previous Test 3 6-6
6.2.4 Previous Test 4 6-7
6.2.5 Summary of Flood Barrier Test Examples 6-8
6.3 Flood Barrier Testing Strategies Workshop 6-10

7 SUMMARY 7-1

8 REFERENCES 8-1

APPENDIX A ADDITIONAL FLOOD PROTECTION FEATURES A-1

APPENDIX B IN-DEPTH REVIEW OF FLOODING WALKDOWN REPORTS OF FIVE NUCLEAR POWER PLANTS B-1

APPENDIX C SUMMARY OF FM APPROVAL STANDARD 2510 .... C-1

LIST OF FIGURES

Figure 2-1 Flood Protection Feature Categorization 2-2
Figure 2-2 Taxonomy of On-Site Flood Protection Features 2-3
Figure 4-1 Wedge Seal [37] 4-2
Figure 4-2 Vulcanizing Foam Seal [38] 4-3
Figure 4-3 Hinged Barrier [39] 4-5
Figure 4-4 Absorbent Pad [40] 4-7
Figure 4-5 Door Flood Gate [41] 4-8
Figure 4-6 Steel Flood Logs [42] 4-8
Figure 4-7 AquaDam® Used in Fort Calhoun Station During the 2011 Flood Event [43] 4-9
Figure 4-8 Hydrostatic Tarp [44] 4-9
Figure 4-9 Portadam® [45] 4-10
Figure 4-10 Modular Plastic Barrier [46] 4-10
Figure 4-11 Sand Barrier Used in Fort Calhoun Station During the 2011 Flood Event [43] 4-11
Figure 4-12 Sand Barrier [47] 4-11
Figure 5-1 Map of U.S. Operating Commercial Nuclear Power Reactors [48] 5-1
Figure 5-2 Map of U.S. Decommissioning Nuclear Power Reactors [50] 5-3
Figure 5-3 Hallway in the EDG Room *(Courtesy of Oyster Creek NPP)* 5-5
Figure 5-4 Access to the Cable Tunnel in the EDG Room *(Courtesy of Oyster Creek NPP)* 5-6
Figure 5-5 Floor Drain in the EDG Enclosure *(Courtesy of Oyster Creek NPP)* 5-6
Figure 5-6 Penetration Seals into the EDG Enclosure *(Courtesy of Oyster Creek NPP)* 5-7
Figure 5-7 Penetrations in the Reactor Building *(Courtesy of Oyster Creek NPP)* 5-7
Figure 5-8 More Penetrations in the Reactor Building *(Courtesy of Oyster Creek NPP)* 5-8
Figure 5-9 ISU Flood Testing Facility PET tank – Backside [34] 5-9
Figure 5-10 ISU Flood Testing Facility PET tank - Front side, with Modular Wall and Inserted Door Barrier [34] 5-9
Figure 5-11 ISU Flood Testing Facility Pump System 1 - Inlet [34] 5-10
Figure 5-12 ISU Flood Testing Facility Pump System 1 [34] 5-10
Figure 5-13 ISU Flood Testing Facility Pump System 1 - 3-Channel Path at the Outlet [34] 5-11
Figure 5-14 ISU Flood Testing Facility Pump System 2 [34] 5-11
Figure 5-15 ISU Flood Testing Facility Pump System 2 - Inlet/Outlet Channels [34] 5-12

Figure 5-16 Flood Testing of a Hollow Door Barrier at ISU flood Testing Facility [34] 5-12
Figure 5-17 Generic Illustration of Framatome Test Apparatus [5] 5-13
Figure 5-18 A Test Deck with Penetration Seal Installed [5] 5-13
Figure 5-19 OSU HWRL Directional Wave Basin [52] 5-14
Figure 5-20 OSU HWRL Tsunami Simulations Using the Directional Wave Basin [52] 5-15
Figure 5-21 OSU HWRL Large Wave Flume [53] 5-15
Figure 5-22 OSU HWRL Flume-Wave Maker [53] 5-16
Figure 5-23 USACE ERDC CHL 10-ft Wave Flume [54] 5-17
Figure 5-24 USACE ERDC CHL Field Research Facility [54] 5-18
Figure 5-25 USACE ERDC CHL CRAB Vessel [54] 5-18
Figure 5-26 USACE ERDC CHL Levee Breach and Hydraulic Facility [54] 5-19
Figure 5-27 China IWHR Main Facility [56] 5-20
Figure 5-28 EDF LNHE Test Loop [57] 5-21
Figure 5-29 Japan CRIEPI Large-Scale Tsunami Physical Simulator [62] 5-23
Figure 6-1 Initial PET Piping Configuration [33] 6-6
Figure A-1 Permanent Manual Barrier [39] A-1
Figure A-2 Membrane Barriers [68] A-2
Figure A-3 Canal Gate [69] A-2
Figure A-4 Hydraulically Activated Barrier [70] A-3
Figure A-5 Airbrick® [71] A-4
Figure A-6 Aquafragma® [72] A-4
Figure A-7 French Drain [73] A-6
Figure B-1 Statistics of Seal Type Flood Barriers in the Reference Plant B-2
Figure B-2 Statistics of Structural Element Type Flood Barriers in the Reference Plant B-3
Figure B-3 Inspection Observations of Flood Barriers in the Reference Plant B-4
Figure B-4 Evaluation Results of Flood Barriers Not Immediately Judged Acceptable B-5
Figure B-5 Statistics of Degraded Flood Barriers Identified During Walkdown B-6
Figure B-6 Statistics of Failed Flood Barriers Identified During Walkdown B-6

LIST OF TABLES

Table 4-1 Categorization Criteria for Common Flood Penetration Seals at NPPs....................4-2
Table 4-2 Common Failure Modes of Flood Penetration Seals at NPPs.................................4-4
Table 4-3 Categorization Criteria for Common Flood Watertight Doors at NPPs 4-6
Table 5-1 Power Reactor Sites Undergoing Decommissioning 5-3
Table 6-1 Comparison of Reviewed Flood Barrier Testing Strategies in Previous Example Tests...6-9
Table A-1 Taxonomy of On-Site Flood Protection Features A-8
Table A-2 Flood Protection-Related Terminology.. A-9
Table B-1 Flood Protection Features Credited in the Reference Plant B-2
Table B-2 Flood Barrier Degradation Modes Identified During Walkdown B-5
Table B-3 Flood Barrier Failure Modes Identified During Walkdown B-5
Table B-4 Performance Metrics of Flood Barriers Inspected During Walkdown B-7
Table C-1 General Component and Material Testing Requirements in ANSI FM 2510 [31]... C-2
Table C-2 Performance Testing Requirements for Opening Barriers in ANSI FM 2510 [31]... C-4
Table C-3 Performance Testing Requirements for Perimeter Barriers in ANSI FM 2510 [31]... C-5

ACKNOWLEDGMENTS

The authors wish to thank Thomas Aird, Joseph Kanney, and Meredith Carr of the U.S. Nuclear Regulatory Commission (NRC) for developing the project scope, providing technical input, and project management. Mike Lee and Nebiyu Tiruneh from the NRC also provided insightful comments and suggestions on the report. Support from the Component Flooding Evaluation Laboratory at Idaho State University and associated students Benjamin Farley, Kean Martinic, and Patience Lamb is greatly appreciated. FM Approvals kindly reviewed and authorized the inclusion of the summary of ANSI FM 2510 provided in Appendix C. Timothy Schmitt of Framatome also kindly reviewed the section on the Framatome facility in Lynchburg, Virginia. Finally, the authors acknowledge the management review from Michael Calley and technical editing from John Shaver and Katherine Stokes at Idaho National Laboratory.

ABBREVIATIONS AND ACRONYMS

ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
CDI	Comprehensive Decommissioning International
CFR	Code of Federal Regulations
CHL	(ERDC) Coastal and Hydraulics Laboratory
CNWRA	Center for Nuclear Waste Regulatory Analyses
CRAB	Coastal Research Amphibious Buggy
CRIEPI	Central Research Institute of Electric Power Industry
CSNI	(NEA) Committee on the Safety of Nuclear Installations
DBFL	design basis flooding level
DM	degradation mode
EDF	Electricité De France
EDG	emergency diesel generator
EPRI	Electric Power Research Institute
ERDC	(U.S. Army Corps of Engineers) Engineer Research and Development Center
ESP	early site permit
FEMA	Federal Emergency Management Agency
FM	failure mode
FRM	Fire Risk Management, Inc. (now Fisher Engineering)
GDC	general design criterion
gpm	gallons per minute
HDI	Holtec Decommissioning International
HWRL	Hinsdale Wave Research Laboratory
IAEA	International Atomic Energy Agency
IAHR	International Association for Hydro-Environmental Engineering and Research
IEEE	Institute of Electrical and Electronics Engineers
IN	information notice
INL	Idaho National Laboratory
IPEEE	Individual Plant Examination of External Events
ISFSI	independent spent fuel storage installation
ISG	interim staff guidance
ISU	Idaho State University
IWHR	Institute of Water Resources and Hydropower Research
LARC	Lighter Amphibious Resupply Cargo
LER	licensee event report
LNHE	National Laboratory of Hydraulics and Environment
NEA	(OECD) Nuclear Energy Agency
NEI	Nuclear Energy Institute

NMSS	Nuclear Material Safety and Safeguards
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NSSS	nuclear steam supply system
OECD	Organization for Economic Cooperation and Development
OSU	Oregon State University
PET	portal evaluation tank
PFHA	probabilistic flood hazard assessment
PRA	probabilistic risk assessment
PWR	pressurized water reactor
SAFB	self-activating flood barrier
SDP	significance determination process
SSC	structures, systems, and components
UL	Underwriters Laboratories
U.S.	United States
USACE	U.S. Army Corps of Engineers

1 INTRODUCTION

1.1 Background

The U.S. Nuclear Regulatory Commission (NRC) has developed regulations regarding the siting and design of nuclear power plants (NPPs) aimed at providing safety from various natural hazards, including flooding. Design criteria for NPPs with respect to natural hazards are provided in the appropriate sections of 10 CFR Parts 50 and 52. Reactor site criteria are provided in 10 CFR Part 100.

The regulatory requirement for protection of structures, systems, and components (SSCs) important to safety against natural phenomena is provided in 10 CFR Part 50 Appendix A, General Design Criterion (GDC) 2 "Design bases for protection against natural phenomena". GDC-2 states that SSCs important to safety shall be designed to withstand the effects of 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. The regulation also states that the design bases shall reflect appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena.

10 CFR Part 52 provides the requirements for the contents of applications for new reactors. Specifically, 10 CFR Part 52.17(a)(1)(vi), for early site permits (ESPs) and 10 CFR Part 52.79 (a)(1)(iii), for combined licenses are related to the hydrologic characteristics of the proposed site with appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area and with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated.

Reactor siting criteria are provided in 10 CFR Part 100. The requirements to consider physical site characteristics (including hydrologic features) in site evaluations are specified in 10 CFR Part 100.10(c) for applications before January 10, 1997, and 10 CFR Part 100.20(c) for applications on or after January 10, 1997.

Flood barriers are designed to prevent water from entering NPP areas containing SSCs important to safety. They are used along with drains, sumps, pumps, valves, plugs, and site grading as part of the plant protection against external or internal flooding and to mitigate the effects of flooding on NPP operations. Flood barriers can be on-site or off-site, permanent or temporary, active or passive. Permanent flood barriers include external and internal walls, watertight doors, and flood penetration seals in external and/or internal walls that allow pipes, cables, conduit, cable trays, ducts, etc. to pass between different areas of the plant. Temporary flood barriers include sandbags, temporary walls, removable doors, and stop-logs.

Performance of flood protection features, including flood barriers at NPPs, has long been an ongoing safety concern. Domestic and international operational experience provides clear indications that flood barrier performance has significant safety implications, especially as a reactor fleet ages. NPPs have submitted a number of Licensee Event Reports (LERs) containing information related to flood barriers (e.g., LER 50-313/2014-001-00, LER 50-410/1989-002-01), and NRC has issued Information Notices (INs) on flood barrier performance (e.g., IN-88-60, IN-07-01, IN-15-01). Section 4.3 of NUREG-1742, "Perspective Gained from the Individual Plant Examination of External Events (IPEEE) Program" [1] [2] further highlights some flood-related protection measures proposed by licensees. NUREG-1742 also presented multiple

plant enhancements that were conducted by licensees on flood protection features including flood barriers, for example, upgraded flood-resistant doors, provision for sandbags, sealing of conduits, refurbishment of existing flood wall and stop logs, addition of a seiche (oscillatory wave action) protection barrier to protect diesel generator fuel oil transfer pumps from flooding, improved penetration seals and door seals to protect against potential flooding. On the other hand, post-Fukushima walkdowns of U.S. NPP flood protection features and procedures resulted in a number of inspection findings related to flood penetration seals which were evaluated through NRC's Significance Determination Process (SDP). Deficiencies observed in flood barrier performance include, but are not limited to, the following:

- Inadequate flood barrier design or installation
- Flood barriers rendered non-functional due to aging and degradation
- Inadequate inspection procedures or acceptance criteria for detecting deficient flood barriers
- Deficient analyses associated with flood barriers
- Discrepancies between tested flood barrier designs and plant-installed designs
- Installed barriers modified but not evaluated or tested
- Deficient flood barriers due to lack of fill or being composed of non-watertight materials
- Missing penetration seals or internal conduit seals.

The observed deficiencies shown above highlight that flood barriers should be designed and installed properly, and also be adequately tested, inspected, and maintained in order to perform their intended functions in the event of flooding.

Probabilistic risk assessment (PRA) modeling provides industry and the NRC with analytical tools for addressing the risk-significance of flood barrier performance but inputs such as basic performance/reliability data on in-service components is lacking. Previous NRC research in this area has focused on developing a protocol for the laboratory testing of flood penetration seals, one of the most common forms of flood barrier. Limited testing was performed using a small number of newly installed seals in penetration and penetrant combinations to evaluate the draft protocol but not to develop performance data on the seals themselves.

This research report reviews available information on flood barriers employed at U.S. NPPs, identifies and evaluates the options available, and presents potential strategies for testing NPP flood barriers. It should be noted that the mention of specific brand names or trade names in this report does not signify recommendation or endorsement by Idaho National laboratory (INL) or NRC.

1.2 Objective

The objective of this research was to identify and assess options and develop strategies for testing NPP flood barriers. Specific topics to be investigated were:

1. The current state of NPP decommissioning, as it impacts opportunities and challenges for harvesting, or acquiring and gathering flood barriers

2. Technical and/or logistical considerations and challenges to harvesting and the laboratory testing of flood barrier components
3. Potential alternatives to harvesting, such as in-situ testing and/or enhanced inspection (note: the phrase “enhanced inspection” in this report refers to examinations of specimens generally and is not referring to regulatory inspections or other NRC oversight processes).
4. Other technical and/or logistical considerations in developing flood barrier testing strategies.

1.3 Research Approach and Scope

This research started with the review of available information on flood barriers employed at U.S. NPPs. This information was derived from previous NRC research; industry activities conducted by the Nuclear Energy Institute (NEI), the Electric Power Research Institute (EPRI), etc.; NPP decommissioning activities; activities of other government agencies such as the U.S. Army Corps of Engineers (USACE) and the Federal Emergency Management Agency (FEMA); as well as summaries of international practices and guidance compiled by the Organization for Economic Cooperation and Development Nuclear Energy Agency Committee on the Safety of Nuclear Installations (OECD/NEA/CSNI).

The research identified and evaluated the options available, presenting potential strategies for testing NPP flood barriers, along with the advantages and disadvantages of each strategy. The research then presented information that may be useful for developing testing strategies (e.g., prospects for harvesting, in-situ non-destructive testing or enhanced inspection, in-site destructive testing, and ex-situ testing).

This research focused on permanent flood barriers (e.g., penetration seals and watertight doors) and temporary flood barriers incorporated into the plant (e.g., removable walls). External flood barriers such as levees and berms were outside the scope of this research.

1.4 Outline

Section 2 of this NUREG/CR report categorizes NPP flood barriers and flood protection features and defines key terms used in this research. Section 3 reviews the literature compiled for this research. Section 4 gives an overview of flood barriers. Section 5 surveys potential flood barrier testing facilities which include the U.S. operating NPPs, decommissioning NPPs, as well as domestic and international testing facilities. Section 6 provides flood barrier testing strategies identified in this research as well as a summary of a public workshop on flood barrier testing strategies at NRC Headquarters in Rockville, Maryland, via a webinar as well, on March 12, 2020. Section 7 summarizes the report itself.

2 FLOOD BARRIER CATEGORIZATION AND TERMINOLOGY

This report focuses on flood barriers, often viewed as a subset of flood protection features. This section intends to categorize flood protection features at NPPs and explain the relationship between flood protection features and flood barriers. Section 2.1 proposes a categorization of flood protection features based on comparing and integrating information from the reviewed literature. Section 2.2 defines the terminology used in this report.

2.1 Categorization

Currently, no widely used standard definitions or categories exist for flood protection features. Various references reviewed for this project (see Section 3) define and categorize flood protection features in different but overlapping ways. A comparison of these categorizations led to the following observations:

- The terms “protection feature,” “protective measure,” and “protection method” are often used interchangeably. “Protection feature” is used by NRC and NEI, “protective measure” by NEA, and “protection method” by The U.S. Army Engineer Research and Development Center (ERDC). The terms could also have slightly different meanings for some users, e.g., “protection feature” could refer to an actual physical structure or system that protects NPPs from flooding, “protection measure” refers to an action or a procedure to be implemented to provide protection against flooding, while “protection method” for a process or planned set of approved actions that could be used to prevent flooding or mitigate the flooding impacts.
- The term “flood protection” can be understood in different ways. For example, some references use “flood protection” and “mitigation” to refer to two distinct but parallel sets of features: “flood protection” encompasses features and/or procedures designed to prevent flooding and is used to mean “flood prevention”; “flood mitigation” encompasses features, procedures, and actions relied upon when a flood event occurs and flood prevention fails, proves inadequate, or is otherwise not available. Other references may use the term “flood protection” to mean flood prevention and mitigation combined. In this report, “flood protection feature” is used as the term that refers to the features (including related procedures and human actions) designed and maintained to protect (prevent or mitigate) SSCs important to safety from external or internal flooding and the effects thereof.
- In the reviewed literature, no explicit distinction is made between “flood barrier” and “flood protection (or protective) feature (or measure/method).” Also, a categorization scheme of flood protection features (i.e., exterior, incorporated, and/or temporary) is adopted in most of the reviewed literature.

By comparing and integrating the categorizations found in the reviewed literature, this report uses a simplified categorization of flood protection features (see Figure 2-1), in accordance with the following assumptions and explanations:

- “Flood protection features” refers to features (including related procedures and human actions) that either prevent or mitigate flooding at NPPs. “Flood barriers” are a subset of “flood protection features,” and flood barriers at NPPs are the focus of this research.
- “On-site” and “off-site” are used in this report as part of the flood feature/barrier categorization. “Incorporated barriers” and “exterior barriers” (refer to the Section 2.2 Glossary) are not explicitly listed in the simplified categorization. On-site permanent barriers can be either incorporated barriers or exterior barriers.

- “Dry site” is not taken as a standalone category or used in this report. Instead, it is a term used in the reviewed literature that determines the selection of flood protection features at NPPs (e.g., exterior features may not apply to a dry site).
- Flood barriers can be on-site or off-site, permanent or temporary, active or passive, incorporated or exterior. While flood barriers such as hinged doors are categorized as active, most are passive. Some types of flood barriers such as berms can be either on-site or off-site.
- This research focuses on on-site permanent flood barriers (e.g., penetration seals and watertight doors) and on-site temporary flood barriers incorporated into the plant (e.g., removable walls).
- Off-site flood barriers and on-site temporary flood barriers not incorporated into the plant are not a focus of this research.

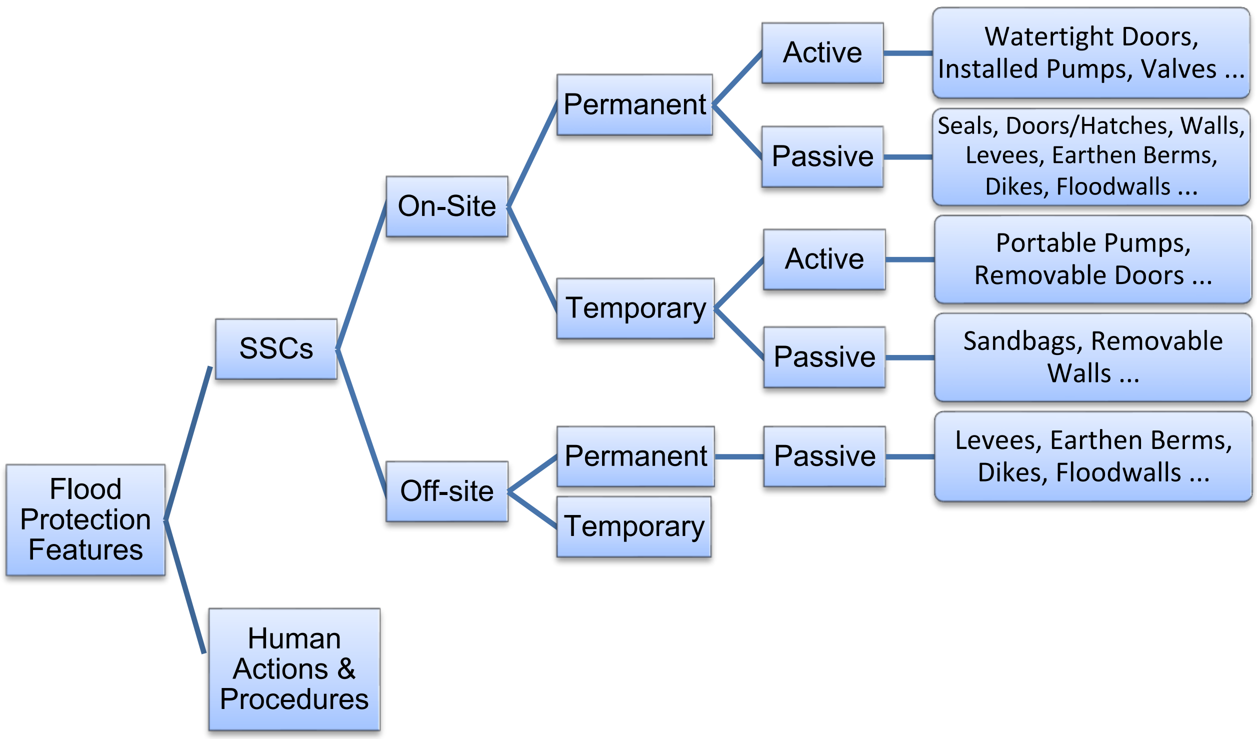

Figure 2-1 Flood Protection Feature Categorization

A taxonomy for on-site flood protection features is provided in Figure 2-2, highlighting the diverse range of features available and how they can be subcategorized. In this taxonomy, flood protection features are categorized as flood barriers if they are devices that enclose a particular area to ensure it stays dry (examples include Anti-flood Airbrick®, Aquafragma®, mechanical boots, and absorbent dams). Flood protection features are categorized as mitigative conveyance drains if they are devices that redirect water flow away from a facility to ensure it remains dry (such as ejector pumps, flap checks, and drain plugs). Circumstantial flood-

affecting structures are those features (such as doors and stairs) not intended for flood prevention but which can mitigate internal flood levels in an NPP. A more detailed look at flood protection features is provided in Section 4 (for penetration seals and on-site temporary flood barriers) and Appendix A (for other types of flood barriers, mitigative conveyance drains, and circumstantial flood-affecting structures).

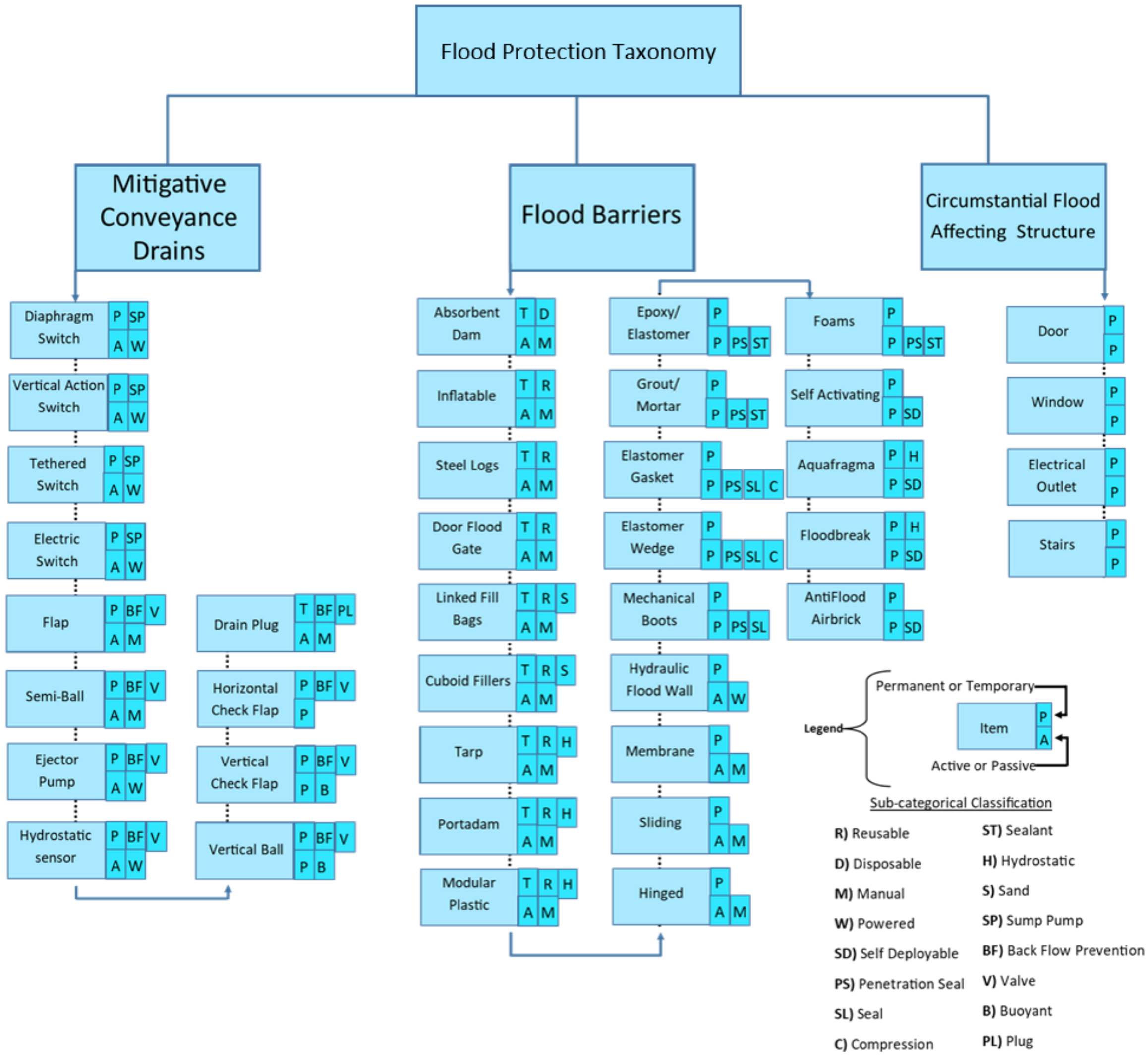

Figure 2-2 Taxonomy of On-Site Flood Protection Features

2.2 Glossary

Active Flood Protection Feature – An incorporated, exterior, or temporary flood protection feature that requires the change of a component's state, depends on external energy inputs (actuation, mechanical movement, or power supply), or needs human action to provide its intended flood protection function. Examples include flood doors (e.g., watertight doors), sump

pumps, portable pumps, isolation and check valves, and flood detection devices (e.g., level switches).

Controlled Area – An area outside a restricted area of a nuclear facility but within the site boundary, to which the licensee can limit access for any reason. This term is defined in the NRC Glossary https://www.nrc.gov/reading-rm/basic-ref/glossary.html.

Decommissioning – The process of safely closing an NPP (or other facility where nuclear materials are handled) to retire it from service after its useful life has ended. This process primarily involves decontaminating the facility to reduce residual radioactivity, then releasing the property for unrestricted or (under certain conditions) restricted use. This often includes dismantling the facility or dedicating it for other purposes. Decommissioning begins after the nuclear fuel, coolant, and radioactive waste are removed. This term is defined in the NRC Glossary https://www.nrc.gov/reading-rm/basic-ref/glossary.html.

DECON (or Dismantling) – A method of reactor decommissioning in which SSCs that contain radioactive contamination are removed from a site and safely disposed of at a commercially operated low-level waste disposal facility, or decontaminated to a level that permits the site to be released for unrestricted use. This term is defined in the NRC Glossary https://www.nrc.gov/reading-rm/basic-ref/glossary.html.

Exclusion Area – The reactor's surrounding area, for which the reactor licensee has the authority to determine all activities, including the exclusion or removal of personnel and property from the area. This term is defined in the NRC Glossary https://www.nrc.gov/reading-rm/basic-ref/glossary.html.

Exterior Barriers – Engineered features external to the immediate plant area, for example, levees, seawalls or floodwalls.

Flood-Associated Effects – Characteristics of a flood event that include such factors as hydrostatic loading, hydrodynamic loading (water velocities, debris, etc.), wind waves, effects of sediment deposition and erosion, clogging due to debris, and groundwater ingress.

Flood Barrier – A device, structure, or emplaced material designed to ensure that protected areas stay dry by preventing/mitigating leakage of water into those areas. Flood barriers may be either permanent or temporary and may be designed to operate actively or passively. Flood barriers may be incorporated or exterior as well as on-site or off-site.

Flood Protection Features – Engineered passive or active features (including related procedures and human actions) designed and maintained to protect (prevent or mitigate) SSCs important to safety from external or internal flooding and the effects thereof. Flood protection features can be on-site or off-site, permanent or temporary, passive or active, incorporated or exterior, preventive or mitigative. Similar terms include "flood protective features," "flood protective measures," "flood protection methods," etc.

Incorporated Barriers – Engineered features in the structure/environment interface, for example, walls, doors, and hatches.

On-Site – An informal term that refers to the immediate area(s) surrounding NPP main structures such as reactor buildings, control buildings, auxiliary buildings, fuel buildings, turbine buildings, and switchyards. It is not directly related to the terms "exclusion area," "restricted area," and "control area" but could be thought of as part of the control area, or the restricted area plus the turbine building and switchyard.

Off-Site – An informal term that refers to any area outside of the immediate area surrounding the NPP main structures.

Passive Flood Protection Feature – An incorporated, exterior, or temporary flood protection feature that does not depend on external energy inputs (actuation, mechanical movement, or power supply), does not require components to change their states, and does not need human action to provide its intended flood protection function. It is generally independent of the duration of a flooding event. Examples include walls, floors, penetration seals, structures, removable wall and roof panels, drains, sumps, basins, yard drainage systems, temporary watertight barriers, dikes, berms, barriers exterior to the immediate plant area that is under licensee control, and cork seals.

Penetration Seals– Devices or materials used to protect against water leakage through penetrations in a structural wall, ceiling, or floor.

Permanent Flood Protection Features – Flood protection features that are permanently installed or incorporated into the plant or the area (either on-site or off-site).

Restricted Area – Any area of a nuclear facility to which access is controlled for protecting individuals from exposure to radiation and radioactive materials. This term is defined in the NRC Glossary https://www.nrc.gov/reading-rm/basic-ref/glossary.html.

SAFSTOR (or Safe Storage) – A method of reactor decommissioning in which a nuclear facility is placed and maintained in a condition that allows the facility to be safely stored and subsequently decontaminated (deferred decontamination) to levels that permit release for unrestricted use. It is a long-term storage condition for a permanently shut-down nuclear power plant. During SAFSTOR, radioactive contamination decreases substantially, making subsequent decontamination and demolition easier and reducing the amount of low-level waste requiring disposal. This term is defined in the NRC Glossary https://www.nrc.gov/reading-rm/basic-ref/glossary.html.

Temporary Flood Protection Features – Flood protection features that are only used for a limited (temporary) period to protect SSCs from flooding and the effects thereof. Temporary features are usually implemented to prevent floodwater from reaching NPP sites or SSCs (e.g., sandbags and removable walls) but can also be used for flood mitigation (e.g., portable pumps).

3 LITERATURE REVIEW

This section surveys the literature compiled for this research, including information on flood barriers employed at U.S. NPPs submitted to NRC by licensees; industry activities conducted by NEI, EPRI, etc.; NPP decommissioning activities; information from other government agencies such as USACE; international practices and guidance compiled by OECD/NEA/CSNI, etc.

3.1 U.S. Nuclear Regulatory Commission

3.1.1 Regulatory Guide 1.102

Regulatory Guide 1.102 [3], "Flood Protection for Nuclear Power Plants" describes various types of flood protection for SSCs important to safety. In this regulatory guide, the types of flood protection acceptable by NRC include dry site (i.e., a plant built above its design basis flooding level, whether due to natural terrain or engineered fill. Note that "dry site" should not be taken literally as a flood risk-free site), exterior barriers (i.e., engineered features external to the immediate plant area), and incorporated barriers (i.e., engineered features in the structure/environment interface). The guide also specifies that temporary barriers are usually not acceptable for construction permit issuance, unless specific after-construction circumstances provide strong justification.

3.1.2 Interim Staff Guidance JLD-ISG-2012-05

Japan Lessons-Learned Project Directorate Interim Staff Guidance, "Guidance for Performing the Integrated Assessment for External Flooding" (JLD-ISG-2012-05) [4], includes both flood protection and mitigation in the scope of its integrated assessment. Methods of flood protection at NPPs are often described in terms of physical features (i.e., incorporated, exterior, or temporary features—each subcategorized as active or passive), manual actions performed by plant personnel (e.g., construction or installation of physical features), and associated procedures. Flood mitigation, which can be viewed as a consecutive phase to flood prevention, refers to the capability of an NPP to maintain key safety functions given insufficient or failed flood protection. This guidance also clarifies the relationship between "flood protection system" and "flood protection feature," meaning that a plant may have multiple flood protection systems, each of which potentially consists of a set of flood protection features.

3.1.3 NUREG-2240

NUREG-2240, "Flood Penetration Seal Testing Protocol Research" [5], focuses on a specific type of flood protection (i.e., flood penetration seals). It provides a summary of NPP flood penetration seal types, sizes, and applications, and it demonstrates the development of a testing protocol for seal performance evaluation. The draft test protocol's feasibility was demonstrated through a trial series of water pressure tests. These research efforts were conducted by the primary contractor, Fire Risk Management, Inc., with NRC input. The contractor's work on profiling flood penetration seals and developing test protocol are documented in [6] and [7], respectively.

3.1.4 Materials Related to Fire Barriers or Fire Tests

Besides focusing on flood barriers, the literature review also included several NRC documents associated with fire barriers or fire tests that could include useful information for this project such as pressure testing standards and protocols for penetration seals:

- NUREG/CR-0152, "Development and Verification of Fire Tests for Cable Systems and System Components" [8]; fire test parameters include burner variables (e.g., burner location, fuel input rate, fuel-air ratio, etc.), test cell size and configuration, and cable materials.
- NUREG/CR-2377, "Tests and Criteria for Fire Protection of Cable Penetrations" [9], provides experiment parameters and results for cable penetrations installed in fire-resistive walls.
- NUREG-1552, "Fire Barrier Penetration Seals in Nuclear Power Plants" [10], introduces test methods and acceptance criteria for NPP fire barrier penetration seals as well as information on fire barrier penetration seal installation, surveillance, maintenance, and repair.

3.2 Nuclear Energy Institute

NEI 12-07, "Guidelines for Performing Verification Walkdowns of Plant Flood Protection Features," Revision 0-A [11], is endorsed by NRC and, as with report JLD-ISG-2012-05 [4], categorizes physical flood protection features as incorporated, exterior, or temporary before subcategorizing them as either active or passive. This guidance adopts "flood protection feature" to mean a feature that protects against or mitigates flood effects. It also provides examples of different categories of features, as shown below:

Examples of incorporated or exterior passive features:

- Earthen features (i.e., a flood protection berm)
- Concrete and steel structures
- Wall, ceiling, and floor seals
- Passive flood barriers or water diversion structures
- Drains and catch basins
- Plugs and manhole covers
- Drainage pathways
- Piping and cable vaults and tunnels, electrical cable conduit
- Floor hatches.

Examples of incorporated or exterior active features:

- Watertight or non-watertight doors
- Pumps
- Water level indication.

Examples of temporary features:

- Portable passive flood barriers
- Portable active pumps.

3.3 Electric Power Research Institute

3.3.1 EPRI 3002005423[1]

EPRI 3002005423, "Flood Protection Systems Guide" [12], describes common flood protection components at NPPs and the design, testing, inspection, and maintenance of these components based on information collected from a consensus of industry peers. The report presents a comprehensive listing of flood protection components and an overview of their functions and applications. Available testing methods, acceptance criteria, and design considerations are provided, with particular attention given to flood penetration seals. The report states that, although testing for valves, drainage, piping, and pumps is covered by established industry codes and standards, there are currently no codes or standards addressing protocol for qualifying flood penetration seals. The report also provides recommendations for the inspection, testing, and maintenance of flood protection features.

3.3.2 EPRI Presentation on External Flood Seal Risk-Ranking Process

EPRI presented its "External Flood Seal Risk-Ranking Process" [13] at the 4th Annual Probabilistic Flood Hazard Assessment Workshop hosted by NRC in 2019. With several hundred penetration seals in a given NPP, this presentation recommended a method to rank flood penetration seals and prioritize which ones are most important for alleviating the risk of plant flooding. The proposed ranking process is a qualitative two-phase process according to the likelihood and consequence of seal failures. Three categories are used for ranking, including low, medium, and high risk significance. Phase 1 conducts a high-level screening of flood seals based on seal failure probabilities and seal leak rates. Seals with low contribution to room flooding and with no direct leaks into flood-significant motor control centers will be ranked as low risk significance and eliminated from further analysis. Phase 2 conducts a detailed ranking of the remaining seals into high, medium, or low risk significance based on their potential risk impact on operation of flood-significant components.

3.4 U.S. Army Corps of Engineers Engineer Research and Development Center

3.4.1 ERDC/CHL TR-15-3

The USACE ERDC report, "Technical Basis for Flood Protection at Nuclear Power Plants" (ERDC/CHL TR-15-3) [14], categorizes flood protection methods as dry sites, exterior (primary) barriers, incorporated (secondary) barriers, temporary barriers, and interior drainage/pumping systems to accommodate local intense precipitation. It specifies that secondary and temporary barriers may supplement primary barriers but cannot substitute for them. It should also be noted that, for dry sites, exterior barriers are not applicable, and those barriers intended to accommodate local intense precipitation become the primary barriers.

---

[1] EPRI reports are available to EPRI members at no additional cost and to the public for a fee.

3.4.2 ERDC TR-07-3

The USACE ERDC report, "Flood-Fighting Structures Demonstration and Evaluation Program: Laboratory and Field Testing in Vicksburg, Mississippi" [15], documents the results of a comprehensive prototype testing and evaluating program conducted by the ERDC of temporary, barrier-type flood-fighting structures. The program tested four alternative technologies of temporary flood barrier, including USACE sandbag levees, Rapid Deployment Flood Walls, Hesco Bastion Concertainer® levees, and Portadam® levees. The testing results were used to evaluate and compare the alternative technologies based on their performance of technical soundness, operational functionality, and economic feasibility. Portadam® and Hesco Bastion Concertainer® levees were selected as the alternatives providing the best overall performance. A more in-depth review of the test described in this ERDC document, including the testing facilities, testing protocol, and testing results, is provided in Section 6.2 "Previous Test Examples" of this report.

3.5 Nuclear Energy Agency

The OECD/NEA draft report, "Concepts and Terminology for Protecting Nuclear Installations from Flood Hazards" [16], developed through a survey of practices in multiple organizations and countries, summarizes flood protection concepts and terminology. This report adopts the term "flooding protective measures" and categorizes such measures as temporary or permanent (permanently installed), active or passive. Also, this report defines "flooding protective measures" as a combination of "flooding preventive measures" and "flooding mitigative measures."

3.6 Center for Nuclear Waste Regulatory Analyses

"Guidance to Support NRC Assessment of Selected Flood Protection Features at Nuclear Power Plants" [17] was prepared for NRC by the Center for Nuclear Waste Regulatory Analyses. This document provides guidance to support NRC assessment in evaluating the effectiveness of selected flood protection features at nuclear power plants. The guidance is focused on (i) estimating the quantity of water splashing over a flood barrier, and (ii) evaluating the adequacy of inspection and maintenance procedures as well as analyses used by the licensees to ensure that credited external watertight doors and watertight pipe penetration seals perform their intended safety functions. The document categorizes watertight doors and watertight pipe penetration seals, respectively, into different types and suggests type-specific requirements for inspection and maintenance procedures to facilitate more detailed NRC review of plant procedures. Overviews of common failure modes of watertight doors and pipe penetration seals are also provided to allow NRC staff to focus their review on those doors or seals that are most important to safety.

3.7 Nuclear Plant Flooding Walkdown Reports

The NRC Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident [18] recommended that walkdowns of current licensing basis flood protection be conducted for the operating NPP fleet (Recommendation 2.3). Subsequently, the NRC issued a Request for Information under Title 10 of the Code of Federal Regulations, Section 50.54(f) [19], in which all U.S. power reactor licensees were requested to perform flooding walkdowns using an NRC-endorsed walkdown methodology (documented in NEI 12-07, Revision 0-A [11]) to inspect and

verify that plant flood protection features credited in the current licensing basis are available, functional, and implementable.

Flooding walkdown reports for several operating or decommissioning nuclear plants [20, 21] [22, 23] [24, 25, 26] [27, 28] [29, 30] were obtained and reviewed, with the detailed review results provided in Appendix B of this report.

3.8 FM Approvals

FM Approvals is a third-party testing laboratory and certification agency that provides certification services regarding a wide range of equipment (such as fire protection equipment) and materials (such as building materials). During a certification process, samples of a product are evaluated and tested according to the requirements listed in the associated Approval Standard. If all the requirements are met, FM Approvals will approve the product—which can then be labeled as "FM Approved"—and conduct periodic surveillance audits if the manufacturer wishes to maintain the product's "FM Approved" status.

FM Approval Standard ANSI FM 2510, "Approval Standard for Flood Mitigation Equipment (Class Number 2510)" [31], dated April 2019, is FM Approvals' latest published version to describe the design and performance requirements for flood mitigation equipment used in riverine-, tidal-, or rainfall-related flood conditions (excluding coastal flood conditions).

ANSI FM 2510 designates and categorizes flood barriers by function (permanent or contingent), operation (active or passive), and the intended application for protection (opening vs. perimeter).

Regarding testing facilities, ANSI FM 2510 requires that performance testing for perimeter barriers be conducted at the USACE ERDC Coastal and Hydraulics Laboratory (CHL) in Vicksburg, Mississippi (refer to Section 5.3.4); alternative testing facilities may not be used unless agreed to by FM Approvals. For opening barriers, ANSI FM 2510 does not designate a specific performance testing facility but presents a general requirement that such tests be conducted within a test enclosure that can withstand the maximum design water depth without permitting significant leakage.

Regarding testing conditions, ANSI FM 2510 requires that perimeter barriers be evaluated/tested to withstand quasi-static and riverine flood conditions, with opening perimeter barriers required to be evaluated/tested to withstand quasi-static flood conditions only. A performance test series for a perimeter barrier application consists of seven tests that must be completed with the same barrier assembly in the following sequence: deployment, hydrostatic load, wave-induced hydrodynamic load, overtopping, debris impact, current, and post-hydrostatic load. The performance test series for an opening barrier application consists of seven tests that must be completed with the same barrier assembly in the following sequence: deployment, two hydrostatic load tests of different durations, re-deploy, dynamic impact load, and two post-hydrostatic load tests with different water depths. For each test, ANSI FM 2510 provides detailed requirements regarding water conditions and duration. More details on testing conditions can be found in Appendix C of this report.[2]

[2] FM Approvals kindly reviewed and authorized the inclusion of the summary of ANSI FM 2510 in Appendix C of this report.

3.9 Materials from Miscellaneous Sources

In addition to the aforementioned references, the following materials from miscellaneous sources were included in the literature review:

- Publications by INL and Idaho State University (ISU) on component flooding fragility experiments conducted at ISU's Component Flooding Evaluation Lab [32] [33]
- FEMA P-936, "Floodproofing Non-Residential Buildings" [34], which covers floodproofing in non-residential buildings located in riverine and coastal areas not subject to wave action
- Publicly available information from flood barrier vendors, e.g., [35].
- MIL-DTL-24705B(SH) [36], which contains watertightness test requirements (including requirements of specimen mounting, test pressure, test duration, and failure criteria) for multiple cable penetrator frames, accessories, and insert materials on Naval ships.

4 FLOOD BARRIER OVERVIEW

This section provides an overview of on-site permanent/temporary flood barriers at NPPs including flood penetration seals, watertight and non-watertight doors, absorbent pads, and flood gates. For reference, Appendix A describes flood barriers, mitigative conveyance drains, and circumstantial flood affecting measures that are included in the taxonomy of on-site flood protection features (Figure 2-2 and Table A-1) but are not the focus of this research. Also, off-site permanent or temporary flood barriers such as seawalls, breakwaters, revetments, levees, and riverine embankments are not the focus of this research and are not discussed further.

4.1 On-Site Permanent Flood Barriers

Permanent flood barriers are fixed at their point of use and often must be considered during the construction phase of the facility. On-site permanent flood barriers pertain to the premises of an NPP (whether inside the structure or along its immediate exterior). Off-site permanent flood barriers attenuate incoming floodwater from nearby bodies of water. Off-site permanent flood barriers are not the focus of this research, and methods to test such barriers are not explored here.

On-site permanent flood barriers can be exterior to or incorporated into NPP buildings to protect SSCs important to safety and prevent floodwater from passing through openings or apertures in the interior and exterior of the plant. On-site permanent incorporated flood barriers include external walls, internal walls, watertight doors, and flood penetration seals in external and internal walls of safety important structures that allow pipes, cables, conduit, cable trays, ducts, and other items to pass between different areas of the plant. On-site permanent exterior barriers include dikes, levees, and earthen berms.

On-site permanent flood barriers can be passive or active.

- Passive barriers do not depend on external energy input or human action to actuate or change position to provide a barrier to flooding. Passive barriers are independent of the duration of a flooding event. On-site permanent passive barriers include walls, floors, and penetration seals.
- Active barriers need external energy input and/or human action to actuate or change position to provide a barrier to flooding. Active barriers must be activated to close off entryways or other areas where personnel or materials generally require access. On-site permanent active barriers include watertight doors.

The following sections describe in greater detail several of the most common NPP on-site permanent flood barriers (penetration seals and doors).

4.1.1 Penetration Seals

Penetration seals are passive barriers that are always in use regardless of the presence of floodwater. At NPPs, flood barrier (or watertight) penetration seals are provided for penetrations designed or modified to allow the passage of mechanical or electrical penetrants. Common flood penetration seals at NPPs can be categorized in a variety of ways, whether seal-related (based on seal/blocking materials and seal/blocking depth), penetration-related (based on the shape and size of penetrations and whether they are sleeved or framed), penetrant-related (based on penetrant type and size), and barrier-related (based on barrier materials and

thickness). Table 4-1 shows detailed categorization criteria developed through a review of [5], [6], and [17]. It should be noted that these criteria, which were developed for common flood penetration seals at NPPs, may not be exhaustive.

Table 4-1 Categorization Criteria for Common Flood Penetration Seals at NPPs

Group No.	Criteria Group	Criterion No.	Categorization Criterion
1	Seal-related	1.1	Seal materials
		1.2	Blocking materials
		1.3	Seal depth
		1.4	Blocking depth
2	Penetration-related	2.1	Penetration shape
		2.2	Penetration size
		2.3	Sleeved or framed
3	Penetrant-related	3.1	Penetrant type
		3.2	Penetrant size
4	Barrier-related	4.1	Barrier materials
		4.2	Barrier thickness

Because penetration seals must fill the space around the penetrant, they must be manually fitted or made of material that automatically fills that space. Per Criterion 1.1, penetration seals can be broadly categorized as made from solid materials (seals) or made from fluids that solidify (sealants).

4.1.1.1 Seals

Mechanical seals that must be manually fitted to fill the penetration are denoted as mechanical boots. These seals expand to the required size via springs or by tightening screws on the seal itself. O-rings made from rubber or elastomer are normally used to complete the seal, but other materials such as flexible graphite can be used when higher temperature applications are required. Mechanical boots are often made of metal, but a wide variety of solid elastomer modules also provide a component of compression sealing.

Other seals that use compression for watertight closure include wedge and gasket seals. Wedge seals are made of waterproof materials that are compressed before insertion into a particular aperture (Figure 4-1). The materials' natural tendency to expand to original size creates a watertight seal. To prevent warping or failure of the structure or conduit, the material surrounding the seal should be taken into careful consideration.

Figure 4-1 Wedge Seal [37]

Gasket seals can be made of several materials, including rubber, silicone, ceramic fiber, and neoprene. Gaskets can be ordered with specific dimensions and aperture size, or cut on-site for unique sizing requirements. Gaskets are placed around the edge of an opening or through-feed to provide waterproofing properties.

4.1.1.2 Sealants

Sealants are administered in a plastic state and solidify into place to address cracks and small openings in the surrounding structural material. Grout and mortar are commonly used sealants when constructing walls or other structures made of brick or stone.

Epoxies and liquid elastomers are painted over porous or cracked surfaces to provide waterproofing properties. They can also be used over piping elbows and joints to provide added strength for identified points at risk of rupture or seepage, or to fill in cracks between floor-wall joints or between concrete segments and windows.

Waterproof foams can be used in much the same way as epoxies and elastomers. They are effective at filling cracks and small openings, though they are much more viscous and can be applied more precisely without risk of runoff into unwanted areas. The two most common waterproofing foams are silicone-based and urethane-based. Silicone foams can be used to fill in multi-cable conduits and through-feeds.

Urethane foams are generally created by mixing two substances which expand to fill the container they occupy. Both silicone and urethane foams are often used as fire retardants as well as for flood protection (Figure 4-2).

Figure 4-2 Vulcanizing Foam Seal [38]

Flood penetration seals are sometimes used in conjunction with blocking (or "damming") materials that close off open spaces within the penetration and provide backing material for the seal material. Per Criterion 1.2, penetration seals can be categorized on the basis of whether blocking materials are installed or not. If blocking materials are used, they can be subcategorized by the type of blocking materials (e.g., ceramic fiber board, calcium silicate board, or rigid insulation foam). In addition, seal depth (Criterion 1.3) and blocking depth (Criterion 1.4) can be used to subcategorize the penetration seals even further.

It should be noted that the categorization criteria are not solely confined to seal properties, since seal performance may be affected by adjacent components (i.e., penetrations, penetrants, and barriers). Penetrations can be characterized according to shape (circular, square, or rectangular [Criterion 2.1]), size (diameter, length, and width [Criterion 2.2]), and whether they are sleeved or not (Criterion 2.3). Penetrants, also known as penetrating items, can be categorized according to type (Criterion 3.1) and size (Criterion 3.2). Common penetrant types include mechanical penetrants (e.g., pipes, tubes, and airlines) and electrical penetrants (e.g., electrical cables, conduits, and cable trays). Barriers can be characterized according to their materials (Criterion 4.1) and thickness (Criterion 4.2).

4.1.1.3 Penetration Seal Failure Modes

Based on a review of [5], [6], and [17], the common failure modes of flood penetration seals at NPPs are summarized in Table 4-2.

Table 4-2 Common Failure Modes of Flood Penetration Seals at NPPs

Group No.	Failure Mode Group	Failure Mode
1	Generic to all seal types	Missing seals
		Broken or degraded seals
		Improperly installed seals
		Incorrect seal materials
		Ejected seals due to water pressure
		Abrupt seal failure due to water pressure
		Dislodged seal due to water pressure
2	Specific to compression seals	Loss of seal material resilience
		Missing or loose compression bolts
		Cracking compression plates
		Corrosion thinning of compression plates
		Space between sleeve and wall
3	Specific to link-type split compression seals	Chain too short (too few links)
		Cracked, missing, or misaligned links
4	Specific to modular framed split compression seals	Incorrect number of layers removed
		Incorrect block size in layer
		Missing stop block
		Broken or missing spacer plates
		Bolt(s) not tightened to specification
5	Specific to water-rated firestop systems	Penetration void not fully stuffed
		Incorrect stuffing used

Table 4-2 Common Failure Modes of Flood Penetration Seals at NPPs (cont.)

Group No.	Failure Mode Group	Failure Mode
		Cracks and holes in sealant
		Sealant thickness not to specification
		Sealant does not penetrate stuffing material
6	Specific to boot seals	Cuts, tears, abrasions in skirt
		Loose or disconnected skirt
		Corrosion in hardware and clamps
		Loose clamps

4.1.2 Doors

A door (or gate) is a hinged, openable barrier that allows ingress and egress into an enclosure (building, room, etc.) so people and items can enter and leave. Different types of doors are used in NPPs (e.g., hinged doors, horizontal or vertical sliding doors, rotating doors, and pressure-tight or watertight doors). While doors are mostly incorporated into buildings/rooms, removable gates or doors are sometimes used in plants.

Hinged barriers operate much like swinging doors and are locked in place manually during flood events to impede waterflow (Figure 4-3). Ample side or swinging room must be available for the barrier to operate unimpeded, and custom sizing allows for hinged barriers to be installed on the interior and exterior of the facility.

Sliding barriers slide into a locked position and are ideal for areas with limited swinging room. The lack of swinging hinges means that only total structural failure will result in unchecked waterflow.

Figure 4-3 Hinged Barrier [39]

A watertight door typically consists of one or more door panels, a door frame, latching or dogging devices, a watertight gasket, and door sealing system (e.g., a gasket retainer).

Common types of watertight doors include marine type and pedestrian type. Each type can be further categorized per their numbers of panels (e.g., single panel and double panel), ways of opening (e.g., sliding or hinged), ways of operating latching or dogging systems (e.g., manual, hydraulic or electrically operated) [17]. The categorization criteria for common flood watertight doors at NPPs are summarized in Table 4-3.

Table 4-3 Categorization Criteria for Common Flood Watertight Doors at NPPs

Criterion No.	Categorization Criterion
1	Door location
2	Door dimension
3	Door type
4	Number of panels
5	Way of opening (e.g., sliding or hinged)
6	Way of operating latching or dogging systems (e.g., manual, hydraulic or electrically operated)

Reference [17] provides the following physical failure modes of watertight doors as well as associated human errors.

Door panels and door frames may fail due to design or material not in accordance with technical specifications; they may also be damaged by activities in the area, by flood pressure, or due to corrosion or degradation of panels or frames. Door frames, which are attached to load bearing walls, could also fail from frame not being anchored to the wall, or due to cracks and degradation of wall structure.

Potential failure modes of door closure systems include misaligned door and frame, displaced frame (due to loosed hinges), inoperable hinges (due to damaged or unlubricated bearings), inoperable latches or dogging system (damaged, not lubricated, not maintained, or misaligned), door not closing securely, and door not compressing the gasket or seal when closed.

Leakage through a door seal could happen due to failure to install gasket, failure to properly secure gasket to door or frame, failure to correctly mate knife edge to gasket, using incorrect gasket material, gasket not being continuous around the periphery of door or partially missing, door panel and gasket not aligning along the knife edge of door to seal indentation, gasket hardened from general aging, use, and environment, gasket degraded or damaged (e.g., cracked, punctured, and torn), gasket not adhering to door or door sill (e.g., detached, loose or degraded gasket).

Besides the aforementioned physical failure modes, human errors can also lead to failures of watertight doors, including improper installation of door, failure to follow proper procedures for inspection or maintenance, and inadequate training on door use, installation or maintenance.

4.2 On-Site Temporary Flood Barriers

On-site temporary flood barriers can be passive or active and are only used to protect SSCs from inundation and the static/dynamic effects of flooding during a limited period. They provide

flood coverage for the exterior perimeter of the facility during the duration of a flood and are removed once the risk of flooding has passed. Thus, they are not permanently fixed in one location and are generally mobilized in flooding scenarios. On-site temporary flood barriers can be disposable (single use) or reusable (multiple uses).

4.2.1 Disposable

Barriers intended for single use are considered disposable. One example of disposable barriers are absorbent pads (Figure 4-4), which retain water but offer no means of expelling it. Disposable barriers can be quickly deployed and are most effective when in close contact with both the internal and external sides of facility penetrations. Users of this type of barrier should be cognizant of its water-holding capacity, since complete saturation results water percolating through the barrier rather than preventing it from impacting the protected area or facility.

Figure 4-4 Absorbent Pad [40]

4.2.2 Reusable

Reusable barriers are designed to be in immediate contact with the facility or form a larger perimeter around it. Those that require immediate contact, such as doors and windows, serve as barricades for access penetrations. Several proprietary variations of door floodgates, once affixed, are manually adjusted to expand and become wedged into penetration frames. These barriers rely on a combination of waterproof fabrics and plastics to prevent water penetration (Figure 4-5). Manual adjustment of these barriers is nominally performed on the side of the barrier facing inward towards the facility's interior, and operations around that aspect should be considered.

The other form of reusable barrier placed in close proximity to an access penetration are steel log stacks (Figure 4-6). Log stacks form sealed layers of flood protection and can be stacked as high as necessary, since they do not need to be affixed in the penetration frame. The drawbacks of this design are that, while the logs themselves are temporary, the slide-in structure in which they are stacked is permanent (though it does not obstruct access in non-flood scenarios) and may limit how many logs can be stacked.

Figure 4-5 Door Flood Gate [41]

Figure 4-6 Steel Flood Logs [42]

Barriers intended to form larger perimeters around a facility may employ inflatable, hydrostatic, or sand-based mechanisms to achieve flood protection. Inflatable barriers such as AquaDams® (Figure 4-7) use nearby floodwater or water from another source to inflate a tube surrounding the facility. This tube is then either strapped or anchored to the facility grounds to prevent mobility. If water levels exceed the capacity of an inflated barrier, it may become buoyant and may attempt to shift from its desired position. Once submerged, these barriers may unfasten and roll about the facility's perimeter, potentially causing stress on the facility's structure. Of

additional concern is that these barriers may interact with floodwater high in debris content, and a punctured barrier may introduce more running water at the facility than if the barrier had not been present. In contrast, hydrostatic barriers do not pose further threat to the facility if they fail. Hydrostatic barriers use the pressure of surrounding floodwater to increase their own structural integrity. They can take the form of rapidly deployable tarps, modular plastic molds, and Portadams®. Of these designs, hydrostatic tarp (Figure 4-8) and Portadam® (Figure 4-9) are vulnerable to debris punctures; however, while high-velocity turbulent flow at the base of a Portadam® may jeopardize the mechanism used to sustain the barrier's overall structure, a punctured hydrostatic tarp still affords some functionality when damaged. If puncture is avoided and water levels rise beyond the height of the hydrostatic tarp, it collapses in on itself once the overhead pressure exceeds the retained hydrostatic pressure, rendering it useless once flood levels recede. Similar expectations can be made for the Portadam®. Being modularly linked, hydrostatic plastic barriers have a higher chance of remaining in an operational position if compromised by overhead flood levels, and may not require manual repair to regain function once water levels recede (Figure 4-10).

Figure 4-7 AquaDam® Used in Fort Calhoun Station During the 2011 Flood Event [43]

Figure 4-8 Hydrostatic Tarp [44]

Figure 4-9 Portadam® [45]

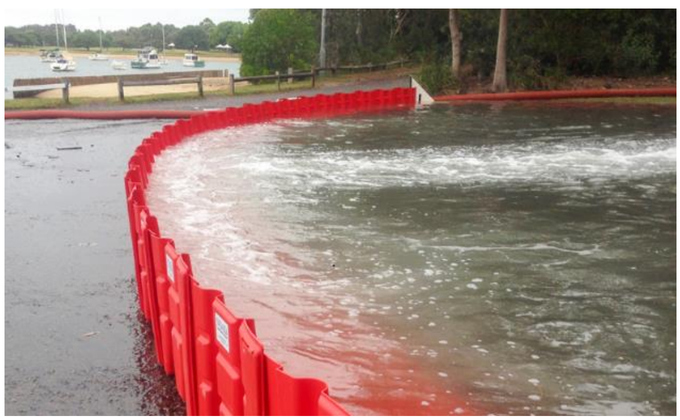

Figure 4-10 Modular Plastic Barrier [46]

Sand-based barriers could be employed in two forms: in arrays of linked fill bags (Figure 4-11) or as modular cuboid fillers that provide a barrier's internal structure (Figure 4-12). The drawback is that large amounts of sand must be brought in to erect them. With regards to the fill bags, once a single array is erected, another empty array can be placed vertically on top, then filled to increase the height of flood coverage. Compacting the sand into the fill bags leads to moderately low rates of seepage and enhanced contour durability of the barrier. Seepage can be further addressed through the implementation of cuboid fillers that, although used as internal structure, keep cubes of sand compartmentalized and prevent wet sand in front from interfering with the integrity of the sand in back. While reusable, these barriers require the most set up and clean-up time of all temporary barriers. If chosen, adequate time for operational fill and placement should be taken into account in related emergency flood protocol.

Figure 4-11 Sand Barrier Used in Fort Calhoun Station During the 2011 Flood Event [43]

Figure 4-12 Sand Barrier [47]

5 POTENTIAL FLOOD BARRIER TESTING FACILITIES

5.1 Operating Nuclear Power Reactors

Currently, there are nearly a hundred operating commercial nuclear power reactors in the United States that are regulated by the NRC. Figure 5-1 shows a map of these power reactors taken from the NRC public website (https://www.nrc.gov/reactors/operating/map-power-reactors.html) [48]. These operating nuclear plants are potential sites to conduct in-situ non-destructive test or enhanced inspection of flood barriers, although testing should be carefully incorporated into the plant's maintenance schedule to avoid inadvertently impacting the safety and reliability of plant operations.

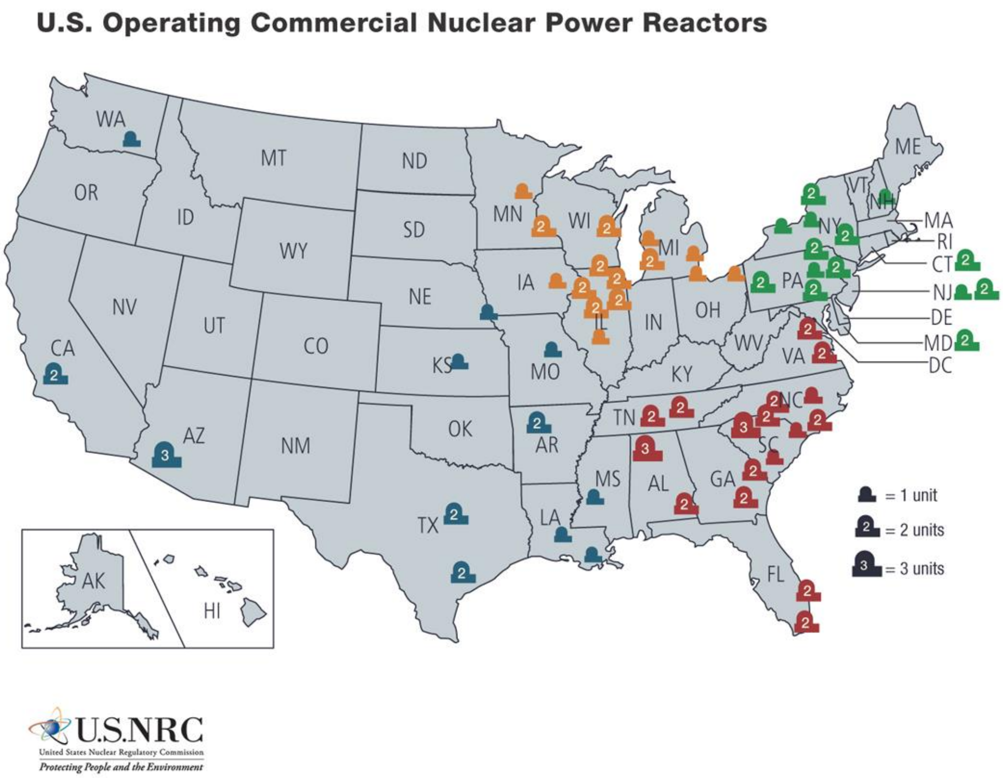

Figure 5-1 Map of U.S. Operating Commercial Nuclear Power Reactors [48]

5.2 Decommissioning Nuclear Power Reactors

Decommissioning is the process of safely closing an NPP (or other facility where nuclear materials are handled) to retire it from service after its useful life has ended. Decommissioning begins after the nuclear fuel, coolant, and radioactive waste are removed. It involves decontaminating the facility to reduce residual radioactivity, moving used nuclear fuel from the spent fuel pool, dismantling the structures, and removing contaminated materials to appropriate disposal facilities. Completion of the decommissioning process typically releases all portions of the site from the current NRC license, except for the Independent Spent Fuel Storage Installation (ISFSI), where spent nuclear fuel is stored in dry casks. There are two major decommissioning strategies: DECON and SAFSTOR.

- DECON (or dismantling) is a method of reactor decommissioning in which contaminated SSCs are removed from a site and safely disposed of at a commercially operated low-level waste disposal facility or decontaminated to a level that permits the site to be released for unrestricted use. This method can remove the facility from regulatory control relatively soon after shutdown. Final dismantling or decontamination activities could begin within a few months and take several years to complete.
- SAFSTOR (or safe storage) is a method of reactor decommissioning in which a nuclear facility is placed and maintained in a condition that allows the facility to be safely stored and subsequently decontaminated (deferred decontamination) to levels that permit release for unrestricted use. SAFSTOR postpones the final decommissioning for a longer period, usually 40–60 years. The nuclear facility is placed into a safe storage configuration for several decades before decommissioning and site restoration is completed. During SAFSTOR, radioactive contamination decreases substantially, making subsequent decontamination and demolition easier and reducing the amount of low-level waste requiring disposal.

These decommissioning plants present unique harvesting opportunities to test flood barriers. For flood barriers remaining in place, in-situ testing could be conducted non-destructively—or even destructively if the location of the barriers is appropriate for direct testing. Otherwise, the flood barriers could be dismantled, decontaminated if needed, and transported to other flood testing facilities for testing. Unlike new flood barriers produced specifically for such testing, flood barriers harvested from decommissioning plants represent as-operated, as-used NPP components.

NUREG-1350, Vol. 32, “2020–2021 Information Digest” [49], and NRC webpages such as https://www.nrc.gov/info-finder/decommissioning/power-reactor/ [50] offer information related to nuclear power reactor sites undergoing decommissioning. The NRC's Office of Nuclear Material Safety and Safeguards (NMSS) has project management responsibilities involving most of the power reactors undergoing decommissioning. The NRC's Office of Nuclear Reactor Regulation (NRR) currently has project management responsibility for two power reactors that have permanently ceased operations: Pilgrim and Three Mile Island Unit 1. Figure 5-2 shows a map of decommissioning power reactors [50]. Table 5-1 lists these reactors and gives information on their locations, thermal electrical power (in MWt), nuclear steam supply system (NSSS) vendors, and reactor shutdown date. Note that the above information was accurate as of February 2021. For the latest information, please refer to the associated NRC webpages.

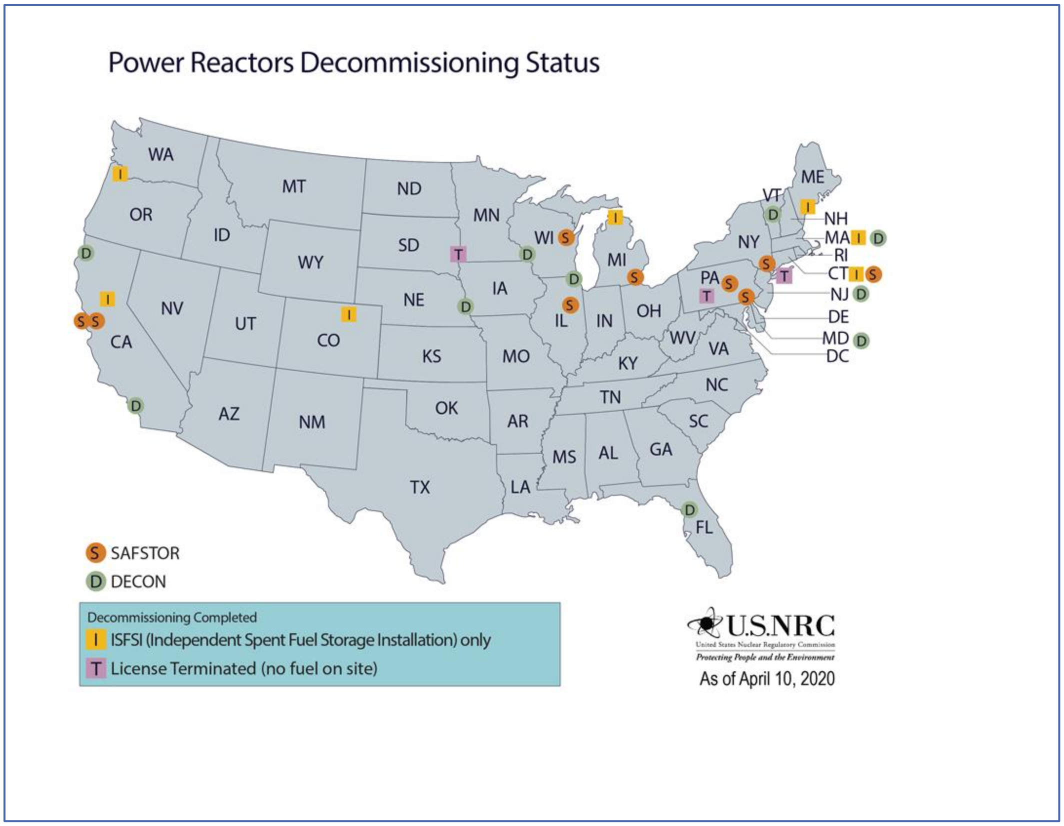

Figure 5-2 Map of U.S. Decommissioning Nuclear Power Reactors [50]

Table 5-1 Power Reactor Sites Undergoing Decommissioning

Unit	Location	MWt	NSSS Vendor	Shut Down Date	Estimated Closure Date	Current License Status
Crystal River 3	Crystal River, FL	2,609	B&W	2/20/2013	2074	SAFSTOR
Dresden 1	Morris, IL	700	GE	10/31/1978	2036	SAFSTOR
Duane Arnold	Palo, IA	1,912	GE	8/10/2020	2080	SAFSTOR
Fermi 1	Newport, MI	200	CE	9/22/1972	2032	SAFSTOR
Fort Calhoun	Ft. Calhoun, NE	1,500	CE	10/24/2016	2076	SAFSTOR
GE EVESR	Sunol, CA	12.5	GE	2/1/1967	2025	SAFSTOR
GE VBWR	Sunol, CA	50	GE	12/19/1963	2025	SAFSTOR
Humboldt Bay 3	Eureka, CA	200	GE	7/2/1976	2019	DECON In Progress
Indian Point 1	Buchanan, NY	615	B&W	10/31/1974	2036	SAFSTOR

Table 5-1 Power Reactor Sites Undergoing Decommissioning (cont.)

Unit	Location	MWt	NSSS Vendor	Shut Down Date	Estimated Closure Date	Current License Status
Indian Point 2	Buchanan, NY	3,216	Westinghouse	4/30/2020	2030s	
Kewaunee	Carlton, WI	1,772	Westinghouse	5/7/2013	2073	SAFSTOR
La Crosse	Genoa, WI	165	AC	4/30/1987	2020	DECON In Progress
Millstone 1	Waterford, CT	2,011	GE	7/21/1998	2056	SAFSTOR
Oyster Creek	Forked River, NJ	1,930	GE	9/17/2018	2078	SAFSTOR
Peach Bottom 1	Delta, PA	115	GA	10/31/1974	2034	SAFSTOR
Pilgrim	Plymouth, MA	2,028	GE	5/31/2019		DECON In Progress
San Onofre 1	San Clemente, CA	1,347	Westinghouse	11/30/1992	2030	SAFSTOR
San Onofre 2	San Clemente, CA	3,438	CE	6/12/2013	2030	DECON In Progress
San Onofre 3	San Clemente, CA	3,438	CE	6/12/2013	2030	DECON In Progress
Savannah, N.S.	Baltimore, MD	74	B&W	11/1/1970	2031	DECON In Progress
Three Mile Island 1	Middletown, PA	2,568	B&W	9/20/2019	2079	SAFSTOR
Three Mile Island 2	Middletown, PA	2,770	B&W	3/28/1979	2053	SAFSTOR
Vermont Yankee	Vernon, VT	1,912	GE	12/29/2014	2030	DECON In Progress
Zion 1	Zion, Il	3,250	Westinghouse	2/21/1997	2020	DECON In Progress
Zion 2	Zion, Il	3,250	Westinghouse	9/19/1996	2020	DECON In Progress

Several companies are currently engaged in NPP decommissioning in the U.S.

- **Holtec -** Holtec Decommissioning International (HDI) is a wholly owned subsidiary of Holtec International and is the licensed operator for NPPs owned by Holtec. It oversees decommissioning work performed by Comprehensive Decommissioning International, Holtec and SNC-Lavalin's jointly owned decommissioning general contractor.
- **NorthStar -** NorthStar has provided services for commercial and government decommissioning and closure projects for over 20 years. NorthStar has also performed several non-power reactor decontamination and decommissioning projects to support NRC License Termination Plans and is currently providing decommissioning services for Vermont Yankee.
- **EnergySolutions -** EnergySolutions is a large nuclear waste company headquartered in Salt Lake City, Utah. Its current reactor decommissioning projects include Zion and La Crosse.

HDI is currently decommissioning Oyster Creek and Pilgrim. HDI has also entered into purchase/sale agreements with Entergy Corporation for Indian Point 2 and Palisades. In November 2020, Three Mile Island's Unit 2 was approved to be transferred to EnergySolutions for decommissioning.

5.3 Decommissioning Plant Site Visit

A team of NRC and INL staff visited the Oyster Creek NPP in November 2019 to perform a walkdown on flood barriers harvestable for testing. Several parts of the facility were toured, including the emergency diesel generator (EDG) building, the turbine building, the reactor containment building, and the surrounding areas of key buildings. Observations from the walkdown are as follows:

- The site seemed level, and it was not determined where water would actually drain to during large storms.
- The EDG building seemed open to the weather but with some drainage, though the cable tunnel/drains may just as easily provide a way into the EDG enclosure as a way out (Figure 5-3 to Figure 5-5).
- Penetrations into the EDG building were considered for harvesting (Figure 5-6).
- It was noted that not many penetrations into the turbine or reactor buildings were observed, so there did not seem to be many pathways for water to enter the two buildings from outside. Figure 5-7 and Figure 5-8 show some penetrations in the reactor building.
- The turbine and reactor buildings contained doors through which water could potentially ingress. Some doors were at ground level, others above ground level.

Figure 5-3 Hallway in the EDG Room ***(Courtesy of Oyster Creek NPP)***

Figure 5-4 Access to the Cable Tunnel in the EDG Room ***(Courtesy of Oyster Creek NPP)***

Figure 5-5 Floor Drain in the EDG Enclosure ***(Courtesy of Oyster Creek NPP)***

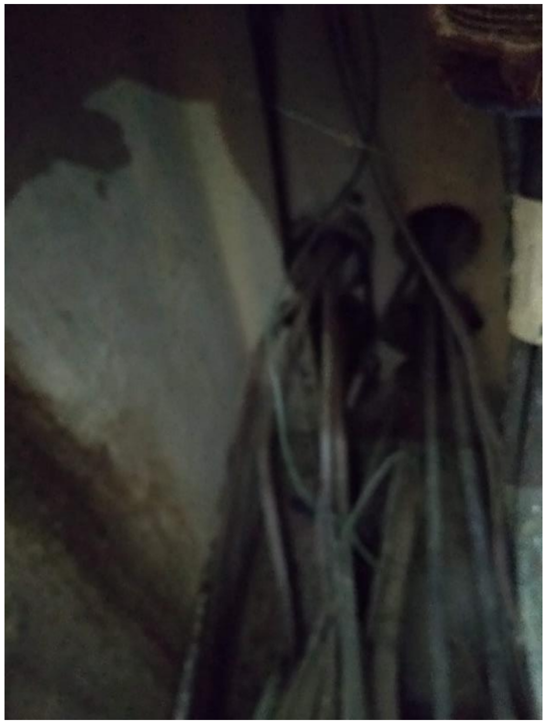

Figure 5-6 Penetration Seals into the EDG Enclosure ***(Courtesy of Oyster Creek NPP)***

Figure 5-7 Penetrations in the Reactor Building ***(Courtesy of Oyster Creek NPP)***

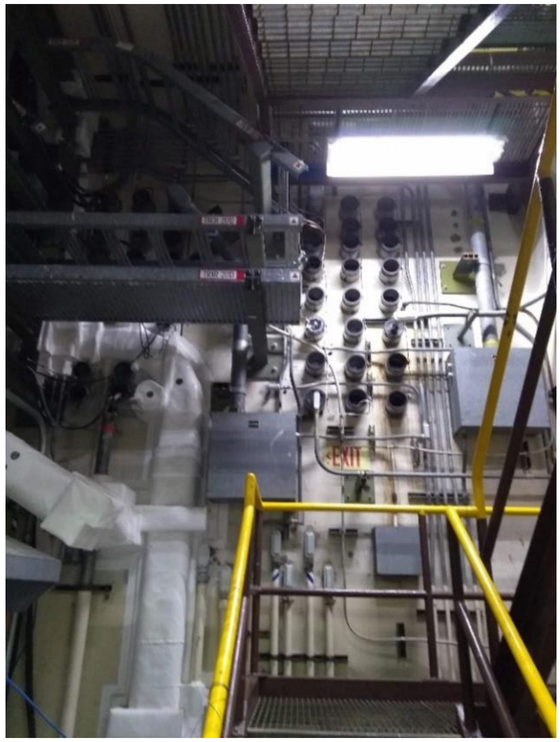

Figure 5-8 More Penetrations in the Reactor Building ***(Courtesy of Oyster Creek NPP)***

5.4 U.S. Flood Testing Facilities

Besides operating and decommissioning plants, domestic and international facilities are available for flood barrier testing. Information was collected on these facilities in hopes of providing insights into flood testing methods of possible application/benefit to nuclear power plants. Four U.S. flood testing facilities are described in this section. Two of them are hosted by public research universities, ISU and Oregon State University (OSU); the third is a Framatome test facility, which constructed a test apparatus in support of prior NRC research into penetration seal testing protocols; and the fourth is the USACE/ERDC Coastal and Hydraulics Laboratory (CHL), operated by the USACE and the required performance testing facility for ANSI FM 2510 certification (refer to Section 3.8).

International flood testing facilities are described in Section 5.5.

5.4.1 Idaho State University Flood Testing Facility

ISU is engaged in the design, development, construction, and operation of flood barrier testing [32] [33] facilities. To obtain an understanding of flood barrier failure, the Portal Evaluation Tank (PET) was designed to test non-contaminated items and collect empirical data on flood barrier integrity in relation to various flooding parameters. Results from these tests are intended as input for fragility models and performance-modeling software.

5.4.1.1 ISU Flood Testing Facility Tank

Components to be tested are affixed to a modular platform which is installed in the PET's non-circular face. Flow channels and the tank itself are equipped with sensors to monitor flow, pressure, and temperature. Pump channels are outfitted with electromagnetic flow meters, while the tank utilizes an exterior pressure transducer and an interior ultrasonic depth sensor. If a leaky barrier remains capable of resisting total structural collapse, the facility uses a weir flow path that directs water bypassing the barrier under a flow rate sensor, enabling the collection of leakage rate data.

Made from carbon steel, the PET has a water capacity of 2,000 gallons (Figure 5-9). Pressurization solely due to the presence water is achieved through the use of air relief valves equipped at the top exterior of the vessel, allowing simulated water depth of up to 20 ft. The tank has a 62.4 ft^2 opening which can hold a custom-designed wall with a specific barrier inserted (Figure 5-10). The vessel has two types of inlet methods, both designed to orient any initial momentum from the water exiting the flow channel away from the barrier being tested, allowing the chamber to test the effects of the flood variables without the influence of water impact. The first inlet, utilized by Pump System 1, utilizes a comparatively wide-diameter piping that is perforated with uniform holes and runs vertically through the center of the tank (Figure 5-11). The second inlet, utilized by Pump System 2, utilizes a narrow elbow pipe oriented upward and is positioned about 1 ft from the base of the tank. Both pumps are connected to an 8,000 gallon supply reservoir. To identify conditions that damage the integrity of the backside of the barrier, the interior of the vessel is outfitted with a waterproof lighting and camera system.

Figure 5-9 ISU Flood Testing Facility PET tank – Backside [34]

Figure 5-10 ISU Flood Testing Facility PET tank - Front side, with Modular Wall and Inserted Door Barrier [34]

Figure 5-11 ISU Flood Testing Facility Pump System 1 - Inlet [34]

5.4.1.2 ISU Flood Testing Facility Pump System 1

Driven by a 45-kW submersible pump, Pump System 1 is divided into up- and downstream halves bisected and centered on the inlet channel to the tank (Figure 5-12). Each stream half is equipped with its own flow-rate meter for determining the flow rate into the chamber. Typical system functionality consists of intaking water from the reservoir upward to the top of the tank, where a portion of the water is then distributed to the inlet while the rest is directed to the downstream. The flow rate at which this takes place is modulated by a valve-based flow bypass control system. This control system regulates the amount of water that can flow back into the reservoir (and thus the flow rate into the tank) by directing downstream water through one of three channels of varying diameters (Figure 5-13). The maximum flow rate into the tank is 4,500 gpm.

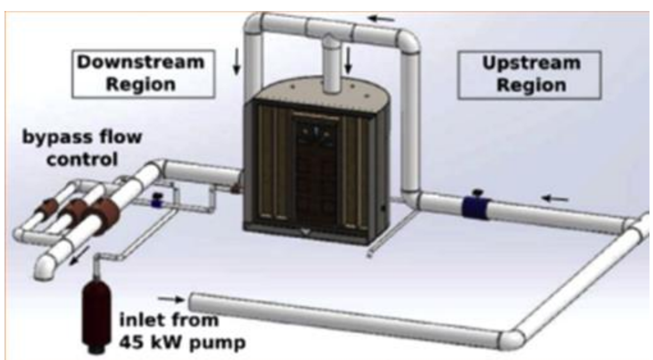

Figure 5-12 ISU Flood Testing Facility Pump System 1 [34]

Figure 5-13 ISU Flood Testing Facility Pump System 1 - 3-Channel Path at the Outlet [34]

5.4.1.3 ISU Flood Testing Facility Pump System 2

Driven by a 3.7-kW submersible pump, Pump System 2 also utilizes a two-part channel system, an inlet, and a drain (Figure 5-14). Unlike Pump System 1, these respective channel paths diverge from each other prior to interfacing with the elbow inlet, and only the inlet path is equipped with a flow meter (Figure 5-15). The entire pump system uses a constant pipe diameter of 3 in., effectively limiting this system to a single flow rate of 300 gpm. Due to the placement of the inlet used by this system to pump water into the tank, the system cannot reach the tank's maximum pressurization capabilities.

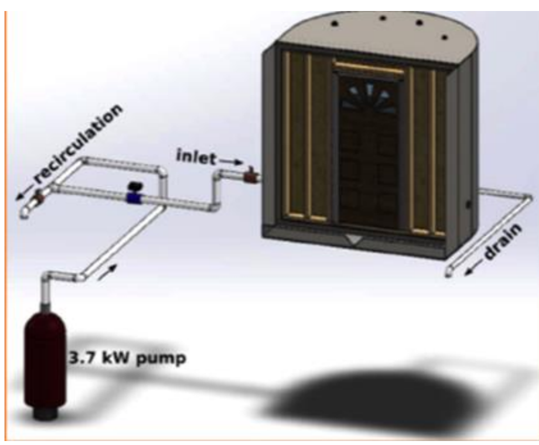

Figure 5-14 ISU Flood Testing Facility Pump System 2 [34]

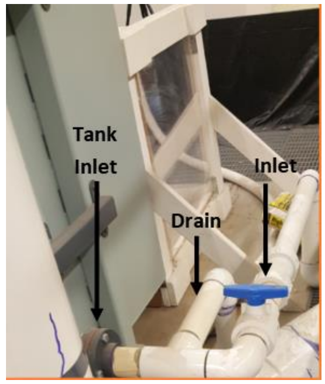

Figure 5-15 ISU Flood Testing Facility Pump System 2 - Inlet/Outlet Channels [34]

5.4.1.4 Tests at ISU Flood Testing Facility

Component flooding fragility experiments conducted at the ISU flood testing facility are described in publicly available technical reports and peer-reviewed papers (e.g., [32] and [33]). Barriers evaluated at this facility consist of different types of doors. Modular frames assembled to occupy the 62.4-ft^2 vessel exposure have been used to test doors of both inward- and outward-swinging orientation. Wood and steel doors have been tested (Figure 5-16). Additionally, custom frames used to test barriers were made to be compatible with deadbolts and other sorts of door locking mechanisms. The ISU flood testing facility could also be modified to expand the testing components from doors to other structures and components if their dimensions fit the facility.

Figure 5-16 Flood Testing of a Hollow Door Barrier at ISU flood Testing Facility [34]

5.4.1.5 To Be Performed at ISU Flood Testing Facility

ISU is preparing a series of new tests that focus on wall penetration-barrier integrity. These types of barriers include electrical outlets and pipe seals that comply with international standards and ingress protection ratings.

5.4.2 Framatome Testing Facility

Framatome constructed a test apparatus at their facility in Lynchburg, Virginia to support FRM's NRC-funded research into penetration seal testing protocols [5]. The test apparatus was constructed to meet all recommendations listed in the draft test protocol developed for that research project. It consists of three main components: a pressure chamber, concrete test deck, and water leakage measurement system (Figure 5-17).

Various test decks were designed and constructed to accommodate different shapes (round, square, rectangular, etc.) and penetration sizes (2–12 in.), different types of seal assemblies (form-in-place, boot, modular, etc.) made from different materials (foam, silicone elastomer, etc.), and different types of penetrants (pipes, cables, conduit, cable trays, etc.). Figure 5-18 shows an example of a test deck after penetration seal installation.

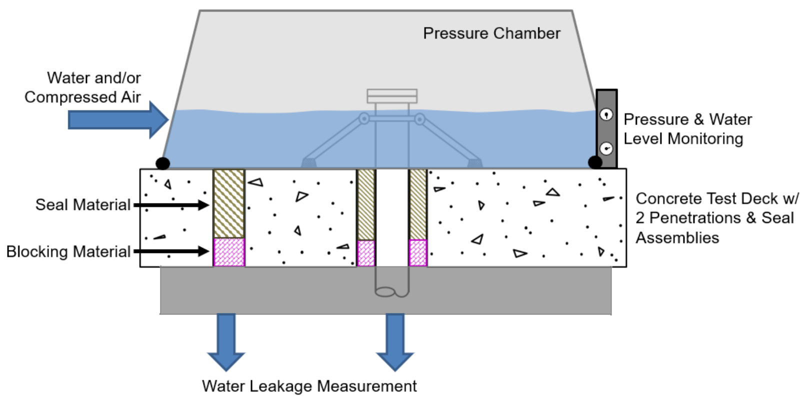

Figure 5-17 Generic Illustration of Framatome Test Apparatus [5]

Figure 5-18 A Test Deck with Penetration Seal Installed [5]

5.4.3 Oregon State University Hinsdale Wave Research Laboratory

The OSU O.H. Hinsdale Wave Research Laboratory (HWRL) was commissioned to investigate the resilience of coastal structures to extreme wave conditions by developing and obtaining data from large-scale dynamic wave generators. This research laboratory offers two separate wave-generating apparatuses, a directional wave basin, and the largest wave flume of its kind in North America. Results yielded from experiments at this facility are used to develop fragility models for wave-structure interactions, thereby improving numerical tools used for coastal wave mitigation [51, 52, 53]. An interview with HWRL staff can be found at https://media.oregonstate.edu/media/t/0_0euvls74.

5.4.3.1 OSU Directional Wave Basin

The directional wave basin is a 62,640-ft^3 apparatus that uses a segmented wave machine to generate a variety of wave forms. These wave forms can effectively replicate tsunami-type inundations and impacts, as well as simulate harbor resonance in the basin. Included in the operable volume is a shore for coastal structures that can be tested against generated conditions (Figure 5-19).

Figure 5-19 OSU HWRL Directional Wave Basin [52]

The basin is 160-ft long, 87-ft wide, and has a maximum depth of 4.5 ft (all of which can be occupied by water). An additional 2-ft freeboard encloses the perimeter of the basin and is not included in the operational volume. Usage of the entire operational volume is optional and can be variably reduced to make use of the sloped floor of the basin, repurposing the shallower regions as a shore upon which structures can be affixed and tested.

This system uses 30 piston-type, electrically driven actuators to generate waves. The wave maker is thus broken up into 30 segments, allowing the paddles controlled by the actuators to move independently of each other and enabling the creation of directional waves. This 30-actuator system can oscillate over periods ranging from 0.5–10 seconds, with a maximum stroke of ~7 ft at ~7 ft/s. Recorded wave limits indicate that this system can produce a maximum wave amplitude of 2.5 ft.

Unistrut fixtures are set every 4 ft along the basin floor. They are used to mount various structures for integrity testing along the basin and offer few limitations in regard to the types or sizes of structures they can securely mount (Figure 5-20). The unistruts are not essential for basin testing and can be covered over with sand, gravel and/or concrete.

Figure 5-20 OSU HWRL Tsunami Simulations Using the Directional Wave Basin [52]

5.4.3.2 OSU Large Wave Flume

The 61,560-ft^3 large wave flume uses a single wave machine to displace water. While this system offers less variability in the waves it can produce (compared to the basin), it is still ideal for both long wave and tsunami generation, offering an apparatus better suited to measure wave absorption and reflection (Figure 5-21). The wave generation capability of the system also opens the possibility of modeling wave impacts (and dynamic loading in general) on flood barriers.

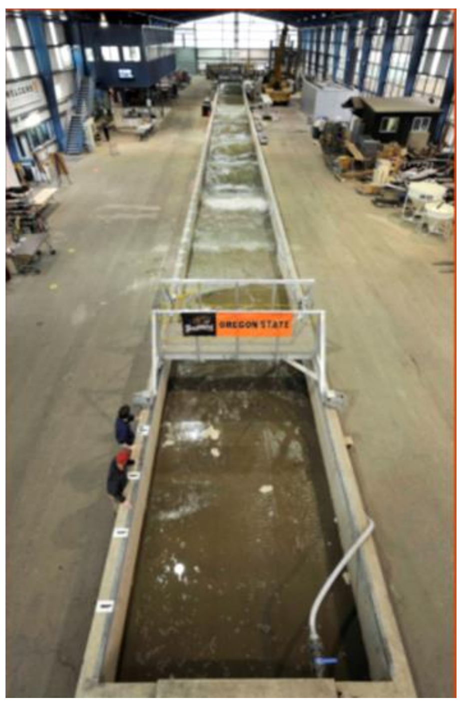

Figure 5-21 OSU HWRL Large Wave Flume [53]

This flume is 342-ft long, 12-ft wide, and has a depth of 15 ft (only ~8.9 ft of which can be used for water depth). In addition to the instrumentation carriage, the internal structure offers optional interfacing for sensors to be placed along the length of the flume.

This system uses a piston-type hydraulic actuator assembly to generate waves. The configuration of this machine uses a wall that is orthogonal to the base of the flume in order to separate hydraulics from the water; this wall is then actuated horizontally by a piston (Figure 5-22). By design, the machine itself is tolerant to the wall's failure, as the piston and its mechanics are affixed at the top of the backside of the wall in order to avoid being touched by water if the wall experiences a penetration or seal tear. The driving piston can oscillate over periods ranging from 0.8–12 seconds, with a maximum actuation stroke of ~13 ft at 13 ft/s. Generated waves have been recorded to reach a maximum of 5.6 ft at the max water depth of ~8.9 ft.

Figure 5-22 OSU HWRL Flume-Wave Maker [53]

5.4.3.3 Tests at OSU Flood Testing Facility

Tests performed at OSU HWRL were not limited to coastal-structure integrity testing. Various studies on wave energy converters were performed at this facility as well. However, most research conducted in this facility consisted of studying coastal processes, flooding, wave-structure interactions, and tsunami dynamics. Most studies carried out there were commissioned by third-party organizations, the most notable and frequent commissioner being the U.S. Department of Homeland Security's Coastal Resilience Center.

Upcoming studies that are relevant to flood-water mitigation and scheduled in the facility for 2020 include:

- Use of mangroves to dissipate wave energy.
- Performance analysis of a self-deployable wall for protecting cities from tsunamis.
- Testing the method for vertically evacuating coastal structures in preparation for tsunamis.

5.4.4 USACE ERDC Coastal and Hydraulics Laboratory

ERDC is the research organization of the USACE and is one of the premier engineering and scientific research organizations in the world. USACE and FM Approvals developed the National Flood Barrier Testing & Certification Program based on the ANSI/FM Approvals Standard 2510 [31]. This program awards national recognition and FM Approval certification for products that can be tested at the ERDC's Coastal and Hydraulics Laboratory (CHL) in Vicksburg, Mississippi and meet the requirements. The CHL complex has 1.5 million ft^2 of specialized physical research facilities,

including those equipped to provide analysis of flood mitigation and damage prevention such as the Wave Flume Facility, SED Flume Facility, and the Full-Scale Levee Breach and Hydraulic Test Facility. CHL also has an internationally recognized coastal observatory, the Field Research Facility in Duck, North Carolina that can constantly record changing waves, winds, tides, and currents [54].

5.4.4.1 CHL Wave Flume Facility

Used for development and structural validation of coastal structures, this facility utilizes two individual flumes (Figure 5-23) to investigate rubble-mound trunk designs and quantify associated wave runup/overtopping. These flumes are additionally utilized to study the hydrodynamics of wave propagation and structure interactions.

Each flume is 208-ft long and 5-ft deep, but they differ in terms of width (5 ft and 10 ft). These flumes are actuated by computer-controlled electro-hydraulic wave generators. Both apparatuses can produce waves at a maximum height of 1.5 ft at periods varying from 0.75–10 seconds. While other flume facilities have modular data sensors, this one is equipped with an automated data-acquisition system consisting of a variety of fluid-measurement and laser-profiling instruments. Data acquired by this system is then directed to a control system that works to establish a steady, continuous operational flow consistent with the desired energy distribution.

Figure 5-23 USACE ERDC CHL 10-ft Wave Flume [54]

5.4.4.2 CHL Field Research Facility

This facility is primary used as an observatory for acquiring coastal field data (Figure 5-24). Outfitted with both deployable sensors and amphibious vehicles, it can monitor data regarding forces involved in the interactions among coastal waves, natural flood barriers, and the facility itself. Data collected at this facility improve flood prediction capabilities by revealing the conditions under which natural barriers begin to erode and perish.

Figure 5-24 USACE ERDC CHL Field Research Facility [54]

The layout of this facility mimics that of a pier, protruding ~1,837 ft from the North Carolina coast and descending 30 ft into the ocean. Located on the pier is a ~131-ft observation tower housing a 10-person data control center. Data-acquisition instruments deployable from this facility include perimeter scanning sonar and vibracoring sediment samplers. Also deployable are two amphibious vehicles, the Coastal Research Amphibious Buggy (CRAB, Figure 5-25) and the Lighter Amphibious Resupply Cargo (LARC-5). While these vehicles are both equipped with sensors similar to those found on the facility's pier, they are limited to respective offshore ranges. CRAB operates in coastal areas no deeper than 9 m, while the LARC-5 may venture out as far as 8 km. Additional noteworthy features of the LARC-5 are a crane with a load capacity of 5 tons and a maximum water speed of 5 knots.

Figure 5-25 USACE ERDC CHL CRAB Vessel [54]

5.4.4.3 CHL Full-Scale Levee Breach & Hydraulic Test Facility

This facility's three basins (Source, Test, and Catch) are separated by two embankments and used to investigate response barriers against flood rates resulting from different degrees of

simulated levee failure. Isolated breaches induced at this facility enable emergency repair responses to be repeatedly tested, thus fostering the development of rapid response tactics here. Breaches are simulated by a floodgate that gradually opens in accordance with different flow rates. Constructed on a slope, the levees convey water via gravity alone, enabling the collection of precise flood-rate data. Various barrier types are then placed in the middle basin to clog the second levee and prevent water from entering into the middle basin. Barrier performance tests are thus performed until the final basin is breached; afterwards, a pump can be used to refill the upper basin.

The source basin (top of slope, Figure 5-26) has a capacity of 2.2 million gallons, an 8836 ft^2 base, and a 17-ft depth. Hydraulic flood gates controlling the simulated breaches in the source basin can actuate at 1 in./s, creating various flow rates that max-out at 2,000 ft^3/s. The test basin (center) that accommodates they experimental barriers has a 150-ft-long base and a 12-ft high levee slope to enable an exit flow rate of 2,100 ft^3/s while ensuring that no overtopping occurs. The 12-ft deep catch basin (bottom) can hold the combined volume of the test and source basins: 4 million gallons. Attached to the catch basin is a stilling basin for dissipating the energy of water entering from the test basin. Overfilling of this basin is prevented by the implementation of a 2-ft riser pipe and emergency spillway. The pump used for returning water to the source basin has a minimum capacity of 1,833 gpm and is 14 in. in diameter. This replenishing system allows for the facility to be used once every 20 hours.

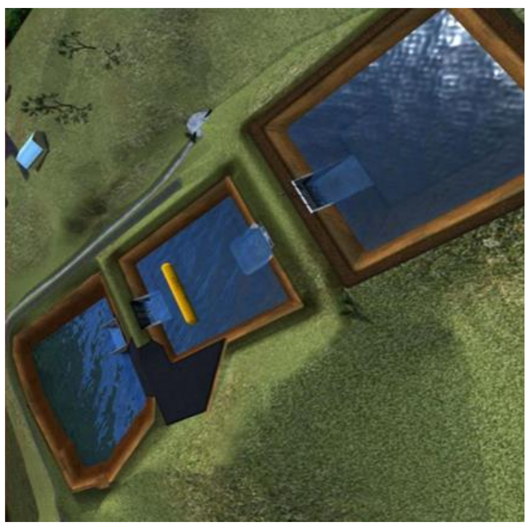

Figure 5-26 USACE ERDC CHL Levee Breach and Hydraulic Facility [54]

5.4.4.4 Tests at CHL

Most of the tests conducted at the CHL focus on the performance of natural sediment barriers against wave conditions generated by all types of coastal forces. Results from these studies go into the production of coastal breakwater armoring (CORE-LOC Technology) and rapid-response solutions for floods caused by large-scale barrier failures (Portable Lightweight Ubiquitous Gasket, Rapidly Emplaced Hydraulic Arch Barrier, Rapidly Emplaced Protection for Earthen Levees). Data not used in the production of new barrier technologies are used to improve prediction models and perform probabilistic risk assessments for extreme weather conditions.

The USACE ERDC report TR-07-3 [15] describes laboratory and field testing on temporary flood barriers such as sandbag and Portadam® that were conducted in Vicksburg, MS during 2004. The laboratory testing was conducted in a modified wave basin at ERDC CHL and the field testing was conducted at the Vicksburg Harbor. The lab and field protocols including performance and operational parameters can be found in [15].

5.5 International Flood Testing Facilities

Three international organizations were identified that focus on NPP flooding hazards and the effects of large external hazards on NPPs. The International Association for Hydro-Environmental Engineering and Research (IAHR) publishes a comprehensive list of institutions from 47 different countries that all focus on hydraulic and hydrological engineering. Each institution makes readily available a database of papers, events, and information [55]. By utilizing this list and consulting with professionals around the world, three institutions outside of the U.S. were found to focus on NPP flooding. These testing facilities were located in China, France, and Japan.

5.5.1 China Institute of Water Resources and Hydropower Research

The China Institute of Water Resources and Hydropower Research (IWHR) consists of 32 different laboratories and over 1,300 staff members [56]. The Laboratory of Hydraulics is internationally renowned for its broad spectrum of studies, including working closely with the China National Nuclear Corporation. Figure 5-27 shows IWHR's main facility in Beijing, China.

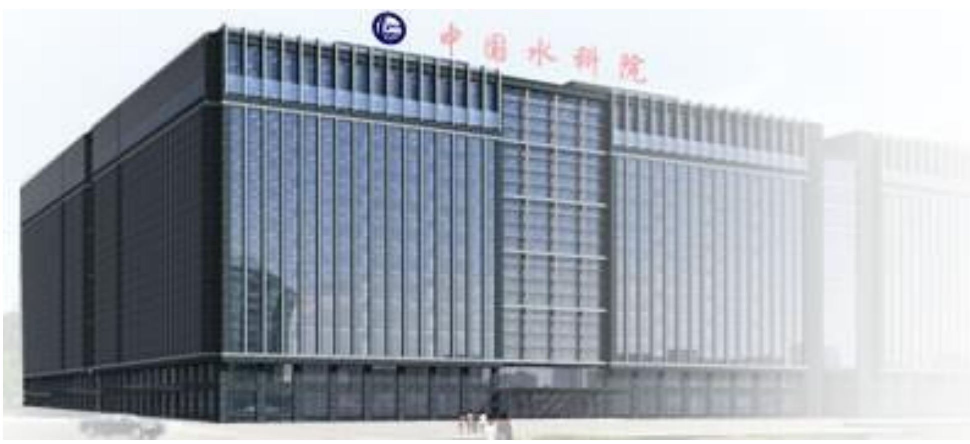

Figure 5-27 China IWHR Main Facility [56]

The Laboratory of Hydraulics consists of five laboratories: The First Laboratory, The Second Laboratory (under construction), The Third Laboratory, The Fourth Laboratory, and The High-speed Flow Research Laboratory.

The First Laboratory has a total area of 6,000 m^2, along with an underground reservoir of 4,000 m^3 that can be used for hydraulics modeling experiments regarding hydraulic structures. The facility has three sets of water supply systems and two water tanks. Its total water supply capacity is 1.7 m^3/s.

The Second Laboratory is currently under construction and will have multiple unique testing capabilities, such as a tidal wave pool, a wind tunnel flume, and special equipment for testing cooling-tower-related water issues. It can be used for hydrodynamics modeling experiments involving sedimentation, tide, outfall, and lake environments, as well as for cooling tower experiments.

The Third and Fourth Laboratories have the same function as the First Laboratory; namely, to conduct hydraulics modeling experiments regarding hydraulic structures. The Third Laboratory has a total area of 3,000 m^2 and a reservoir that is 50 m in length, 18 m in width, and 4 m in depth. The Fourth Laboratory has a total area of 900 m^2, with a circular reservoir of 1,000 m^3 and a total water supply capacity of 0.7 m^3/s provided by four pumps.

The High-speed Flow Research Laboratory conducts hydraulic cavitation research within a building that is 30 m in length, 12 m in width, and 16 m in height. The laboratory consists of three floors. The ground floor contains water pumps and supplies, the second floor contains machinery to manufacture models, and the third floor contains the laboratory. The third floor also features a reservoir that can hold 450 m^3 of water and contains a circulating water tunnel and a vacuum tank.

IWHR does hydraulic testing for existing and planned NPPs in China—more specifically, analyses regarding how to increase the effectiveness of cooling towers, the effects of low-level radioactive waste water from the Liaoning Hongyanhe Nuclear Power Station, the effects of pollutants in the water intake of NPPs, ecological concerns regarding water intake for the Binhai Nuclear Power Plant, and the redesign of the foundation of the Sanmen Nuclear Power Plant Station Circulating Pump House with regards to flooding.

5.5.2 Electricité De France

Electricité De France (EDF) provides in-depth flooding research through its National Laboratory of Hydraulics and Environment (LNHE) in Chatou, France [57].

LNHE sits on 130,000 m^2 of land, houses 500 researchers, and consists of three research departments. LNHE has the ability to numerically and physically model hydraulic systems. Components and systems can be modeled on-site. The two prominent physical modeling exhibits touted by EDF are the test loops. These test loops have a flow rate of up to 160 m^3/hr and provide demineralized, “oxygen free” water to test and optimize heat exchangers, pumps, valves, etc. It also allows the laboratory to test the reliability of hydraulic conditions under single- or multiphase flows of water, air, or freon. Figure 5-28 shows a test loop within LNHE.

Figure 5-28 EDF LNHE Test Loop [57]

Following the Blayais Nuclear Power Plant flooding incident in December 1999, EDF created a program to support flood hazard assessments for French NPPs. Following the program's success, German NPPs were evaluated, and EDF's LNHE garnered international attention [58, 59].

In 2000, EDF launched a Global Action Program in which NPPs undergo international review. The Global Action Plan released design reviews that highlighted four areas [59]:

- "hydrology, calculation of the maximum design flood level"
- "fixed of mobile protection works for the platform, the units, and especially the pumping stations"
- "warning systems"
- "operating procedure, equipment required for switching to and maintaining an emergency shutdown condition"

The resultant studies changed the way French and German NPPs are designed, and these changes were implemented in 2000.

In 2015, EDF was granted a U.S. patent for an NPP water intake system "suitable for establishment on a coastline vulnerable to tsunami flooding" [60]. The system utilizes a suction tunnel and basin to supply water despite external hazards caused by tsunamis or obstructions in the valves, thereby maintaining reactor water levels. Following a tsunami, the suction basin will detect an abnormal system state and create a watertight seal to cover the emergency pumps and emergency water reserves in order to keep seawater out.

5.5.3 Central Research Institute of Electric Power Industry (Japan)

The Central Research Institute of Electric Power Industry (CRIEPI) is a Japanese non-profit foundation that conducts research to support the electric power industry [61]. Their laboratories located around Japan focus on improving multiple areas within the electric power industry.

CRIEPI operates a civil engineering laboratory and an environmental science laboratory, both located near Abiko (Chiba Prefecture).

The Civil Engineering Research Laboratory is broken up into five sectors:

- Geosphere Sector – focused on studying geological conditions regarding site location and construction of power plants.
- Earthquake Engineering Sector – focused on researching seismic-resistant power plants.
- Structure Engineering Sector – focused on studying power plants affected by earthquakes.
- Fluid Dynamics Sector – focused on investigating how wind, rain, snow, and tsunami conditions affect power plants. Another focus is fluid dynamic technology optimization in NPPs.
- Nuclear Fuel Cycle Back-end Research Center – focused on low- and high-level radioactive waste disposal, along with the reuse of components following an NPP decommissioning.

The Environmental Science Research Laboratory primarily focuses on the biological and environmental effects of power plants. For the sake of brevity, this summary will not cover the Environmental Science Research Laboratory.

CRIEPI is known for its Large-Scale Tsunami Physical Simulator. Installed in 2014, it conducted a 1/3-scale simulation of the tsunami observed in Kesennuma City [62]. The facility is mainly utilized in fragility experiments by evaluating tsunami hydrodynamic loads, debris impact loads, and damage to structures under tsunami-like conditions. The testbed is 20 meters in length, 4 meters in width, and 2.5 meters in height, generating a maximum velocity of 7 m/s and a flow rate of 10 tons/s. The tank can hold 650 tons of water at a depth of 6.5 m. Figure 5-29 shows an overhead view of the Large-scale Tsunami Physical Simulator.

Figure 5-29 Japan CRIEPI Large-Scale Tsunami Physical Simulator [62]

Following the Fukushima Daiichi nuclear disaster, CRIEPI has spearheaded research on seismic stability, the fragility of NPP facilities, and the effects of tsunamis and large seismic events [63].

In 2014, CRIEPI developed a “constitutive model for a two-dimensional nonlinear time history response” to evaluate the stability of NPP foundations during major earthquakes [63]. The physical model consisted of multiple springs to simulate foundation stress, strain, and tensile failure. In addition to the physical model, CRIEPI developed a computational one to confirm the validity of the results.

In the same year, CRIEPI evaluated the concept of using rubble mounds to protect NPPs from tsunami breakwaters, exploring the potential mass of the mounds and the overflow velocity of various-sized waves. Numerical models validated the experimental data obtained in the Large-scale Tsunami Physical Simulator.

Using the Large-scale Tsunami Physical Simulator, experiments regarding seawalls and support columns showed the amount of pressure that structures can withstand before tsunamis cause

them to fail. The simulation used additional forms of debris, such as wooden logs and a car, to determine how such debris affects structural integrity during a tsunami.

6 DEVELOPING FLOOD BARRIER TESTING STRATEGIES

6.1 Testing Strategies

When developing flood barrier testing strategies, the following factors should be considered and addressed:

- Which flood barriers are to be tested?
- Which type(s) of flood barrier is to be tested?
- Are there codes, standards, and/or protocols available for flood barrier testing?
- What medium is to be used for the testing?
- What are the parameters (input and output)?
- Are the acceptance criteria needed and what are they?
- Where will testing be conducted?
- Are testing facilities or devices available, or do they need to be constructed?
- What other considerations could be made based on material type, barrier age, changes in material strength over year (stress-strain relationships) including thermal effects, mechanical effects, etc., for a given flood barrier type?

6.1.1 Selection of Flood Barriers for Testing

NPPs can have hundreds of flood barriers (penetration seals, doors, etc.) providing flood protection. These flood barriers may vary in safety (or risk) importance, qualities, operational conditions, and capabilities. An evaluation should be performed to prioritize the flood barriers and determine which ones are selected for testing (or enhanced inspection), which testing intervals are used, and which testing strategies are implemented.

One approach to such evaluation was introduced in EPRI's "External Flood Seal Risk-Ranking Process" [13], which presents a risk-ranking process for external flood seals that prioritizes which ones are potentially most important for mitigating plant flooding risk. To help focus resources on risk-significant items, it details the important characteristics of specific flood seals and specifies what they protect. For similar flood seals with similar ages, the accessibility of the seals could also be included in the considerations to select those seals at more accessible locations.

It should be noted that, although enhanced inspection is not a "test" in the literal sense, its unique cost advantage and easier, quicker implementation potentially make it worth considering along with other flood barrier testing strategies as part of an integrated testing plan. For example, it could be conducted on flood barriers of lesser risk significance while ones of higher risk significance undergo more expensive testing methods.

6.1.2 Type of Flood Barriers for Testing

The type of flood barriers to be tested could include different kinds of penetration seals, doors, walls, floors, and temporary barriers incorporated into the plant (though walls and floors may be

excluded from testing save in special situations). Different testing strategies should be applied to different types of flood barriers.

6.1.3 Codes and Standards for Flood Barrier Tests

EPRI 3002005423 [12] identifies testing protocols including the codes and standards used to qualify flood barriers at NPPs in regard to pressure resistance as below.

6.1.3.1 Penetration Seals

Currently, no codes or standards address protocol for testing the pressure resistance of flood barrier penetration seals, though test standards from Underwriters Laboratories (UL), the Institute of Electrical and Electronics Engineers, and the American Society for Testing and Materials (ASTM) exist for fire barrier penetration seals. Of these, UL 1479, Standard for Fire Tests of Through-Penetration Firestops [64], and UL 2079, Standard for Tests for Fire Resistance of Building Joint Systems [65], contain provisions for the pressure testing of penetration seals. In addition, a military specification MIL-DTL-24705B(SH) [36] contains watertightness test requirements (including requirements of specimen mounting, test pressure, test duration, and failure criteria) for multiple cable penetrator frames, accessories, and insert materials on Naval ships.

6.1.3.2 Doors

Testing for doors is generally covered by door testing standards or analytical methods. For example, ASTM E331 is a testing standard describing procedures for determining the water penetration resistance of structures such as doors [66].

6.1.3.3 Base Structures (Walls and Floors)

Testing of base structures (i.e., walls and floors) is typically governed by the design criteria for SSCs, as well as accepted analytical methods.

6.1.4 Protocols and Plans for Flood Barrier Tests

6.1.4.1 Location

Possible locations of flood barrier testing are:

- Ex-situ and off-site (using off-site testing facilities). If harvesting of flood barriers is possible, the flood barriers from operating or decommissioning nuclear plants can be obtained and transported to off-site testing facilities for testing. This would be the most feasible and flexible approach to test flood barriers as (1) it would not impact (or be impacted by) the nuclear plant operational schedules; (2) the testing facilities are usually more experienced in conducting the tests.
- In-situ (in plant, in place). If harvesting of flood barriers is not possible or when it is desired, in-situ testing in operating or decommissioning nuclear plants could be pursued. This approach could obtain the testing results that best reflect as-is flood barrier with its authentic working environment. However, the approach would be restricted by the accessibility of the flood barriers, the space available and required by the testing platform, and the plant operational schedules.

- Ex-situ but on-site (not in place, but on-site). This approach would alleviate the restrictions as those in the in-situ testing above, but it still needs to bring the testing platform to the plant and the testing schedules need to be incorporated into the routine plant schedules.
- Enhanced Inspection (in plant, in place). As stated in Section 6.1.1, enhanced inspection is not a full test of the barrier's function and capacity. But it is an easier and quicker approach that could be incorporated to the plant's other operating and maintenance schedules, and it could be part of the integrated testing plan for those flood barriers with lesser risk significance while more expensive testing methods being conducted for higher risk significant flood barriers.

6.1.4.2 Flood Effect and Failure Modes

Possible flood effects to be considered in flood barrier testing are hydrostatic pressure, hydrodynamic pressure, and debris impact.

Possible failure modes of flood barriers are excessive leakage, loss of integrity, displacement, and overtopping.

6.1.4.3 Mediums for Flood Barrier Tests

Water, air, and steam can be used as mediums in flood barrier tests. Besides freshwater and saltwater, there are other types of fluids (such as borated water) might also be of interest to impact flood barriers in NPPs. The mediums could be standing (without pressure) for static pressure testing, under pressure (via pump or air) for dynamic pressure testing, or with simulated wave action.

6.1.4.4 Parameters for Flood Barrier Tests

Parameters for flood barrier tests can be categorized into input parameters, output parameters, and miscellaneous parameters. Input parameters are those that can be varied in the test, such as test pressure, water level, flow rate, duration of applied pressure, rate of pressure change, and debris size. Output parameters are those measured and used in the acceptance criteria for the test, such as leakage rate and the maximum pressure before loss of integrity occurs in the flood barrier.

Miscellaneous parameters that should also be recorded during testing include water temperature, test duration, and the time history of the input and output parameters.

6.1.4.5 Performance-based Testing for Flood Barriers

Traditionally, binary pass/fail has been used as acceptance criteria for barrier testing. One lesson learned from previous fire barrier tests is that we should stay away from the binary pass/fail test. Instead, performance-based testing should be conducted to correspond with the functional requirements of the flood barriers to be tested, which could measure the margins and support the risk-informed decision making process. The performance of the tested flood barriers instead of pass/fail threshold should be evaluated, e.g., whether the flood barriers have any leakage under different pressures, how long the flood barriers can endure under pressure without leakage, whether (and how well) the barriers can maintain integrity under various static and/or dynamic pressure.

6.1.4.6 Other Aspects

Other aspects to be considered in flood barrier testing protocol and plans include whether the test is destructive or non-destructive, whether testing devices are available or need construction/installation, whether sample and/or actual flood barriers in the plant are tested, etc. Other considerations could also be made based on material type, barrier age, changes in material strength over year (stress-strain relationships) including thermal effects, mechanical effects, etc., for a given flood barrier type. For example, to consider the aging effects on the barriers, components at different ages (10 years, 20 years, etc.) can be tested and see how the failure rates change.

6.2 Previous Test Examples

This section introduces a few examples of flood barrier tests already conducted.

6.2.1 Previous Test 1

This was an ex-situ test on penetration seals.

6.2.1.1 Test Apparatus

As documented in [5], an ex-situ testing protocol for evaluating the performance of flood penetration seals at NPPs was developed. The effectiveness of the testing protocol was assessed by performing a series of flood tests at a Framatome facility in Lynchburg, Virginia in 2018. The test apparatus is shown in Figure 5-17, adapted from [5]. It consisted of three main components: a pressure chamber, test deck, and water leakage measurement system. Five test decks were constructed, each consisting of a square concrete slab to support the installation of various penetrations. It should be noted that the penetrations used in the test were all new with no aging or wear. Also, the test set a maximum test duration of approximately 180 minutes.

6.2.1.2 Test Sample

The size, number, and configuration of seals varied among the five test decks. Five or six seals were installed on each test deck. The seals were characterized using penetration-related parameters (i.e., shape, size, sleeved or not), seal-related parameters (i.e., seal materials and whether formed-in-place or mechanical), and penetrant-related parameters (i.e., penetrant and its type, braced or not, etc.).

6.2.1.3 Test Procedure

For each test, the two main variables were analyzed in regard to water pressure and the duration thereof. Initially, the chamber was pressurized to a specific value and held there for several minutes. This initial pressurization was used to verify the water-tightness of the test apparatus. After this period, test pressures were progressively increased.

The rate of pressure increases varied from test to test. Both rapid and slow pressure change rates were used. Water pressure could sometimes be held constant, creating hydrostatic pressure on the penetration seals. During a test, the test apparatus’s data acquisition system recorded the following parameters in 1-second intervals: test chamber pressure, water temperature, and water volumetric flow rates from individual seals.

The overall duration of each test was determined by one of two events: 1) reaching the chosen maximum test duration; or 2) experiencing catastrophic penetration seal failure.

6.2.1.4 Test Results

The results of testing included approximate test duration, approximate maximum water pressure, test termination cause, pressure vs. time graphs, leakage flow rate vs. time graphs, and in-test and post-test visual observations.

6.2.2 Previous Test 2

This was an ex-situ test on doors.

6.2.2.1 Test Apparatus

As documented in [32] and [33], non-watertight doors, commonly found in NPPs, were tested to determine their performance under flooding conditions. Flood tests were conducted at the ISU flood testing facility described in Section 5.3.

6.2.2.2 Test Sample

Doors—the types of which varied among the tests—were characterized by door orientation (inward or outward swinging), door materials (wooden hollow core or steel), and door hardware. Wooden hollow core doors were tested first, followed by steel door tests (not deadbolted, merely latched, deadbolted, latched and deadbolted, and with new latch handles installed) Outward swinging doors were tested before inward swinging doors, regardless of door type.

6.2.2.3 Test Procedure

Figure 6-1 shows the test procedure given in [33].

Each test began with preset valve positions, then the recording started, followed by water supply pump activation. In the PET filling phase, filling rates varied among the tests.

During a test using the initial PET piping configuration, measurements included flow rate into the PET, tank water depth, and water temperature. During a test using the modified PET piping configuration, measurements included upstream and downstream flow rates for multiple pipeline sizes, two water depths for averaging, and water temperature. In both configurations, the PET could also measure small leakage rates not exceeding the weir and pressures for simulated hydrostatic head once the PET was filled.

The overall duration of each test was determined by one of two events: (1) a failure state or (2) the water leakage rate equalizing or exceeding the filling rate.

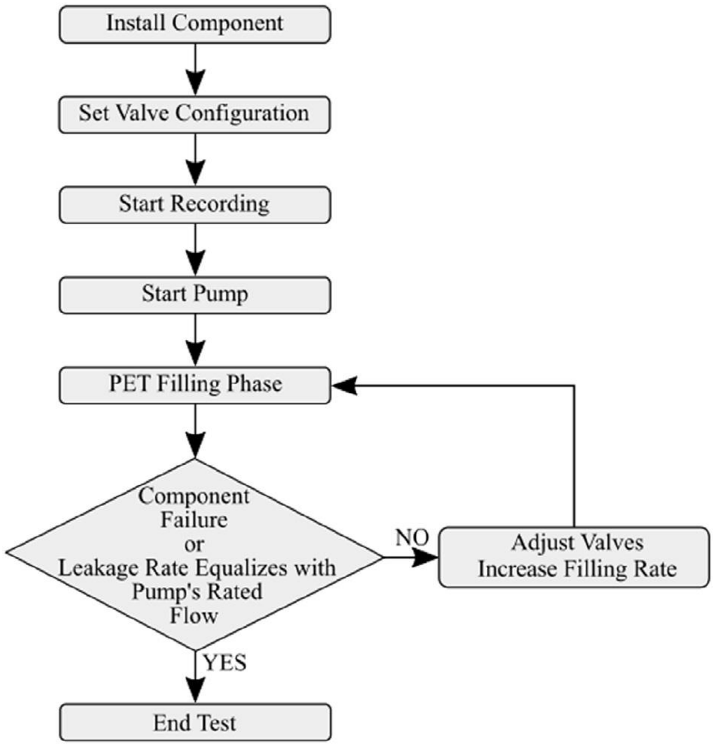

Figure 6-1 Initial PET Piping Configuration [33]

6.2.2.4 Test Results

The results of testing included time to failure, maximum water depth (referred to as "failure depth"), water depth vs. time graphs, and observed failure modes.

6.2.3 Previous Test 3

This was an ex-situ test on temporary barriers.

6.2.3.1 Test Apparatus

As documented in [15], three commercial temporary flood barrier products and a USACE sandbag barrier were tested and evaluated at a natural site subject to natural high water. This site is located in Vicksburg, Mississippi on the southern bank of a turning basin directly connected to the Mississippi River via a canal. The tested barriers were constructed on- site. Concrete sump pits were constructed on the protected side of each barrier to capture and measure the seepage water. Three instrumentation arrays were used at the test site, including (1) a video monitoring system that recorded a complete time history of all construction, testing, and removal of tested barriers from different angles, (2) a water level monitoring system consisting of water level gages and sensors in addition to associated data collection and processing systems, and (3) a total station theodolite for barrier dimension measuring.

6.2.3.2 Test Sample

Four full-scale temporary flood barriers were constructed and tested, including a USACE sandbag levee, a Rapid Deployment Flood Wall, a Hesco Bastion Concertainer® levee (granular-filled, fabric-lined wire baskets), and a Portadam® levee (impermeable membrane liner with supporting frame).

6.2.3.3 Test Procedure

For each tested barrier, the beginning of the test was defined when the river rose to a level at which the water contacted the structure. During the tests, seepage was collected in the concrete sump pits, and the barriers were continuously monitored for structural damage, material loss, and structural failure or fatigue. For most tested barriers, testing ended when the barrier was overtopped by water flowing freely over the structure and exceeding pump capacity on the protected side.

6.2.3.4 Test Results

Test results related to flood barrier performance included seepage flow rates, wetted surface area of a structure, seepage rate vs. wetted perimeter area graphs, and seepage rate vs. stage of the river graphs. Other test results pertained to operational concerns, such as ease of construction (including time, effort, manpower, and equipment), ease of removal (time, effort, manpower, and equipment), easy of repair, barrier durability, and barrier reusability.

6.2.4 Previous Test 4

This was also an ex-situ test on temporary barriers.

6.2.4.1 Test Apparatus

Concurrent with the temporary barrier field tests described in Section 6.2.3, the barrier products were tested in a controlled laboratory setting in a wave research basin at ERDC in Vicksburg, Mississippi [15]. The test facility was laid out along the perimeter wall of a reservoir. Each barrier was constructed within a common geometric testing zone laid out on a smooth concrete floor. Fresh, clean water was impounded against each barrier for specified common test configurations simulating floodwater conditions. A circular pit was constructed on the protected side of each barrier to catch any seepage or overflow water from the barrier. Pumps were installed in the pit to pump the accumulated water back into the wave basin. During testing, instruments were used to measure the flow rate from the pumps, determine the water level inside the pit, and monitor barrier displacements (both horizontal and overturning). Wave basin data (reservoir height, wave generation, and hydraulic parameters) were monitored separately.

6.2.4.2 Test Sample

As with the field testing, four full-scale temporary flood barriers were constructed and tested, including a USACE sandbag levee, a Rapid Deployment Flood Wall, a Hesco Bastion Concertainer® levee, and a Portadam® levee.

6.2.4.3 Test Procedure

The barriers were tested according to a protocol developed by ERDC. For each barrier, the conducted tests included (1) hydrostatic testing, (2) hydrodynamic testing, (3) barrier overtopping, and (4) debris impact testing.

For hydrostatic tests, three gradually increasing pool elevations were utilized in front of the dam, with a minimum of 22 hours at each. For the hydrodynamic tests, two different pool elevations were used. At the lower pool elevation, 3-inch waves were continually generated for a period of 7 hours, followed by 7- to 9-inch waves impacting the barrier for three 10-minute intervals. Next, 10- to 13-inch waves were generated, impacting the barrier for a total of 10 minutes. These tests were repeated once the water level was raised to a higher elevation.

For overtopping tests, the water level was raised until water spilled over the top of the barrier. The test began when the pool elevation reached a certain value, the pumps were working at maximum capacity, or the water level in the pit remained constant—whichever came first. The test ended after a pre-determined period or once the barrier failed. Furthermore, two separate impact tests were conducted using logs of two different sizes to impact each barrier at equal speed.

6.2.4.4 Test Results

Test results related to flood barrier performance included seepage flow rates, barrier displacements, seepage per linear foot vs. time graphs, and seepage & overtopping vs. time graphs. Other test results pertained to operational concerns, such as ease of construction (including time, effort, manpower, and equipment), ease of removal (time, effort, manpower, and equipment), easy of repair, barrier durability, and barrier reusability.

6.2.5 Summary of Flood Barrier Test Examples

Table 6-1 provides a summary of the flood barrier test examples described in previous sections.

Table 6-1 Comparison of Reviewed Flood Barrier Testing Strategies in Previous Example Tests

	Test 1	Test 2	Test 3	Test 4
Flood Barrier Type	Penetration seals	Doors	Temporary barriers	Temporary barriers
Testing Location	Ex-situ	Ex-situ	Ex-situ	Ex-situ
Facility Type	Test deck with pressure chamber	Tank	Natural site	Research basin
Testing Type	Destructive	Destructive	Destructive	Destructive
Included Tests	Hydrostatic, hydrodynamic	Hydrostatic, hydrodynamic	Hydrostatic, hydrodynamic	Hydrostatic, hydrodynamic, overtopping, debris impact
Test Variables	Water pressure, duration of applied pressure, rate of pressure change	Tank filling rate	Natural flooding	Water level, wave size, wave duration, debris size
Test Measurements	Test chamber pressure, water temperature, water volumetric flow rates from individual seals	Flow rates into the tank, tank water depth, water temperature, small leakage rates, pressures for simulated hydrostatic head	Water levels in seepage collection pits, time history of construction/testing/removal of tested barriers, barrier dimensions	Water levels in seepage collection pits, time history of construction/testing/removal of tested barriers, barrier dimensions
Test Termination	Until maximum test duration was exceeded, or seal failure occurred	Until door failure or the water leakage rate equalizing or exceeding the filling rate	Until a barrier was overtopped by water flowing freely over the barrier and exceeding pump capacity on the protected side	Until maximum test duration was exceeded, or barrier failure occurred
Test Outputs (Numerical)	Test duration, maximum water pressure, pressure vs. time graphs, leakage flow rates vs. time graphs	Time to failure, failure water depth, water depth vs. time graphs	Seepage flow rates, seepage rate vs. wetted perimeter area graphs, seepage rate vs. stage of the river graphs, operational concerns (e.g., ease of construction, barrier durability and reusability)	Seepage flow rates, barrier displacements, seepage per linear foot vs. time graphs, seepage & overtopping vs. time graphs, operational concerns (e.g., ease of construction, barrier durability and reusability)

6.3 Flood Barrier Testing Strategies Workshop

NRC and INL organized a half-day workshop on flood barrier testing strategies at NRC Headquarters in Rockville, Maryland on March 12, 2020. The workshop was a public meeting attended by members of the public, NRC technical staff, management, and contractors, and staff from INL, ISU, and other agencies. An overview of the research on flood barrier testing strategies as well as the preliminary research results from the project were presented. Industry stakeholders and technical experts provided valuable inputs and insights on flood barrier testing strategies. The discussions from the workshop have led several follow-up actions for the research that were thereafter incorporated in this report, for example, the review of ANSI FM 2510, the discussion of the USACE ERDC flood testing facility in Vicksburg, Mississippi, the review of more nuclear plant flood walkdown reports.

INL/EXT 20-57927 [67] is a publicly available INL report that documents the materials presented, participant questions and answers, and summaries of an open discussion during this workshop.

7 SUMMARY

This report presents research, performed by INL for the NRC, to develop NPP flood barrier testing strategies. Flood barrier performance at NPPs may have significant safety implications and has long been an ongoing safety concern. This research identifies and develops strategies for testing NPP flood barriers by reviewing available information on flood barriers employed at NPPs and assessing (1) the current state of NPP decommissioning for potential harvesting, (2) the technical and logistical considerations and challenges to harvesting and the laboratory testing of flood barriers, and (3) potential alternatives to harvesting, such as in-situ testing and enhanced inspection.

A categorization of flood protection features is proposed per the following categorization criteria: physical features or devices vs. human actions and procedures, on-site vs. off-site, exterior vs incorporated, permanent vs. temporary, and active vs. passive. In addition, a taxonomy of physical, on-site flood protection features was developed that included flood barriers, mitigative conveyance drains, and circumstantial flood-affecting structures. Detailed descriptions and examples of flood barriers and flood protection features are provided. Key terms related to flood protection features used in this report are also defined. As there are no standard definitions for many flood protection features, the definitions in this report may vary slightly from those in other literature.

This report documents the results of a literature review on flood barriers at NPPs and their testing strategies. The reviewed materials were mainly gathered from various U.S. and international agencies, as well as from miscellaneous sources such as workshop proceedings and flood barrier vendors. The review focuses on permanent flood barriers (e.g., penetration seals and watertight doors) in addition to temporary flood barriers incorporated into the plant. Off-site flood barriers such as levees and berms are not a focus of the review. The results of the literature review were summarized as follows: flood barrier categorization, flood barrier descriptions, potential flood barrier testing facilities, and flood barrier testing strategies.

Flood barrier testing facilities that could potentially be used in the research are described in Section 5. These facilities include operating power reactors, decommissioning power reactors, and domestic and international flood testing facilities.

Section 6 presents flood barrier testing strategies suggested by this research, which began with questions and considerations pertaining to testing strategies and quickly led to preliminary deliberations on considerations that could later be utilized in testing strategy development. Several examples of previously conducted flood barrier tests are introduced, including laboratory testing of penetration seals at Framatome, laboratory testing for doors at ISU, field testing for temporary barriers, and laboratory testing for temporary barriers at USACE ERDC. These sample tests were compared in various aspects, including flood barrier type, testing location, facility type, testing type, test variables, test measurements, test termination rules, and numerical test outputs.

This research contributes to a comprehensive understanding of flood barriers and available testing strategies at NPPs and may be used to guide development of actual testing programs by stakeholders. It may also serve as the basis for developing new testing strategies in connection with future research.

8 REFERENCES

[1] U.S. Nuclear Regulatory Commission, "Perspective Gained from the Individual Plant Examination of External Events (IPEEE) Program," NUREG-1742, Volume 1, Part 2, 2002 (ADAMS Accession No. ML021270122).

[2] U.S. Nuclear Regulatory Commission, "Perspective Gained from the Individual Plant Examination of External Events (IPEEE) Program," NUREG-1742, Volume 2, 2002 (ADAMS Accession No. ML021270674).

[3] U.S. Nuclear Regulatory Commission, "Flood Protection for Nuclear Power Plants," Regulatory Guide 1.102, Revision 1, 1976 (ADAMS Accession No. ML003740308).

[4] U.S. Nuclear Regulatory Commission, "Japan Lessons-Learned Project Directorate, Guidance for Performing the Integrated Assessment for External Flooding," Interim Staff Guidance JLD-ISG-2012-05, Revision 0, 2012 (ADAMS Accession No. ML12311A214).

[5] U.S. Nuclear Regulatory Commission, "Flood Penetration Seal Testing Protocol Research," Previous Title: "Development of an Ex Situ Performance Testing Protocol for Nuclear Power Plant Flood Penetration Seals," NUREG-2240, 2022 (ADAMS Accession No. ML22042B319).

[6] Fire Risk Management Inc., "Flood Penetration Seal Assemblies at Operating Nuclear Power Plants," 2016 (ADAMS Accession No. ML18043B094).

[7] Fire Risk Management Inc., "Draft Methodology for Testing and Evaluating the Performance Flood Penetration Seals," 2018 (ADAMS Accession No. ML18043B093).

[8] L. Przybyla and W. J. Christian, "Development and Verification of Fire Tests for Cable Systems and System Components," NUREG/CR-0152, U.S. Nuclear Regulatory Commission, 1978 (ADAMS Accession No. ML071690017).

[9] R. B. Williamson and F. L. Fisher, "Tests and Criteria for Fire Protection of Cable Penetrations," NUREG/CR-2377, U.S. Nuclear Regulatory Commission, 1981 (ADAMS Accession No. ML071690424).

[10] C. S. Bajwa and K. S. West, "Fire Barrier Penetration Seals in Nuclear Power Plants," NUREG-1552, U.S. Nuclear Regulatory Commission, 1996 (ADAMS Accession No. ML070600315).

[11] Nuclear Energy Institute, "Guidelines for Performing Verification Walkdowns of Plant Flood Protection Features," NEI 12-07, Revision 0-A, 2012.

[12] Electric Power Research Institute, "Flood Protection Systems Guide," EPRI Product No. 3002005423, 2015.

[13] R. Schneider and M. Randelovic, "External Flood Seal Risk-Ranking Process," in *4th Annual Probabilistic Flood Hazard Assessment Workshop*, 2019 (ADAMS Accession No. ML19156A447).

[14] J. Leech, L. Wehmeyer, D. Margo, L. Lee, A. Byrd and D. Ward, "Technical Basis for Flood Protection at Nuclear Power Plants," ERDC/CHL TR-15-3, U.S. Army Crops of Engineers, Engineer Research and Development Center, 2015.

[15] F. Pinkard, T. Pratt, D. Ward, T. Holmes, J. Kelley, L. Lee, G. Sills, E. Smith, P. Taylor, N. Torres, L. Wakeley and J. Wibowo, "Flood-Fighting Structures Demonstration and Evaluation Program: Laboratory and Field Testing in Vicksburg, Mississippi," ERDC TR-07-3, U.S. Army Corps of Engineers, Engineer Research and Development Center, 2007.

[16] Nuclear Energy Agency, "Concepts and Terminology for Protecting Nuclear Installations from Flood Hazards," Draft, 20xx.

[17] G. Wittmeyer, O. Osidele, B. Dasgupta and R. Fosdick, "Guidance to Support NRC Assessment of Selected Flood Protection Features at Nuclear Power Plants," Center for Nuclear Waste Regulatory Analyses, 2014.

[18] U.S. Nuclear Regulatory Commission, "Recommendations for Enhancing Reactor Safety in the 21st Century - the Near-Term Task Force Review of Insights from the Fukushima Dai-Ichi Accident," 2011 (ADAMS Accession No. ML111861807).

[19] U.S. Nuclear Regulatory Commission, "Request for Information Pursuant to Title 10 of the Code of Federal Regulations 50.54(f) Regarding Recommendations 2.1, 2.3, and 9.3, of the Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident," 2012 (ADAMS Accession No. ML12053A340).

[20] Entergy Nuclear, "Arkansas Nuclear One Unit 1 Flooding Walkdown Submittal Report for Resolution of Fukushima Near-Term Task Force Recommendation 2.3: Flooding," 2012 (ADAMS Accession No. ML12334A009).

[21] U.S. Nuclear Regulatory Commission, "Arkansas Nuclear One, Units 1 and 2 - Staff Assessment of the Flooding Walkdown Report Supporting Implementation of Near-Term Task Force Recommendation 2.3 Related to the Fukushima Dai-chi Nuclear Power Plant Accident," 2014 (ADAMS Accession No. ML14178A821).

[22] Nebraska Public Power District, "Cooper Nuclear Station Flooding Walkdown Report," 2012 (ADAMS Accession No. ML12333A320).

[23] U.S. Nuclear Regulatory Commission, "Cooper Nuclear Station - Staff Assessment of the Flooding Walkdown Report Supporting Implementation of Near-Term Task Force Recommendation 2.3 Related to the Fukushima Dai-chi Nuclear Power Plant Accident," 2014 (ADAMS Accession No. ML14149A146).

[24] Exelon Generation, "Supplemental Response to NRC Request for Information Pursuant to NRC Request for Information Pursuant to 10 CFR 50.54(f) Regarding the Flooding Aspects of Recommendaiton 2.3 of the Near-Term Task Force Review of Insights from Fukushima Dai-ichi Accident," 2013 (ADAMS Accession No. ML13241A288).

[25] U.S. Nuclear Regulatory Commission, "Oyster Creek Nuclear Generating Station - Staff Assessment of the Flooding Walkdown Report Supporting Implementation of Near-Term Task Force Recommendation 2.3 Related to the Fukushima Dai-chi Nuclear Power Plant Accident," 2014 (ADAMS Accession No. ML14065A232).

[26] U.S. Nuclear Regulatory Commission, "Oyster Creek Nuclear Generating Station - Audit Report Regarding Flooding Walkdowns to Support Implementation of Near-Term Task Force Recommendation 2.3 Related to the Fukushima Dai-chi Nuclear Power Plant Accident," 2014 (ADAMS Accession No. ML13277A223).

[27] NextEra Energy Point Beach, LLC., "NextEra Energy Point Beach, LLC Response to 10 CFR 50.54(f) Request for Information Regarding Near-Term Task Force Recommendation 2.3, Flooding," 2012 (ADAMS Accession No. ML12326A713).

[28] U.S. Nuclear Regulatory Commission, "Point Beach Nuclear Plant, Units 1 and 2 - Staff Assessment of the Flooding Walkdown Report Supporting Implementation of Near-Term Task Force Recommendation 2.3 Related to the Fukushima Dai-chi Nuclear Power Plant Accident," 2014 (ADAMS Accession No. ML14147A011).

[29] Florida Power & Light Company, "Flooding Walkdown Report in Response to the 50.54(f) Information Request Regarding Near-Term Task Force Recommendation 2.3: Flooding," 2012 (ADAMS Accession No. ML12335A202).

[30] U.S. Nuclear Regulatory Commission, "St. Lucie Plant, Units 1 and 2 - Staff Assessment of the Flooding Walkdown Report Supporting Implementation of Near-Term Task Force Recommendation 2.3 Related to the Fukushima Dai-chi Nuclear Power Plant Accident," 2014 (ADAMS Accession No. ML14135A422).

[31] FM Approvals, "American National Standard for Flood Mitigation Equipment," ANSI/FM Approvals 2510-2020, 2020.

[32] C. Pope, B. Savage, B. Johnson, C. Muchmore, L. Nichols, G. Roberts, E. Ryan, S. Suresh, A. Tahhan, R. Tuladhar, A. Wells and C. Smith, "Light Water Reactor Sustainability Program, Nuclear Power Plant Mechanical Component Flooding Fragility Experiments Status," INL/EXT-17-42728, Idaho National Laboratory, 2017.

[33] A. Wells, E. Ryan, B. Savage, A. Tahhan, S. Suresh, C. Muchmore, C. Smith and C. Pope, "Non-watertight door performance experiments and analysis under flooding scenarios," *Results in Engineering,* 2019.

[34] Federal Emergency Management Agency, "Floodproofing Non-Residential Buildings," FEMA P-936, 2013.

[35] A Better City, "Passive Flood Barrier Overview and Product Comparisons," 2015.

[36] U.S. Naval Sea Systems Command, "Detail Specification: Penetrators, Multiple Cable, Electric Cable, General Specification For," MIL-DTL-24705B(SH), 2010.

[37] Elite Garage Floors Co., "Solid Aluminum Threshold," [Online]. Available: https://www.elitegaragefloors.com/solid-aluminum-threshold-4-w-x-16-4-l/. [Accessed 23 February 2021].

[38] Thorne & Derrick International Co., "Duct Seals & Sealing," [Online]. Available: https://www.powerandcables.com/product/duct-seals/. [Accessed 23 February 2021].

[39] PS Flood Barriers Co., "Hinged Flood Barrier (Single)," [Online]. Available: https://www.psfloodbarriers.com/product/hinged-flood-barrier-single/. [Accessed 23 February 2021].

[40] WaterSlayer, "OSMO Flood Barrier," [Online]. Available: https://waterslayer.com/products/10-ft-flood-barrier. [Accessed 23 February 2021].

[41] Floodshield, "Floodshield," [Online]. Available: https://floodshield.com/. [Accessed 23 February 2021].

[42] PS Flood Barriers Co., "HydroDefense® Flood Plank™," [Online]. Available: https://www.psfloodbarriers.com/product/hydrodefense-flood-plank/. [Accessed 23 February 2021].

[43] G. A. George, "Reflection on Fort Calhoun Station Yellow Flood Finding and 2011 Flood Event Response," U.S. Nuclear Regulatory Commission, 5th Annual Probabilistic Flood Hazard Assessment Workshop, Rockville, MD, 2020 (ADAMS Accession No. ML20080M154).

[44] Quick Dams Co., "Water-Gate WL," [Online]. Available: https://quickdams.com/index.php/product/water-gate-wl/. [Accessed 23 February 2021].

[45] Portadam, Inc., "Portadam," [Online]. Available: https://portadam.com/. [Accessed 23 February 2021].

[46] Gadelius, "NOAQ AB Flood Protection System," [Online]. Available: https://www.gadelius.com/products/disaster_relief/03_e.html. [Accessed 23 February 2021].

[47] Surf-Tec Corp., "Flood Control," [Online]. Available: https://www.surf-tec.ca/index.php/flood-control/. [Accessed 23 February 2021].

[48] U.S. Nuclear Regulatory Commission, "Map of Power Reactor Sites," [Online]. Available: https://www.nrc.gov/reactors/operating/map-power-reactors.html. [Accessed 19 February 2021].

[49] U.S. Nuclear Regulatory Commission, "2020-2021 Information Digest," NUREG-1350, Volume 32, 2020 (ADAMS Accession No. ML20282A632).

[50] U.S. Nuclear Regulatory Commission, "Power Reactors Decommissioning Status," [Online]. Available: https://www.nrc.gov/images/reading-rm/doc-collections/maps/power-reactors-decommissioning-sites.png. [Accessed 19 February 2021].

[51] Oregon State University, "Design Safe-CI, Experimental Facility," Oregon State University, [Online]. Available: https://oregonstate.designsafe-ci.org/. [Accessed July 2020].

[52] Oregon State University, O.H. Hinsdale Wave Research Laboratory, "Directional Wave Basin," [Online]. Available: https://wave.oregonstate.edu. [Accessed July 2020].

[53] Oregon State University, O.H. Hinsdale Wave Research Laboratory, "Large Wave Flume," [Online]. Available: https://wave.oregonstate.edu. [Accessed July 2020].

[54] U.S. Army Corps of Engineers, Engineer Research and Development Center, "CHL Facilities," [Online]. Available: https://www.erdc.usace.army.mil/Locations/CHL/Facilities.aspx. [Accessed July 2020].

[55] IAHR, International Association for Hydro-Environmental Engineering and Research, "IAHR Institute Members," [Online]. Available: https://www.iahr.org/index/institute-member. [Accessed 19 June 2020].

[56] IWHR (China Institute of Water Resources and Hydropower Research), "IWHR Laboratory of Hydraulics," [Online]. Available: http://www.iwhr.com/IWHR-English/Research/Laboratories/webinfo/2009/08/1434029684176345.htm. [Accessed 19 June 2020].

[57] EDF, France, "EDF - Our Activities," [Online]. Available: https://www.edf.fr/en/the-edf-group/who-we-are/activities/research-and-development/our-activities. [Accessed 19 June 2020].

[58] A. Gorbatchev, J. M. Mattéi, V. Rebour and E. Via, "Report on Flooding of Le Blayais Power Plant on 27 December 1999," 2000.

[59] J. M. Mattei, E. Vial, V. Rebour and H. Liemersdorf, "Generic Results and Conclusions of Re-Evaluating the Flooding Protection in French and German Nuclear Power Plants," 2002.

[60] C. Legendre, "Water Intake Installation for Cooling a Nuclear Power Plant Comprisong Such an Installation". US Patent 2015/0357064 A1, 23 July 2015.

[61] CRIEPI, "Abiko Area- Civil Engineering Research Laboratory/ Environmental Science Research Laboratory/ Abiko Operation & Service Center/ Procurement Center," [Online]. Available: https://criepi.denken.or.jp/en/publications/pamphletslabo/abiko_201604.pdf.. [Accessed 28 June 2020].

[62] CRIEPI, "Large-Scale Physical Tsunami Physical Simulator," [Online]. Available: https://criepi.denken.or.jp/en/publications/annual/2014/041.pdf. [Accessed 15 July 2020].

[63] CRIEPI, "Assessment of Fragility of Nuclear Facilities due to External Natural Events," [Online]. Available: https://criepi.denken.or.jp/en/publications/annual/2015/P12-P13_project04.pdf. [Accessed 15 July 2020].

[64] Underwriters Laboratories, "Standard for Fire Tests of Penetration Firestop," UL 1479, 2015.

[65] Underwriters Laboratories, "Standard for Tests for Fire Resistance of Building Joint Systems," UL 2079, 2015.

[66] American Society for Testing and Materials, "Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference," ASTM E331-00, 2016.

[67] S. Zhang, Z. Ma and C. Smith, "Summary of Nuclear Regulatory Commission Flood Barrier Testing Strategies Workshop," INL/EXT 20-57927, Idaho National Laboratory, 2020.

[68] ILC Dover, "Flex-Gate Stairwell," [Online]. Available: https://www.ilcdover.com/catalog/stairwell-flex-gate/. [Accessed 21 March 2021].

[69] Waterman Industries, "Canal gate C-20," [Online]. Available: https://www.agriexpo.online/prod/waterman-industries/product-174233-19231.html. [Accessed 21 March 2021].

[70] Flood Control International Limited, "FloodControl - Flip Up Flood Barrier," [Online]. Available: https://www.environmental-expert.com/products/floodcontrol-flip-up-flood-barrier-646448. [Accessed 21 March 2021].

[71] Flood Protection Solutions, "Anti-Flood Airbrick," [Online]. Available: https://www.floodprotectionsolutions.co.uk/products/airbrick/. [Accessed 21 March 2021].

[72] AquaFragma, "Aquafragma Self-Operated Liquid Barrier," [Online]. Available: https://aquafragma.com/. [Accessed 21 March 2021].

[73] Conneticut Basement Systems, "Sump Pumps," [Online]. Available: https://www.connecticutbasementsystems.com/basement-waterproofing/sump-pump.html. [Accessed 21 March 2021].

[74] National Flood Barrier Testing & Certification Program, "Product Material Testing," [Online]. Available: https://nationalfloodbarrier.org/#!/roles-product. [Accessed 2020].

[75] American Society for Testing and Materials, "Standard Test Methods for Rubber Property—Compression Set," ASTM D395-18, 2018.

[76] American Society for Testing and Materials, "Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers—Tension," ASTM D412-16, 2016.

[77] American Society for Testing and Materials, "Standard Specification for Flexible Cellular Materials—Sponge or Expanded Rubber," ASTM D1056-14, 2014.

[78] American Society for Testing and Materials, "Standard Test Method for Static Puncture Resistance of Roofing Membrane Specimens," ASTM D5602M-18, 2018.

[79] American Society for Testing and Materials, "Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials," ASTM G155-13, 2013.

[80] American Society for Testing and Materials, "Standard Practice for Operating Salt Spray (Fog) Appratus," ASTM B117-19, 2019.

[81] National Flood Barrier Testing & Certification Program, "Water Testing Criteria," [Online]. Available: https://nationalfloodbarrier.org/#!/roles-product. [Accessed 2020].

[82] Metraflex Co., "High/Low Temperature Seal," [Online]. Available: https://www.metraflex.com/products/high-low-temperature-seal/. [Accessed 23 February 2021].

[83] U.S. Nuclear Regulatory Commission, "Proceedings of the Fifth Annual Probabilistic Flood Hazard Assessment Workshop," 2020 (ADAMS Accession No. ML21027A213).

[84] J. Hanna, "Risk and Operational Insights of St. Luice Flooding Event," U.S. Nuclear Regulatory Commission, 5th Annual Probabilistic Flood Hazard Assessment Workshop, Rockville, MD, 2020 (ADAMS Accession No. ML20080M153).

[85] PS Flood Barriers, "Hinged Flood Barrier (Single)," [Online]. Available: https://www.psfloodbarriers.com/product/hinged-flood-barrier-single/. [Accessed 21 March 2021].

APPENDIX A
ADDITIONAL FLOOD PROTECTION FEATURES

A.1 Other Flood Barriers

A.1.1 Active Barriers

Active barriers are used as contingencies to stop floodwater that has entered, or threatens to enter, a facility. Such barriers are generally stored in areas that do not hinder personnel or workflow but are close enough for quick access and deployment when needed.

A.1.1.1 Manual

Flood barriers that must be deployed by human interaction during flooding conditions should be robust enough to withstand high hydrostatic pressure, but also able to be set up quickly. Manual barriers should be accompanied by an interior drainage system to handle any floodwater that leaks under or around the barrier structure. Such barriers include hinged, sliding, membrane, and Canal Gate types.

Hinged barriers operate much like swinging doors and are locked into place manually during flood events to impede waterflow (Figure A-1). Ample side or swinging room should be available for the barrier to operate unimpeded, and custom sizing allows for hinged barriers to be installed on the interior and exterior of a facility.

Sliding barriers slide into a locked position and are ideal for areas with limited swinging room. The lack of swinging hinges means that only total structural failure will result in unchecked waterflow.

Figure A-1 Permanent Manual Barrier [39]

Membrane-type barriers are textile barriers anchored by metal posts (Figure A-2). They are installed on-site and deployed/retracted manually by an operator. Membrane barriers often remain in a retracted position with a metal cover on top that is level with the ground in order to avoid becoming a trip hazard. Such barriers are most effective against a gradual rise in water level and can be installed to surround the entire complex or simply close off doorways. These barriers are also commercially used in horizontal orientation to block off descending staircases, as is the case in subways systems.

Figure A-2 Membrane Barriers [68]

Canal Gates are robust barriers that can be raised and lowered manually to allow floodwater to flow through canals and culverts to divert it to safer areas (Figure A-3). While these gates would traditionally be categorized as exterior barriers, this may not be the case for coastal NPPs that nominally utilize a water intake system from nearby bodies, thus placing this structure within facility operation and jurisdiction.

Figure A-3 Canal Gate [69]

A.1.1.2 Powered

Hydraulic floodwalls are solid, vertically deployed barriers raised and lowered remotely (Figure A-4). In the retracted position, they are level with the ground to avoid becoming trip hazards. When in the vertical position, they uncover a trench drain immediately posterior to them in order to provide both dry and wet flood protection. Hydraulic floodwalls are typically installed on the exterior of facilities to close off entryways, but they can be fitted to close off interior doorways, as well.

Figure A-4 Hydraulically Activated Barrier [70]

A.1.2 Self-Deployable

Several of the active, manually deployed flood barriers discussed have self-activating options. Hydrostatic pressure can release latches that automatically deploy the system. Examples of these barriers include Aquafragma®, the Self-Activating Flood Barrier, Anti-flood Airbrick®, and the FloodBreak® System, which comes in both Gate and Vent Shaft varieties.

Hollow airbricks are a common way to enable airflow to enter the foundation of a building. This, however, also allows floodwater to seep in. The Anti-flood Airbrick® automatically closes off once inundated (Figure A-5).

Figure A-5 Airbrick® [71]

Aquafragma® is a passive barrier that utilizes a combination of hydrostatic pressure and buoyancy in order to actuate (Figure A-6). The main latching mechanism for this structure is, by design, vulnerable to hydrostatic pressure and thus unhooks in the presence of water. Opening this latch allows water to flow into the storage bed of the structure, which then rises accordingly with the buoyant hinge. This implies that the orientation of this structure must be such that the latch faces away from the facility to be protected, as incident floodwater effectively holds the barrier upright.

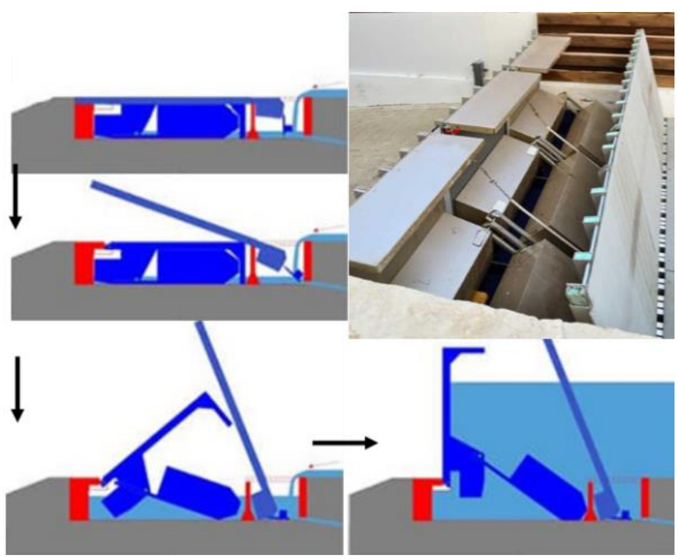

Figure A-6 Aquafragma® [72]

Known as self-activating flood barriers, these employ Pascal's principle to actuate. The idea is that, as incoming floodwater fills a frontal basin, it allows an equal exchange of water pressure to be applied beneath the barrier, effectively lifting it up. Once the front basin is filled, the floodwall locks into place. Benefits of this design include the fact that a concealed basin must fill up for the barrier to actuate, implying total coverage of basin depth plus barrier height.

Using very similar mechanics as employed in the Aquafragma® design, the FloodBreak® System is also activated by hydrostatic pressure from floodwater. Important differences lie in FloodBreak's additionally supplied drain, which redirects water away from the location of barrier protection. Accompanying this feature is another mechanism that soft locks the barrier into place while drainage occurs. FloodBreak® also offers horizontal flood prevention for lower-level areas of facilities through horizontal structures called the "FloodBreak® Vent Shaft System." This system utilizes a series of FloodBreak® mechanisms to collect and contain water running into ventilated below-grade rooms. While effective, horizontal implementation of FloodBreak® requires more structural consideration than a horizontally oriented membrane barrier.

A.2 Mitigative Conveyance Drains

Mitigative drainage systems serve to redirect unwanted water attempting to enter a facility. These systems address the presence of water by either blocking its entry through existing plumbing or collecting water that leaked in through foundational seams and then pumping it to the exterior of the facility. These systems are most effective when both methods are integrated, then implemented in more than one location at a facility. While the devices utilized in these systems can help ensure the dry floodproofing of a facility, implementation of them alone will not suffice for complete flood protection, since mitigative conveyance drains only protect plumbing and below-grade rooms from becoming volatile sources of internal facility flooding.

A.2.1 French Drain Sump Pumps

French drains address potential hydrostatic pressure acting on foundational seams of below-grade rooms. Rather than preventing water from penetrating a facility, these drains offer an immediate pathway on the internal side of the seam, thereby directing seeping water to a sump pump. Sump pumps are submersible, powered components of French drains and are located beneath the foundation of a facility enclosed in a fillable pit containing plumping leading off-site. This design can only accommodate rates of leakage into the facility that do not exceed the capacity of the pump, thereby indicating the need for a drainage system that runs to several parallel sump pumps in order to provide adequate assurance that the pump enclosures do not overfill.

Once deciding upon implementing a French drain sump pump, careful consideration needs to be made as to the placement of the pump and the type of activation switch utilized (Figure A-7). Placement of a sump pump should take into account the resistance of current flow and the ease of supplying power to the location of placement. While the resistance of water current may be minimalized leading into the pit, orientation of the plumbing for redirecting water off-site should harness gravity in favor of the system's overall flow. Activation switches liberate the pump from manual actuation and allow the system to function autonomously in the presence of water, but the respective pros and cons of each switch type differentiate the sump enough to make one particular design preferable. Sump switches include diaphragm switches activated by water pressure, though the activation limit is usually intrinsic to the specific switch and cannot be adjusted for a different pit dimension. More versatile switches take the form of floats, which can

either be tethered or vertically rodded, and actuate when the switch becomes buoyant and rises beyond a designated level. The designated actuation point for a float switch is typically adjustable and should be calibrated for the depth of the pit the respective pump resides in. Caution when using float switches should be taken, as they are vulnerable to obstructive debris/sediment buildup that may cause their moving parts to fail. There are also electronic switches that actuate in the presence of water regardless of parameters. As electronic switches rely solely on wire contact with water to actuate, they have no limiting activation point and no moving parts vulnerable to malfunction.

Figure A-7 French Drain [73]

A.2.2 Backflow Prevention

Backflow prevention devices are implementable active/passive add-ons to plumbing intended for non-flood related drainage. Backflow occurs when plumbing leading to the exterior of a facility becomes an inlet for floodwater. Efforts to mitigate this phenomenon include temporary (plugs) and permanent (valves) solutions, both with the underlying mechanic of limiting the direction of water.

A.2.2.1 Valves

Valves are permanent devices that control the direction of water flow. Implementation within the internal structure of drain systems has led to the development of passive valve designs that utilize fluid mechanics to create a one-directional passage. However, the readily inaccessible placement of valves makes it difficult to address the potential failure of passive mechanisms. In such an event, active valves actuated from outside the immediate drain system can be utilized as back-up.

A.2.2.1.1 Active

Active valves require more structural consideration when being implemented, as external handles and power will need to be connected to the valve in the drain system. Despite this, manual actuation can force clogged valves to close, and powered valves can sound an alarm when malfunctioning—offering interactive valve functionality assurance to a degree not found in passive valves.

<u>Manual</u>

Most manual valves utilize a handwheel or lever to aid operators in manual opening and closing. Mechanisms designed for manual valve actuation include flap checks and semi-balls, with the latter being less prone to having debris hinder valve closure. While manual valves can be more reliable than passive valves, foresight is needed to incorporate operator closure time into emergency flood protocol.

<u>Powered</u>

In circumstances where water is present on both side of the valve, implementation of a powered valve should be considered. Powered valves may use an ejector pump to direct water inside the facility around the valve itself, or they may use a hydrostatic pressure sensor to open and close the valve appropriately. Being powered, these valves will not operate if power is lost, nor should they be expected to function passively as a last resort.

A.2.2.1.2 Passive

Most commonly, passive valves are flap check valves that swing open or shut if water presses against the hinge. Variations of flap checks exist for both horizontal and vertical orientations, with the vertical flap checks varying in terms of the buoyant float attached to the side opposing the one-way current. Other vertical valves utilize a buoyant rubber ball to clog an aperture in the upper section of the valve. These valves operate autonomously in the event of a flood but cannot be considered reliable for water with heavy debris content, as clogging may occur.

A.2.2.2 Plugs

Plugs are temporary devices that seal off drain openings. Nominally made of rubber or other elastomers, plugs are intended for recreational drains such as lavatory and floor drains. Plugs must not exceed the diameter of the drain hole they intend to seal off, but rather wedge within the drain and effectively clog it. The depth to which a plug descends into a drain should be considered, as this depth reinforces the plug’s integrity in withstanding hydrostatic pressure.

A.3 <u>Circumstantial Flood Affecting Measures</u>

Facilities contain barrier-like structures intended for recreational use rather than flood mitigation. Regardless of the structure’s intended purpose, these recreational barriers still restrict floodwater from permeating throughout a facility and are thus considered circumstantial, last-resort flood protection features. The integrity of these structures as flood barriers may be improved by constructing them from durable materials, applying seals or sealants, and, in the case of opening structures, opening orientation. The circumstantial flood affecting structures that can be upgraded to higher levels of flood protection are doors, windows, and electrical wall

outlets. Additionally, internal flights of ascending stairs may function to mitigate floodwater from reaching higher floors within a facility. The effectiveness of stair structures depends on their steepness and riser-to-tread ratio, but overall, the rate of incoming floodwater is dominate in this matter. It should be noted that these barriers alone are ineffective for preventing floodwater penetration but can serve as a last-resort failsafe.

A.4 Taxonomy and Terminology in Appendix A

Table A-1 and Table A-2 present the taxonomy and terminology that apply to the descriptions of the flood protection features in this appendix.

Table A-1 Taxonomy of On-Site Flood Protection Features

Flood Barriers	Mitigative Conveyance Drains	Circumstantial Flood Affecting Structures
• Permanent, Active ◦ Hinged ◦ Hydraulic Floodwall ◦ Membrane ◦ Sliding • Permanent, Passive ◦ Anti-flood Airbrick® ◦ Aquafragma® ◦ Elastomer Gasket ◦ Elastomer Wedge ◦ Epoxies/Elastomers ◦ FloodBreak® ◦ Foams ◦ Grout/Mortar ◦ Mechanical Boots • Temporary, Active ◦ Absorbent Dam ◦ Cuboid Fillers ◦ Door Flood Gate ◦ Inflatable ◦ Linked Fill Bags ◦ Modular Plastic ◦ Portadam® ◦ Steel Logs ◦ Tarp	• Permanent, Active ◦ Diaphragm Switch ◦ Ejector Pump ◦ Electric Switch ◦ Flap ◦ Hydrostatic Sensor ◦ Semi-Ball ◦ Tethered Switch ◦ Vertical Action Switch • Permanent, Passive ◦ Horizontal Flap Check ◦ Vertical Flap Check ◦ Vertical Ball • Temporary, Active ◦ Drain Plug	• Permanent, Active ◦ Door ◦ Electrical Outlet ◦ Stairs ◦ Window

Table A-2 Flood Protection-related Terminology

Term	Description
Active	Requires human deployment or power for functional use
Backflow Prevention	A drain add-on or adjustment that prevents the movement of water into the facility via a drain
Buoyant	A passive mechanic recognized for different types of vertical valves
Circumstantial Flood Affecting Device	A structure intended for a purpose other than flood prevention, but which can act to mitigate internal flood levels within a facility
Compression	A mechanic of a seal that allows it to achieve maximum effectiveness when pressurized between structures or components
Disposable	Intended for single use or until no longer effective, then thrown away and replaced
Exterior Barriers	Engineered features external to the immediate plant area, for example, levees, seawalls or floodwalls
Flood Barrier	A device with the intended purpose of enclosing a facility to ensure its internal area stays dry
French Drain Sump Pumps	A powered drain system located beneath the facility that collects water seeping in and redirects it to the external region of the facility
Hydrostatic	Utilizes the pressure of floodwater to increase the coverage/protection integrity of a barrier
Incorporated Barriers	Engineered features in the structure/ environment interface, for example, walls, doors, and hatches.
Manual	A type of active protection deployed through human operation
Mitigative Conveyance Drain	A plumbing device with the intended purpose of redirecting water flow away from a facility to ensure that its internal area stays dry
Passive	Operates automatically without human intervention or power
Penetration Seals	Devices or materials used to protect against water leakage through penetrations in a structural wall, ceiling, or floor.
Permanent	Fixed in location, stored at point of use, immobile, and requiring structural considerations
Plug	A drain component that prohibits the flow of water into a recreational drain opening
Powered	A type of active protection that will not function unless supplied with mechanical or electrical energy
Reusable	Able to be used more than once
Sand	A granule material used for filling or packing in barriers
Sealant	A material coating that vulcanizes once sprayed in place and renders facility walls watertight by addressing cracks and other small openings
Seals	A solid lining for making doors, windows, outlets, piping, etc. watertight
Self-deployable	A type of passive barrier that deploys automatically in the presence of water and recedes with floodwater
Temporary	Neither fixed in location, nor stored at point of use; must be deployed to function and may be either reusable or disposable
Valve	A drain component that limits water current to a single direction

APPENDIX B
IN-DEPTH REVIEW OF FLOODING WALKDOWN REPORTS OF FIVE NUCLEAR POWER PLANTS

This appendix presents an in-depth review of flooding walkdown reports for five nuclear power plants, as introduced in Section 3.7. The flood protection features credited in the current licensing basis for protection and mitigation regarding external flood events were inspected during flooding walkdowns at the five reference plants. The inspection results were documented in written form as a “flooding walkdown report” and reviewed by NRC.

In the flooding walkdowns, the acceptability of a flood protection feature was determined by comparing the results of the visual inspection conducted during the walkdown to the acceptance criteria defined in NEI 12-07, Revision 0-A [11] and the plant-developed supplemental walkdown inspection guidance. Section 6 of NEI 12-07, Revision 0-A defines “acceptance” as:

> *Flood protection features are considered acceptable if no conditions adverse to quality were identified during walkdowns, verification activities, or program reviews as determined by the licensee’s Corrective Action Program. Conditions adverse to quality are those that prevent the flood protection feature from performing its credited function during a design basis external flooding event and are “deficiencies.”* [11]

Each flooding walkdown report followed the same documentation structure, including plant-specific protection feature effectiveness, implementation of the walkdown process, findings and corrective actions taken or planned, etc. All five plants reviewed provided details on the flood protection features that did not meet the acceptance criteria. One plant also provided details on acceptable flood protection features; this plant, hereafter referred to as the “reference plant,” was selected as a focus of this review. The flooding walkdown reports from the other four plants were also reviewed but not included in this appendix, since the deficiencies identified in these plants were either associated with non-barrier-type flood protection features, or enveloped in the deficiencies found in the reference plant.

B.1 Flood Barrier Configuration in the Reference Plant

Over 400 flood protection features were inspected during flooding walkdown at the reference plant. The majority of inspected flood protection features in the reference plant were flood barriers, accounting for 88% of the total features, with non-barrier features comprising a relatively small portion: 12% (Table B-1).

All the inspected flood barriers were categorized as passive, and all were incorporated into the plant apart from a few exterior dikes. Flood barriers in the reference plant were either penetration seals or structural elements. Breakdowns of these two flood-barrier types are provided in Figures B-1 and B-2, respectively.

Table B-1 Flood Protection Features Credited in the Reference Plant

Feature Type	Classified as Barrier	Barrier Type	Percentage
Seal	Yes	Incorporated	79%
Structure	Yes	Incorporated	8%
Drain	No	n/a	8%
Scupper	No	n/a	4%
Dike	Yes	Exterior	1%
Sump	No	n/a	<1%
Monitor Well	No	n/a	<1%
Percentage of Barrier Type Flood Protection Features			88%
Percentage of Non-Barrier Type Flood Protection Features			12%

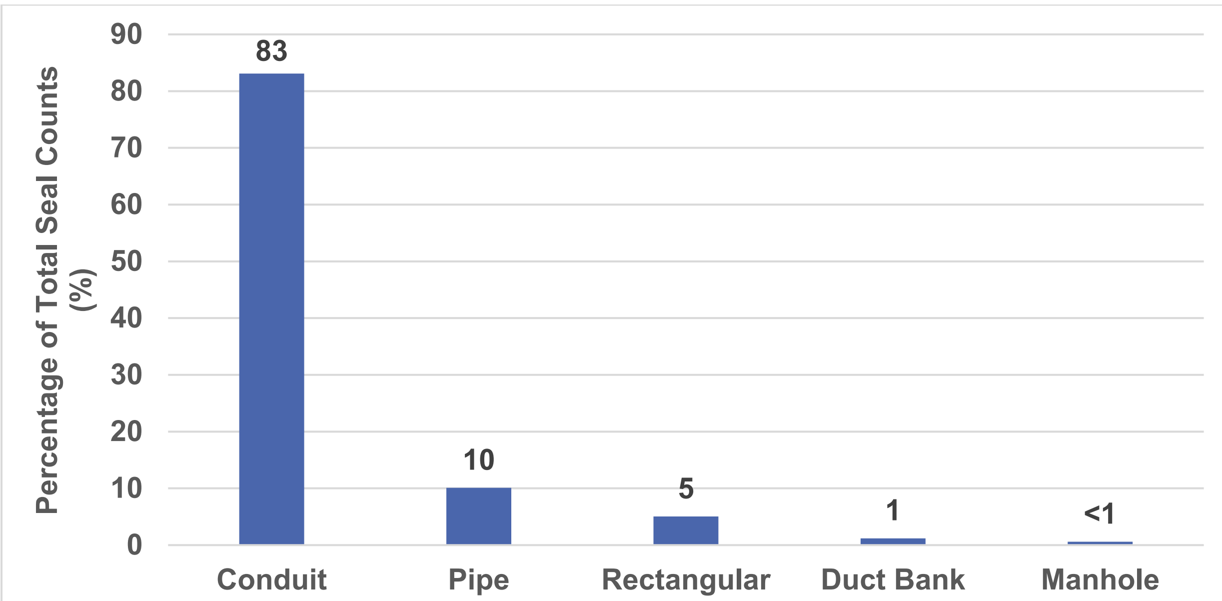

Figure B-1 Statistics of Seal Type Flood Barriers in the Reference Plant

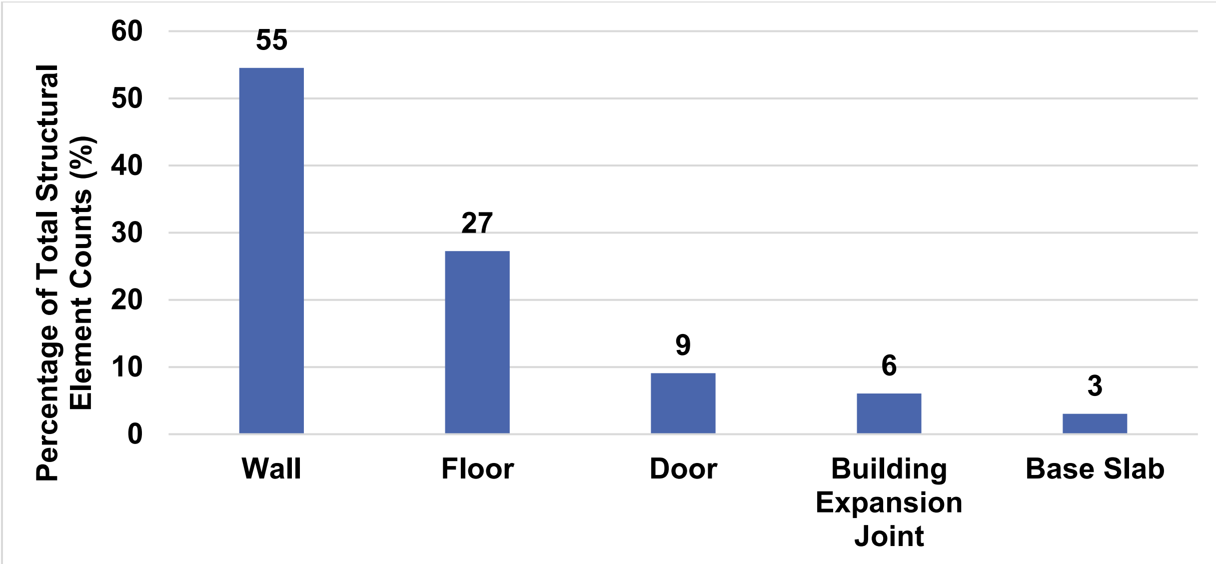

Figure B-2 Statistics of Structural Element Type Flood Barriers in the Reference Plant

B.2 Flood Barrier Performance in the Reference Plant

Most flood barriers were inspected during the flooding walkdown; some with restricted access were inspected during a later refueling outage. Most flood barriers were immediately judged acceptable via visual inspections, though a small portion were either not immediately judged acceptable or were found to be inaccessible. Statistics on the inspection observations are provided in Figure B-3.

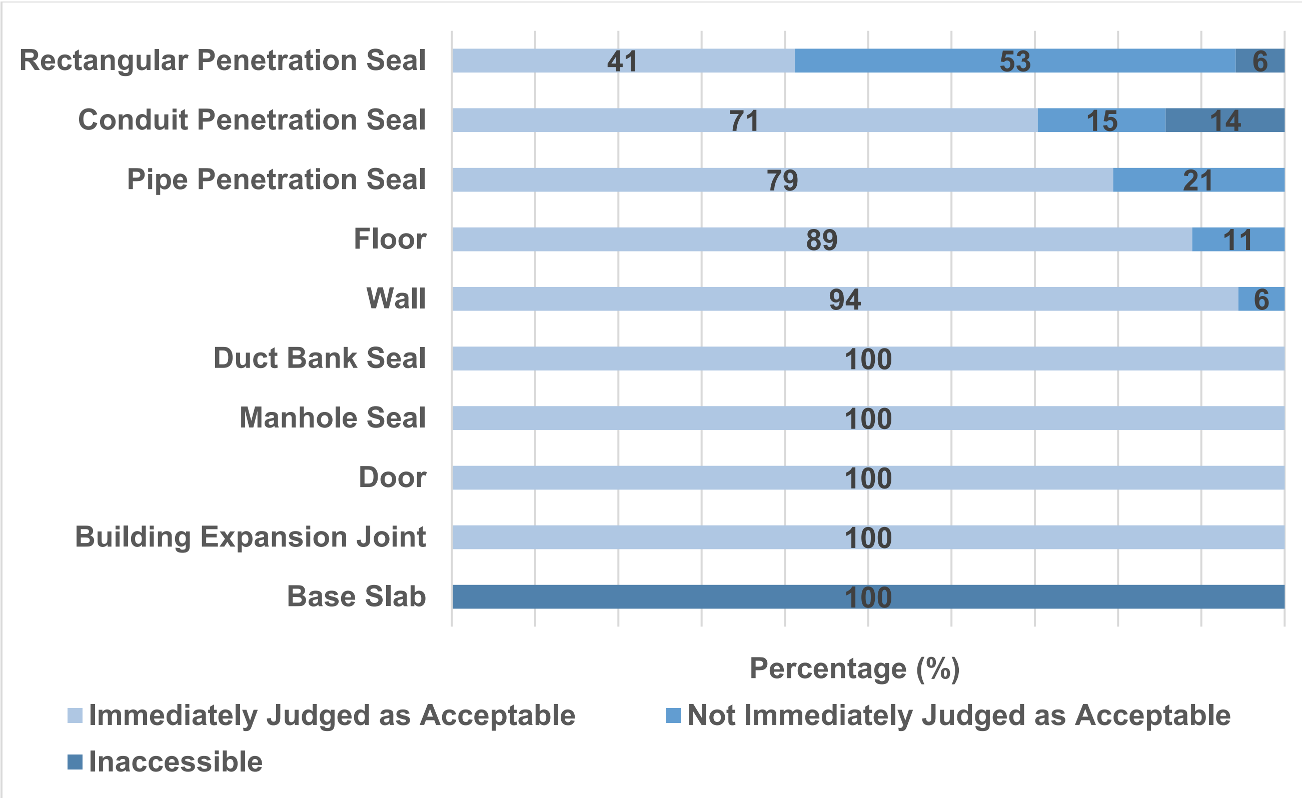

Figure B-3 Inspection Observations of Flood Barriers in the Reference Plant

Flood barriers not immediately judged acceptable were entered into a corrective-action program for evaluating potential deficiencies. The evaluation revealed that most such flood barriers were degraded yet operable, though a small portion were deemed inoperable or failed (Figure B-4). The observed degradation modes (DMs) and failure modes (FMs) are summarized in Tables B-2 and B-3, respectively. Barrier-type-specific statistics on degraded or failed barriers are shown in Figures B-5 and B-6, respectively.

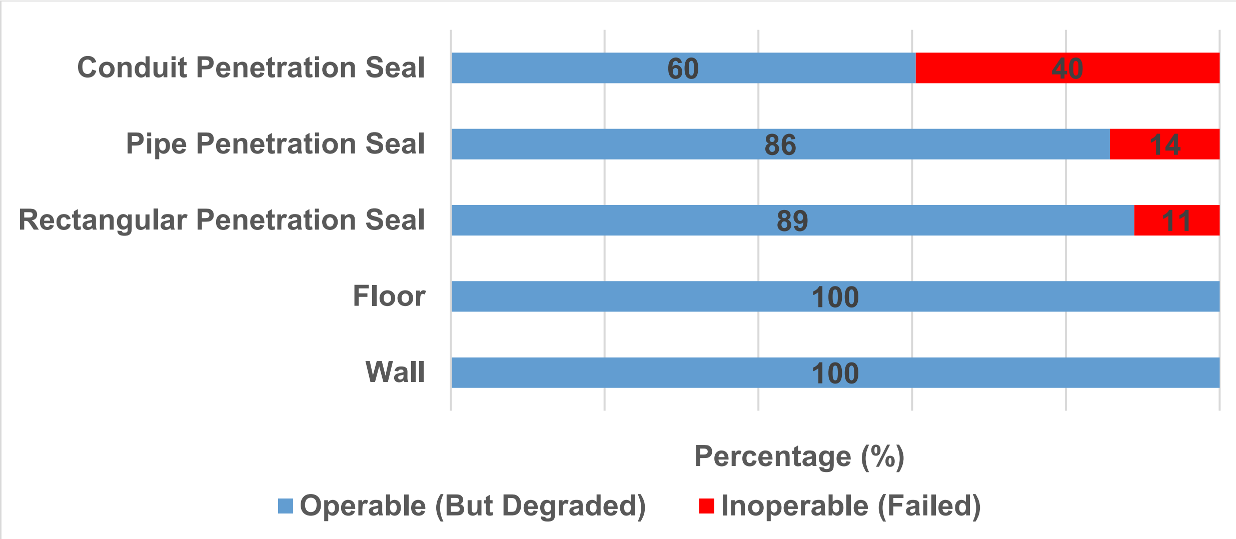

Figure B-4 Evaluation Results of Flood Barriers Not Immediately Judged Acceptable

Table B-2 Flood Barrier Degradation Modes Identified During Walkdown

No.	Degradation Mode
DM1	Corrosion on penetration and signs of water seepage on wall.
DM2	Staining on wall below penetration, or at construction joints of penetration and immediately below.
DM3	No seal could be observed for this penetration.
DM4	Staining on wall and corrosion on penetration.
DM5	Extensive corrosion on penetration sleeves, and stalactite growth underneath the penetration and cap.
DM6	Cracks greater than 0.04" wide in the wall/floor slab.
DM7	Penetration covered by a catch and inaccessible. Staining on the wall below the catch.
DM8	Staining on penetration and signs of water seepage on wall.
DM9	Cracks greater than 0.04" wide in the grout sealing penetration, and slight staining below pipes.
DM10	Due to an obstructed view, an internal seal for this pipe sleeve could not be verified.

Table B-3 Flood Barrier Failure Modes Identified During Walkdown

No.	Failure Mode
FM1	Penetration seals appeared severely degraded. Signs of past water intrusion on walls underneath.
FM2	Water intrusion through penetrations observed at roughly 40 drops per minute during a light rainstorm.
FM3	Penetrating conduit was cut and uncapped.
FM4	Penetrating conduit was cut and uncapped. A seal inside the penetrating conduit was not visible.

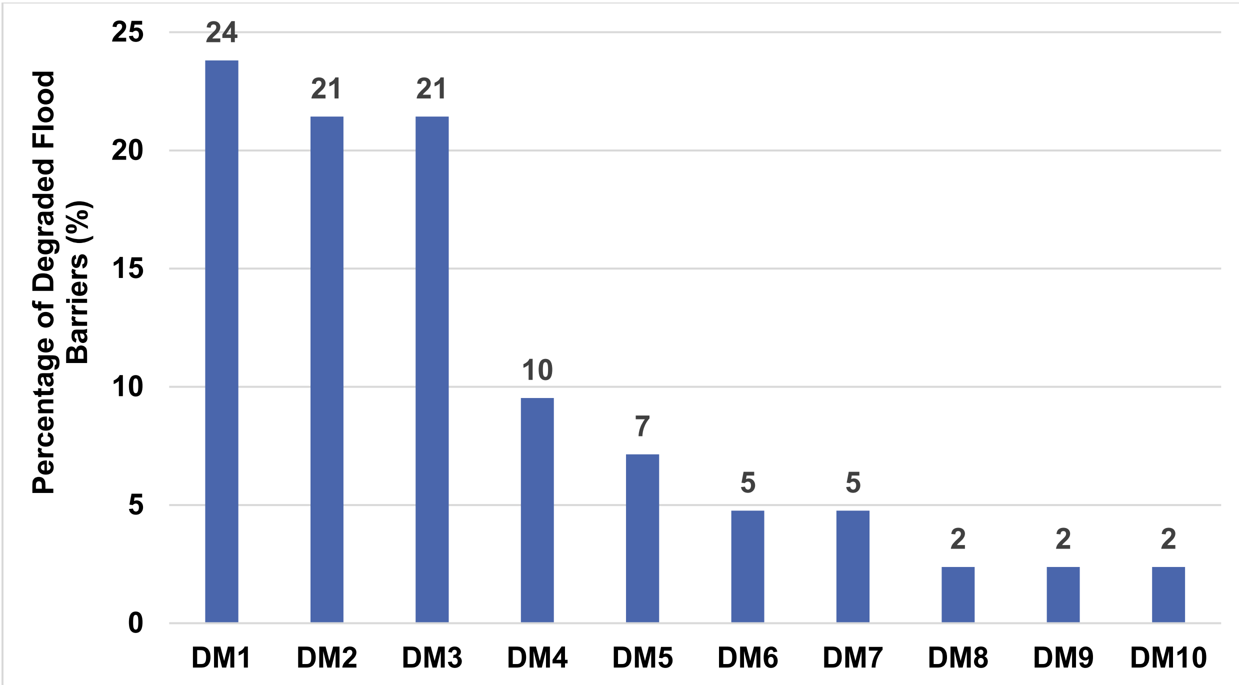

Figure B-5 Statistics of Degraded Flood Barriers Identified During Walkdown

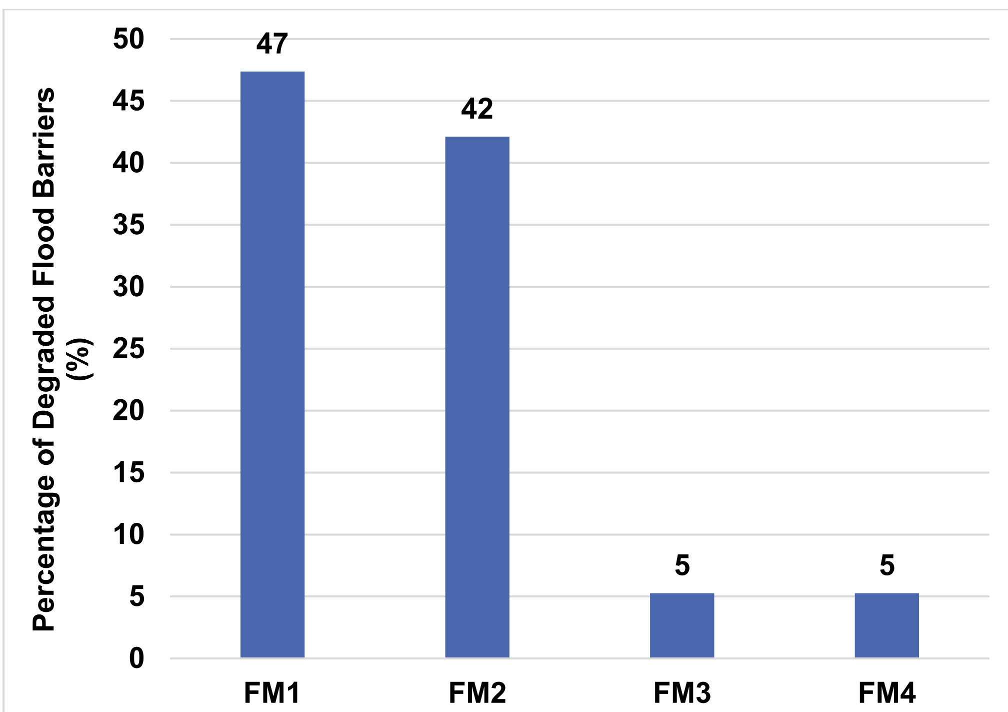

Figure B-6 Statistics of Failed Flood Barriers Identified During Walkdown

B.3 Implications of Walkdown Observations on Flood Barrier Testing-Strategy Development

Review of the reference plant flood protection walkdown results provided information on the types, numbers, and conditions of flood barriers. Based on this information, the analysis documented in this subsection proposes definitions of three performance metrics and performs a preliminary calculation (Table B-4). Success probability is calculated as the number of flood barriers immediately judged acceptable, divided by the total number of flood barriers (excluding the inaccessible ones). Degradation probability is calculated as the ratio of the number of operable but degraded flood barriers to the total number of flood barriers. Failure probability is calculated as the number of inoperable flood barriers divided by the total number of flood barriers.

Observations from these performance metrics include: (1) penetration seals exhibited higher non-success probabilities than other types of flood barriers, and conduit penetration seals had the highest failure probability while rectangular penetration seals had the lowest success probability; (2) two structural-element-type flood barriers (i.e., floor and wall) did not exhibit failure though degradations did exist; (3) the other flood barrier types (i.e., building expansion joint, door, manhole seal, and duct bank seal) did not exhibit degradation or failure.

Note that these performance metrics are both plant- and time-specific (i.e., if the walkdown had been conducted at a different plant or at this plant at a different time, the performance metrics might have been different). However, these metrics still show promise in serving as input for the development of a flood barrier testing strategy (e.g., failure probability could be one of multiple factors considered in test prioritization).

Table B-4 Performance Metrics of Flood Barriers Inspected During Walkdown

Flood Barrier	Probability		
	Success	Degradation	Failure
Conduit Penetration Seal	0.82	0.11	0.07
Rectangular Penetration Seal	0.44	0.50	0.06
Pipe Penetration Seal	0.79	0.18	0.03
Floor	0.89	0.11	0.00
Wall	0.94	0.06	0.00
Building Expansion Joint	1.00	0.00	0.00
Door	1.00	0.00	0.00
Manhole Seal	1.00	0.00	0.00
Duct Bank Seal	1.00	0.00	0.00

APPENDIX C
SUMMARY OF FM APPROVAL STANDARD 2510

This appendix presents a summary review of FM Approval Standard 2510, or ANSI FM 2510.

ANSI FM 2510 [31] is used as the testing standard for the National Flood Barrier Testing and Certification Program, which is implemented by the Association of State Floodplain Manager in partnership with FM Approvals and the USACE. This program has an intent of objectively testing and certifying products of five flood mitigation equipment types, including flood barriers for opening and perimeter barrier applications, flood mitigation valves and pumps, and penetration sealing devices. ANSI FM 2510 presents two different categories of testing requirements, including general component and material testing requirements generic to five flood mitigation equipment types and performance testing requirements specific to equipment type. A product needs to be tested in accordance with both generic and equipment type-specific requirements. A certified product will receive an FM Approved mark authorized by FM Approvals.

C.1 General Component and Material Testing for Flood Mitigation Equipment

General component and material testing requirements refer to a suite of tests that will examine an equipment's ability to withstand forces of nature that impinge upon the equipment when deployed [74]. It is to be noted that, although these requirements are generic to five types of flood mitigation equipment, not all these tests are applicable to every product design. For some of the tests, the following ASTM standards are referenced:

- ASTM D395, "Standard Test Methods for Rubber Property—Compression Set" [75]
- ASTM D412, "Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers—Tension" [76]
- ASTM D1056, "Standard Specification for Flexible Cellular Materials—Sponge or Expanded Rubber" [77]
- ASTM D5602, "Standard Test Method for Static Puncture Resistance of Roofing Membrane Specimens" [78]
- ASTM G155, "Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials" [79]
- ASTM B117, "Standard Practice for Operating Salt Spray (Fog) Apparatus" [80]

General component and material tests along with their testing conditions and acceptance criteria are summarized in Table C-1.

Table C-1 General Component and Material Testing Requirements in ANSI FM 2510 [31]

No.	Test	Testing Condition	Testing Acceptance Criteria
1	Pre-test examination	Examined and compared to the manufacturer's production drawings and specifications as well as general requirements developed by FM Approvals	All test samples conform to drawings, specifications, and requirements
2	Pressure test	150% of maximum system operating pressure for 5 minutes	No rupture, cracking or permanent distortion; remain fully functional
3	Leakage test	120% of maximum system operating pressure	No visible leakage
4	Durability test	500 cycles of operation	No wear or damage
5	Vibration resistance test	Installed and secured on a vibration table with 0.020-inch vibration displacement, 18 to 37 Hz (variable) vibration frequency for 5 hours	No crack, loosening, separation, excessive wear, or other damage that would impair its proper operation or function
6	Impact and wear resistance test	First placed in a refrigeration chamber and exposed to a temperature of 10 °F for 24 hours, then be applied impact, force or torque	No crack or signs of degradation
7	Salt spray corrosion test	Exposed to salt spray as specified by ASTM B117 for a period of 240 hours	No deterioration, crack, or loss of functionality
8	Tensile strength, ultimate elongation, and tensile set tests	Test in accordance with ASTM D412, Method A	Meeting minimum requirements of tensile strength, ultimate elongation, and tensile set
9	Accelerated aging test	First exposed to 212 °F for 70 hours, then tested in accordance with ASTM D412 or ASTM D1056 as appropriate	Meeting minimum requirements of as-received tensile strength and ultimate elongation, and not exceeding maximum allowances of compression deflection change

Table C-1 General Component and Material Testing Requirements in ANSI FM 2510 (cont.)

No.	Test	Testing Condition	Testing Acceptance Criteria
10	Compression set test	Test in accordance with ASTM D395, Method B or ASTM D1056 as appropriate	Not exceeding maximum allowances of compression set
11	Ultraviolet light and water test	Test in accordance with ASTM G155	No crack, crazing, or loss of functionality
12	Air-oven aging tests	Exposed to 158 °F for 180 days	No deterioration, crack or crazing for nonmetallic components; No deterioration or loss of adhesive function, the force required to separate gasket from barrier material sample not decrease by more than 50% for gasket adhesives
13	Environmental corrosion resistance	Exposed to a moist CO_2-SO_2-air mixture for 10 days	No deterioration or failure
14	Extreme temperatures operation test	First submerged in water for 30 minutes, conditioned in an environment chamber at -40 °F for 24 hours, then conditioned in an environment chamber at 130 °F for 24 hours	No loss of functionality, signs of cracking or degradation
15	Abrasion resistance test	3000 cycles	No signs of wear or damage
16	Hail resistance test	Steel ball dropped onto the sample for a minimum of ten times	No signs of cracking, crazing, peeling, puncture, rupture or splitting
17	Tear and puncture resistance test	Test in accordance with ASTM D5602	No tear or puncture

C.2 Performance Testing Requirements for Flood Barriers

Performance testing requirements, also known as “water testing”, refer to a suite of tests that will thoroughly examine an equipment’s ability to withstand flood-related conditions [81]. ANSI FM 2510 requires perimeter flood barriers to be tested for quasi-static and riverine flood conditions at the USACE ERDC Coastal and Hydraulics Laboratory in Vicksburg, Mississippi.

Opening flood barriers are required to be tested for quasi-static flood conditions only; ANSI FM 2510 does not designate a specific performance testing facility and presents a general requirement that such tests shall be conducted with a test enclosure with the capability of withstanding the maximum design water depth without significant leakage. Performance tests along with their testing conditions and acceptance criteria for flood barriers for opening barrier applications and perimeter barrier applications are summarized in Table C-2 and C-3, respectively. It is to be noted that all these tests are required to be completed in sequences as shown in the tables.

Table C-2 Performance Testing Requirements for Opening Barriers in ANSI FM 2510 [31]

No.	Test	Testing Condition	Testing Acceptance Criteria
1	Pre-deployment installation configurations	Review manufacturer's specification and post-installation checklist	Specification and checklist verified as accurate and complete
2	Deployment	Document barrier deployment with a video camera, then compare the video with manufacturer's specification	Compliance with manufacturer's specification
3	Hydrostatic load test	Still water depth of $10\% \times h$ for 2 hours, and $100\% \times h$ for 20 hours	Leakage rate not exceeding 0.08 gallons per hour per linear foot
4	Redeployment	Remove barrier and evaluate for wear or damage, and then redeploy; during redeployment, document barrier deployment with a video camera, then compare the video with manufacturer's specification	Compliance with manufacturer's specification
5	Dynamic impact load test	Apply two impacts of 600J each from a rigid falling object simulating floating debris	No loss of functionality
6	Post hydrostatic load test	Still water depth of $10\% \times h$ and $100\% \times h$, each for 1 hour	Leakage rate not exceeding 0.08 gallons per hour per linear foot

* h denotes the manufacturer's specified maximum design water depth for the barrier

Table C-3 Performance Testing Requirements for Perimeter Barriers in ANSI FM 2510 [31]

No.	Test	Testing Condition	Testing Acceptance Criteria
1	Deployment	Document barrier deployment with a video camera, then compare the video with manufacturer's specification	Compliance with manufacturer's specification
2	Hydrostatic load test	Still water depths of 1 ft, 2 ft, and $100\% \times h$, each for 22 hours	Leakage rate not exceeding 15 gallons per hour per foot length; permanent deflection not exceeding 6 inches
3	Wave-induced hydrodynamic load test	Still water depths of $66.7\% \times h$ and $80\% \times h$; at each water depth, exposed to waves of different heights (low waves for 7 hours, medium waves for 10 minutes of 3 times, high waves for 10 minutes)	Leakage rate not exceeding 15 gallons per hour per foot length (for low-wave conditions); permanent deflection not exceeding 6 inches
4	Overtopping test	Not less than 1 inch overflow for 1 hour	Not float, overturn or experience catastrophic failure; permanent deflection not exceeding 6 inches
5	Debris impact test	At water depth of $66.7\% \times h$, pull a 610 lb. floating log then a 790 lb. floating log into center wall of barrier, at a velocity of 7 ft per second	Leakage rate not exceeding 15 gallons per hour per foot length; permanent deflection not exceeding 6 inches
6	Current test	At water depth of $66.7\% \times h$, generate and maintain a current of 7 ft per second for 1 hour	Leakage rate not exceeding 15 gallons per hour per foot length; permanent deflection not exceeding 6 inches
7	Post hydrostatic load test	Still water depth of $100\% \times h$ for a minimum of 1 hour and a maximum of 22 hours	Leakage rate not exceeding 15 gallons per hour per foot length; permanent deflection not exceeding 6 inches

* h denotes the manufacturer's specified maximum design water depth for the barrier

NRC FORM 335 (12-2010) NRCMD 3.7 — U.S. NUCLEAR REGULATORY COMMISSION **BIBLIOGRAPHIC DATA SHEET** *(See instructions on the reverse)*	1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.) NUREG/CR-7279
2. TITLE AND SUBTITLE Research to Develop Flood Barrier Testing Strategies for Nuclear Power Plants	3. DATE REPORT PUBLISHED MONTH: February — YEAR: 2022 4. FIN OR GRANT NUMBER
5. AUTHOR(S) Z. Ma[1] S. Zhang[1] C. Pope[2] C. Smith[1]	6. TYPE OF REPORT Technical 7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

[1]Idaho National Laboratory
PO BOX 1625
Idaho Falls, ID 83415

[2]Idaho State University
921 South 8th Avenue
Pocatello, Idaho 83209

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address.)

Division of Risk Analysis
Office of Nuclear Regulatory Research
Nuclear Regulatory Commission
Washington, D.C. 20555-0001

10. SUPPLEMENTARY NOTES

T. Aird, NRC Project Manager

11. ABSTRACT (200 words or less)

This report presents results of research performed by Idaho National Laboratory (INL) for the Nuclear Regulatory Commission (NRC) to identify and develop strategies for testing nuclear power plant (NPP) flood barriers. This research project began with a literature review that documented the results of previous NRC-funded research, work performed by other government agencies, reports generated by industry organizations, NRC licensee submittals, information from testing facilities, and information from commercial firms engaged in NPP decommissioning. This literature review was then used to develop a simplified flood protection categorization scheme and related glossaries. Using this categorization scheme and glossaries, a survey of currently used flood barriers was conducted, focusing on both permanent and temporary flood barriers. External flood barriers such as levees and berms were outside the scope of this survey. This research project also assessed the current state of NPP decommissioning for potential flood barrier harvesting opportunities, surveyed capabilities of domestic and international flood testing facilities, and explored technical challenges to harvesting and testing of flood barriers. Other factors that should be considered in developing flood barrier testing strategies were also explored and are documented in this report (e.g., selection of flood barriers for testing, codes and standards for flood barrier testing, potential alternatives to harvesting such as in-situ testing, testing performance criteria, and testing parameters).

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)	
flood barriers, penetration seals, watertight doors, testing, protocols, testing laboratories, flood protection, probabilistic flood hazard assessment, pfha, active barriers, flood mitigation, risk assessment, flood risk, pra, external hazards	13. AVAILABILITY STATEMENT unlimited 14. SECURITY CLASSIFICATION *(This Page)* unclassified *(This Report)* unclassified 15. NUMBER OF PAGES 16. PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

OFFICIAL BUSINESS

@NRCgov

NUREG/CR-7279 **Research to Develop Flood Barrier Testing Strategies for Nuclear Power Plants** **February 2022**