External Flooding Event Modeling and Risk Quantification

1. Objectives and Scope

The objective of this guidance is to improve and ensure continued consistency in external flooding risk assessments by documenting methods, datasets, and references that risk analysts could use to analyze the risk of external flooding events, discussing common issues related to key aspects of external flooding assessment, and presenting the experience from recent Significance Determination Process (SDP) analyses. Because of the diverse nature of external flooding events and lack of widely accepted methods for aspects of modeling and quantifying the risk of external flooding events, development of a detailed and step-by-step guidance that covers all aspects of external flooding assessments was viewed to be impractical at the time this guidance was developed. Nevertheless, consistency in external flooding assesments could be maintained and enhanced by identifying potential issues and discussing their treatment in previous analyses. The scope of this guidance includes evaluations of those events that could not be dispositioned with simple screening methods and, therefore, require detailed assessments.

This guidance discusses sources of information related to flooding analyses (Section 2), considerations in using methods and datasets used for external flood hazard assessments (Section 3), and considerations in evaluation of flood protection features and human reliability (Section 4). Brief descriptions of several findings related to external flooding are provided in Appendices A and B. Finally, Appendix C provides a summary of point estimate failure rates for dams that are broken down by all sized dams.

2. Source of Information

Section 2.4 of Final safety analysis reports (FSARs) describes, among other subjects, design-basis floods for nuclear power plants. These reports provide valuable information regarding a flood caused by one or an appropriate combination of several hydrometeorological, geoseimic, or structural-failure phenomena, which results in the most severe hazards such as flooding due to precipitation, storm surge, or rupture of an impoundment. The precipitation can be in the form of extreme rainfall or a rapidly melting snow pack. The dam or dike rupture can be due to overtopping by flood or “blue sky” piping and collapse. Storm surge is typically a coastal phenomenon. Tsunamis and seiches are seismic and shoreline geography phenomena. The NRC has developed a database that contains information provided in FSARs relevant to external flooding such as flood mechanisms, heights and durations along with sources of data utilized for design-basis floods evaluations by the licensees. In addition to FSARs, plant procedures also describe the flood mitigation actions, which at times should be evaluated and quantified as a part of the overall risk assessment. Licensees also performed evaluations of external flood hazards, with varying degrees, as part of the individual plant examinations of external events (IPEEEs). External flood hazards are mostly evaluated deterministically in IPEEEs. Furthermore, IPEEEs provide no or limited information on external flood plant impact assessments and equipment fragilities. NRR/DRA has developed spreadsheets that contain risk information, if available, including risk of external flooding.

NUREG/CR-7046, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America," (Reference 1) describes general approaches, including some probabilistic aspects, for evaluating flood hazards consistent with present-day guidance and methods applicable to new reactors. Appendix A to NUREG/CR-7046 identifies and discusses the data and data sources that should be considered for collection depending on specific modeling tasks and levels of detail required. This Appendix places special emphasis on using nationally available datasets. Moreover, NUREG/CR-7046 contains appendices that describe currently available hydrometeorological datasets and geographical information system techniques that are useful in data preprocessing and synthesis of model inputs along with flood estimation techniques for various flood-causing mechanisms, such as local intense precipitation, dam breaches and failures, storm surges and seiche. In addition to this NUREG/CR, EPRI Report 3002005292 (Reference 6) examines probabilistic methods currently available to assess the external flooding risks and their uncertainties for local intense precipitation, riverine flooding, dam failure, and storm surge.

JLD-ISG-12-06, "Interim Staff Guidance for Performing a Tsunami, Surge, or Seiche Hazard Assessment," dated January 4, 2013, (Reference 2) describes methods acceptable to NRC staff for performing a tsunami, surge, or seiche hazard assessment in response to the 50.54(f) letter. While this ISG references some components that are probabilistically informed (e.g., selection of hurricane storm parameters using the Joint Probability Method) it does not describe a framework for a full probabilistic characterization of coastal hazards.

JLD-ISG-2013-01, "Guidance for Assessment of Flooding Hazards Due to Dam Failure," dated July 29, 2013, (Reference 3) describes methods acceptable to NRC staff for re-evaluating flooding hazards from dam failure in response to the 50.54(f) letter. This ISG does not describe a framework for probabilistic characterization of hazards from dam failure (with the exception of using a probabilistic seismic hazard assessment for defining seismic loads on dams). The ISG stated that "[probabilistic] seismic hazard analysis is accepted current practice in both the nuclear and dam safety communities […]. Probabilistic approaches for estimating the extreme rainfall and flood events of interest in [the Dam Failure ISG] (e.g., 1×10^{-4} per year or lower annual exceedance probability) exist, but there are no industry consensus standards or Federal guidance that defines current accepted practice. NRC has established probabilistic screening criteria for man-related hazards (e.g., between 1×10^{-7} and 1×10^{-6} annual exceedance probability) that are, in theory, applicable to sunny-day dam failures. However, no widely accepted methodology exists for estimating sunny-day dam failure probabilities on the order of 1×10^{-7} [to] 1×10^{-6} annual exceedance probability."

NRC Information Notice 2012-02, "Potentially Nonconservative Screening Value for Dam Failure Frequency in Probabilistic Risk Assessments," dated March 5, 2012, (Reference 4) discusses a potentially nonconservative screening value for dam failure frequency contained in Nuclear Safety Analysis Center (NSAC) report NSAC-60, "A Probabilistic Risk Assessment of Oconee Unit 3," issued June 1984. NRC IN 2012-02 states that although historical dam failure information discussed in the information notice can "provide useful qualitative insights on the general performance and failure modes for certain dam types, its applicability to site-specific dams has to be assessed to establish sufficient technical bases. This is due to the variability in site-specific characteristics (i.e., hydrologic, geologic, and operational) and the potential contributions of site-specific failure modes not covered by databases." In addition, by referring to DSO-04-08, "Hydrologic Hazard Curve Estimating Procedures," (Reference 5), IN 2012-02 stated that frequency extrapolations of severe weather phenomena with insufficient basis may not be fully justified depending on the quality and quantity of the supporting information beyond certain values.

Finally, various state and federal agencies currently utilize flood frequency analysis and other related methods as a means to probabilistically characterize flooding hazards for their applications (e.g., References 7 and 8). Information on probabilistic flood hazard assessment (PFHA) in other applications is documented in NUREG/CP-0302 "Proceedings of the Workshop on Probabilistic Flood Hazard Assessment (PFHA) held at U.S. NRC Headquarters, January 29 – 31, 2013" (Reference 9).

3. Flood Hazard Assessment

To evaluate the risk of external flooding events, risk analysts often need to assess the likelihood that a specified parameter or set of parameters representing flood severity (e.g., flood elevation, flood event duration, and associated effects) are exceeded at a site during a specified exposure time. This can then be characterized into hazard exceedance information for input in risk assessment as frequencies or annual exceedance probabilities.

The current state of practice in flood hazard assessment used for siting of nuclear power plants is deterministic. Regulatory Guide 1.59, "Design-Basis Floods for Nuclear Power Plants" (Reference 10) describes the design basis floods that nuclear power plants should be designed to withstand using the concept of a probable maximum event. As discussed later, data for developing probable maximum events, such probable maximum hurricane (PMH) and probable maximum precipitation (PMP), only goes back 100 to 200 years. In additions, these probable maximum events are single value parameters that are deterministic and only of limited use for probabilistic risk assessment (PRA).

3.1 Current State-of-Practice

Although discrete components of a PFHA are available, a comprehensive PFHA methodology has not yet been developed. As discussed in Section 3.2, the risk analyst should note that because of limitations on using historical data no single approach or data source is sufficient for providing estimates of flood parameters over the full range of annual exceedance frequencies required for risk assessment applications (Reference 7). Therefore, results from a number of approaches may need to be considered to address modeling errors considerations and to appropriately consider epistemic uncertainties and to yield a family of hazard curves. Methods developed for generating flood hazard curves include, but are not limited to, at-site frequency analysis (using site-specific data and fitting a probability distribution to data with extrapolation to ranges beyond available data), regional frequency analysis (using regional data where site-specific information is rarely available using methods such as the average parameter approach, the index flood approach, and the specific frequency approach (Reference 11)), and stochastic event-based modeling. Under a stochastic event-based modeling approach, hydrologic/hydraulic model inputs (e.g., meteorological and climatological parameters as well as model inputs such as antecedent and initial conditions) are treated as random variables. Typically, Monte Carlo sampling procedures are used to simulate events by allowing the input variables to vary in accordance with their respective probability distributions, including dependencies among relevant parameters. A large number of simulations are performed to support development of magnitude-frequency curves. Examples A.5 and A.2 in Appendix A are instances where regional frequency analysis and stochastic event-based modeling were used, respectively. In reviewing licensees' analyses that utilize these models and methods, the limitations of these methods as well as their differences, to the extent practical, should be recognized. Furthermore, the employed data, models, and methods should be consistent with the range of hazards of relevance to the site.

3.2 Credible Extrapolation Ranges

Developing hazard curves for risk assessment uses the length of record and type of data to determine the extrapolation limits for flood frequency analysis. The limits of data and flood experience for any site or region place practical limits on the range of the floods to which annual exceedance frequencies can be assigned. Flood frequency analyses are typically performed for regional applications and address return periods of less than 1,000 years. For nuclear power plant safety risk assessments, flood estimates are needed for return periods of up to 1 million years (exceedance probability of 1 in a million). Developing credible estimates at these low probabilities generally could not be achieved, even by combining data from multiple sources and a regional approach.

Table 1 lists the different types of data that can be used as a basis for flood frequency estimates and the typical and optimal limits of credible extrapolation for annual exceedance probabilities (Reference 5). In general, the scientific limit to which the flood frequency relationship can be credibly extended, based upon any characteristics of the data and the record length, will fall short of the floods that need to be evaluated in risk-informed applications.

Table 1. Hydrometeorological data types and extrapolation limits for flood frequency analysis

Type of data used for flood frequency analysis	Limit of credible extrapolation for annual exceedance probability	
	Typical	Optimal
At-site stream flow data	1 in 100	1 in 200
Regional stream flow data	1 in 500	1 in 1,000
At-site stream flow and at-site paleoflood data	1 in 4,000	1 in 10,000
Regional precipitation data	1 in 2,000	1 in 10,000
Regional stream flow and regional paleoflood data	1 in 15,000	1 in 40,000
Combinations of regional data sets and extrapolation	1 in 40,000	1 in 100,000

Floods can be categorized, according to Reference 12, as large, rare, and extreme. These flood categories are shown in Figure 1 (Reference 7). Large floods generally encompass events for which direct observations and measurements are available. Rare floods represent events located in the range between direct observations and the credible limit of extrapolation from the data. Extreme floods generally have very small annual exceedance probabilities, which are beyond the credible limit of extrapolation but are still needed for risk assessments. Although external flooding events with annual exceedance probabilities in the large floods range have been assessed, extrapolation beyond the data is often performed by the licensees to provide information needed for risk assessments.

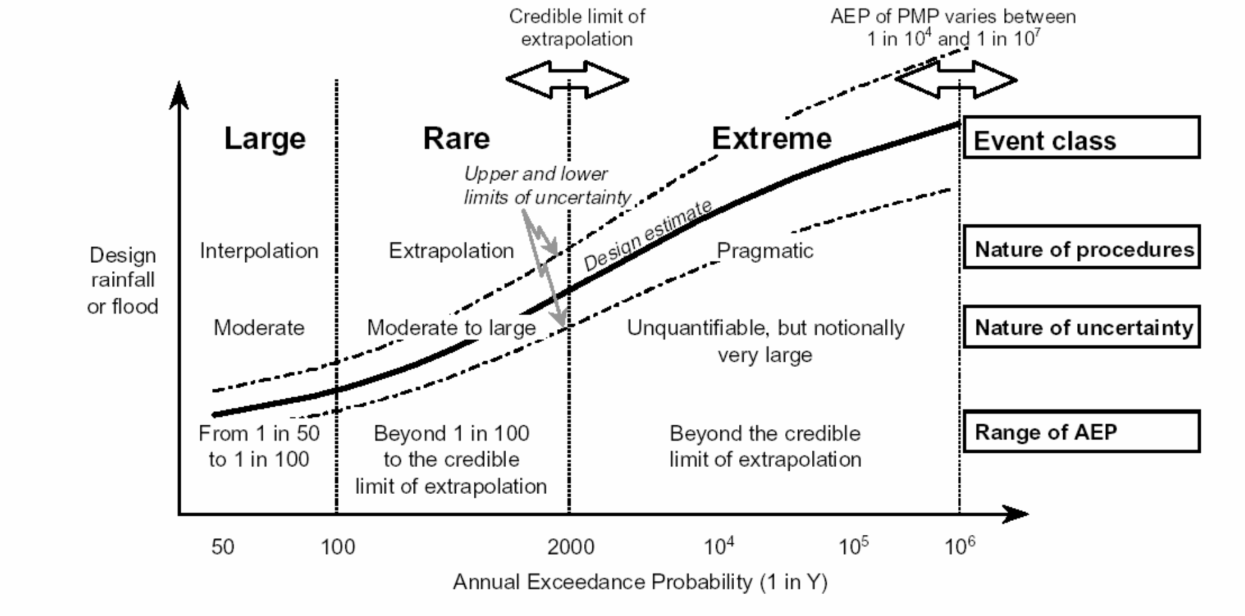

Figure 1. - Characteristics of notional floods (Reference 12)

Traditional sources of information used for estimating probabilities of floods (e.g., gauged stream flow records, indirect discharge measurements, tidal gauges, wind speed measures, and precipitation gauge records) have records that are less than 100 years in length with varying degrees of stationarity and homogeneity. Therefore, for large floods in Figure 1, the external flood hazard can be assessed with available data and records. Section 2 provides some references used to collect data. However, the limitations on length of records result in limits on the credible and technically defensible extrapolation of rare and extreme floods estimates based on conventional flood frequency analysis. Bulletin No. 17B[1], "Guidelines for Determining Flood Flow Frequency," (Reference 13), which is a consensus document among federal agencies, describes the data and procedures for computing flood flow frequency curves where systematic stream gaging records of sufficient length to warrant statistical analysis are available. This report recommends use of the Pearson Type III distribution with log transformation of data (log-Pearson Type III distribution) as a base method for flood flow frequency studies. This distribution is used to extrapolate the hazard curve in the rare floods range. Detailed process for using the log-Pearson III distribution is discussed in many documents, such as (Reference 14). The limits of extrapolation for rare flooding events are determined by evaluating the lengths of records, number of stations in a hydrologically homogeneous region,

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[1] Bulletin 17C, "Guidelines For Determining Flood Flow Frequency," which is the proposed update to Bulletin 17B, was in the public review process when this guidance was under development.

degree of correlation between stations, and other data characteristics that may affect the accuracy of the data. The risk analyst may request assistance form NRR/DRA for subject matter expert to expedite this analysis by providing insights on limits of extrapolation for rare flooding events. In accordance with Reference 15, it is acknowledged that "the mathematical formula that should be used for the extrapolation [when using Bulletin 17B] is not known with any confidence, and there is no agreed-upon procedure to assess or quantify the uncertainty in the extrapolation formula." Reference 15 also provides "rules" regarding extrapolation: (1) don't extrapolate unless necessary, (2) only extrapolate as far as necessary, (3) seek independent corroboration of extrapolated values and (4) "don't give too much credibility to or place too much reliance on the extrapolated values." While the appropriate limits on extrapolation for conventional flood frequency methods vary from site to site, they are generally limited to return periods ranging from 500-1000 years for typical sites and data sources. As a result, these methods alone are not appropriate for use in developing hazards curves for the entire range of return periods potentially required for external flood event assessments.

The uncertainty associated with extreme floods is very large. Oftentimes, these floods may result from unforeseen and unusual combinations of hydrologic parameters generally not represented in the flood history at a particular location (Reference 7). Because the extrapolation of hazard curves for the large return periods is not supported by flood frequency analyses, the risk analyst should consider the consequences of those extreme floods in making a risk-informed decision even though the hazard frequency cannot be practically characterized due to large uncertainties. Performing analyses using upper bound estimates may help determining whether further assessment of uncertainties is warranted. It is also important to note that probabilistic flooding analyses utilize the hazard curves, in combination with additional considerations and associated uncertainties, and a potential upper bound to the largest flood at a particular site or the probable maximum flood alone do not typically provide all the insights necessary for making risk informed decisions. Considering a spectrum of flooding events, including levels that are considerably lower than the PMF level, could also provide additional insights. For example, there may be be a significant increase in risk when a flood elevation exceeds the switchyard elevations, which could be much lower than the PMF elevation.

3.3 Other Considerations

In analyzing recent event assessments for the SDP, some licensees performed detailed deterministic calculations for hazard assessment. The risk analyst may consult with experts in the fields relevant to flood-causing mechanisms considered in the analysis (e.g., hydrology, meteorology, oceanography) to develop an understanding of assumptions, determine the validity of the methods used in those deterministic assessments, and account for technically defensible interpretations of available data, models, and methods, which may vary based on the severity of floods to which frequencies must be assigned. As flooding SDP analyses are often analyzed using Appendix M, the deterministic assessment is one input to overall qualitative assessment of the events.

A flood of a given severity can occur from any combination of constituent contributing factors (e.g., combinations of climatological, meteorological, and antecedent conditions) or mechanisms (e.g., storm surge concurrent with a, potentially dependent, river flood at a site located near where the river enters the ocean). The risk analyst should ensure that the hazard assessment captures hazard contributions from all relevant flood-causing mechanisms and combinations of events. To address relevant mechanisms, the licensees may develop a composite flooding hazard curve combining all plausible mechanisms to obtain a single hazard curve. The analyst should note that sites that are affected by multiple flood hazards may use different strategies to protect against or mitigate the different flood hazards and, therefore, it may be inappropriate to consider a single composite hazard curve and plant fragility function.

In characterizing flood hazards, it is important to consider associated effects in addition to flood height (i.e., factors in addition to stillwater elevation such as wind waves and run-up effects; hydrodynamic loading, including debris; effects caused by sediment deposition and erosion; concurrent site conditions, including adverse weather conditions such as wind; groundwater ingress; and other pertinent factors, Reference 16). Flood event duration should also be considered in addition to the hazard flood height and associated effects in characterization of the hazard.

3.4 Sensitivity and Uncertainty

PRA typically utilizes the mean hazard for the frequency of occurrence of different external flood severities. However, significant insights can be gained as a result of understanding the uncertainties in the hazard. Consideration of these uncertainties is an important component of a risk-informed regulatory process.[2]

Appropriate treatment of aleatory variability and epistemic uncertainties allows for decision making on a range of relevant factors (e.g., insights from mean hazard curves as well as the comparison of the mean to various fractile hazard curves). The spatial, temporal and other relevant characteristics of future realizations of meteorological, climatological, hydrological, hydraulic, or other parameters typically is associated with aleatory variability and expressed by a hazard curve. There are various options for addressing epistemic uncertainty (e.g., in probabilistic seismic hazard analysis, it is common to treat epistemic uncertainty through logic trees). Epistemic uncertainty is expressed by incorporating multiple assumptions and technically defensible data, models, and methods using multiple hazard curves from which a mean, median or other fractile hazard curve can be derived. While the mean and median hazard curves convey the central tendency of the calculated exceedance frequencies, the separation among fractile curves conveys the effect of uncertainties. Examples of epistemic uncertainty include: the selection of the probability distribution that is appropriate for capturing aleatory uncertainty in parameters, selection of a technique to parse available datasets for relevance to a particular site, the appropriate hydrologic or hydraulic model to use, and the choice of various parameters needed to utilize existing models.

New information related to hazard assessment beyond the information available in sources such as FSARs or IPEEEs may become available in licensees' analyses of the flooding events. The

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[2] NUREG-1855 (Reference 17) describes treatment of uncertainties in PRAs used for risk-informed decision making. EPRI 1016737, "Treatment of Parameter and Model Uncertainty for Probabilistic Risk Assessments" (Reference 18) provides general guidance for the treatment of uncertainties in PRAs to supplement and complement the guidance in NUREG-1855. NUREG-1885 also references EPRI 1026511, "Practical Guidance on the Use of PRA in Risk-Informed Applications with a Focus on the Treatment of Uncertainty" (Reference 19), which supplements guidance in EPRI 1016737.

validity of the new information should be assessed and the appropriate manner that the new information should be considered in making the risk-informed decision should be determined.

4. Flood Protection Measures

4.1 Reliability of Flood Barriers and Flood Protection Features

There are vast differences from plant to plant with regard to the flood protection features used. Examples of these features are provided in Interim Staff Guidance 12-05, "Guidance for Performing the Integrated Assessment for External Flooding," (Reference 16). JLD-ISG-2012-05, in part, provides generic guidance on performing an evaluation of the capability of the site flood protection to protect systems, structures, and components (SSCs) important to safety for each set of flood scenario parameters. The generic guidance in JLD-ISG-2012-05 does not provide detailed guidance on determining different failure modes of various physical barriers or evaluating and quantifying the reliability of the degraded physical barriers.

During recent plant walkdowns and flooding events, many instances have been found where physical barriers credited to protect safety-related SSCs from inundation and static/dynamic effects of external floods were not able to reliably accommodate the flood scenario parameters. Appendix A provides examples of deficiencies in flood protection features analyzed through SDP. These examples include various deficiencies such as degradation of storm drain capacity and degraded conduits that lacked flooding barriers (Example A.1), degradation of penetration and conduit seals, unsealed shims, gap in the weather stripping along door, unsealed pump leak off hub drains (Example A.2), electrical conduit penetration seals (Example A.3), conduit couplings in the air intake tunnel (Example A.4), and unsealed penetrations (Examples A.5 and A.6). These deficiencies revealed pathways that were not effectively sealed against flooding and affected or could affect equipment in the auxiliary building (A.1, A.4 and A.6), reactor building, EDG building, service water building (A.2), and battery rooms (A.5). No method or guidance is available at this time for the wide range of physical flood barriers to appropriately assess the performance of the degraded physical barriers and account for their reliability at both the feature- and system-levels during a postulated design basis flooding event. In a case-by-case basis, the risk analyst must attempt to obtain information on the nature of failure modes of the flood protection system under review and consider potential ingress pathways for floodwaters (e.g., through conduits or ducts). In analyzing past events, in which the performance deficiencies were related to degraded physical flood barriers, PRA analysts have not typically given any credits to flood protection features intended to protect a specific SSC or group of SSCs and those SSCs were assumed to be failed in the analysis. Based on additional information that may be provided later, the assumption for complete failure of the barrier and, consequently, the protected SSCs may be revised and appropriate credits may be considered.

As stated in the Near-Term Task Force report, the flooding risks are of concern due to a "cliff-edge" effect, in that the safely consequences of a flooding event may increase sharply with a small increase in the flooding level. Therefore, the risk analyst should be aware and consider potential impact on the results of analyses due to this effect.

4.2 Human Reliability Considerations

Human Reliability Analysis (HRA) methods for evaluating flood mitigation actions, such as construction of flood protection are not well established. In the absence of specific guidance for modeling HRA in external flooding events, PRA analysts have used SPAR-H to quantify human error probabilities (HEPs) in analyzing the past performance deficiencies. Although the focus of SPAR-H is on at-power and LP/SD HEP determination, heuristics described in NUREG/CR-6883, “The SPAR-H Human Reliability Analysis Method,” (Reference 20) may apply to other situations such as fire, flood, seismic events to estimate the HEPs associated with the new or re-quantified flood mitigation actions. By utilizing performance shaping factors (PSFs), the SPAR-H provides a framework that account for factors, such as timeliness, procedures, training and stress, which could significantly affect the risk in external flooding events.

For evaluating the human interactions to implement the site-wide flood mitigation strategies, the analyst may need to consider new basic events representing those human actions. The analyst may also need to consider whether any human actions embedded in the SPAR model should be re-quantified to account for specific conditions resulted from the external flooding. Once the human failure events (HFEs) are identified and characterized, the analyst must identify the salient performance drivers by reviewing SPAR-H PSFs. Each PSF needs to be examined with respect to the context of the HFE. Appendix C to JLD-ISG-2012-05, (Reference 16) adopts SPAR-H guidance and provides guidance on assigning PSF levels in the context of external flooding. Appendix B to this guidance provides a brief discussion of PSFs along with examples of past SDP analyses related to external flooding. The past SDP analyses show that a number of HEPs or multiple PSFs could be affected by the performance deficiencies on external flooding. For instance, in Example B.1, the HEP for plant workers failing to install levee/bin wall flood barriers was assumed 1.0 (always failed) for the deficient case because of inadequate time. The other HEPs affected by the performance deficiency in Example B.1 included the HEP for failing to protect the reactor building from flooding via alternate means (such as sandbagging) and the HEP for manual operation of reactor core isolation cooling system (RCIC) and the hard pipe vent during extended station blackout. A significant credit was not given for protecting the reactor building via alternate means because the timing, plant configuration, staffing, etc., when it is realized that the reactor building needs to be protected via this option was unclear. The risk analyst also found the operation of RCIC and the hard pipe vent under an extended station blackout with significant site-wide flooding that was expected to last for several days to be challenging. The procedure for operating RCIC without electric power stated that reactor level and RCIC turbine speed may not be available. Radiation, temperature, lighting, etc. may also represent challenges to the operators. In Example B.3, an assessment was performed to determine the feasibility of providing inventory make-up during a flooding event. In this example, although Available Time was significantly greater than the estimated time, procedures that identify the need for make-up did not provide sufficient detail to connect to a primary system above the peak flood level, which adversely affected the PSF for Procedures. In addition, after loss of AC power and subsequent depletion of the 125 VDC batteries, Control Room instrumentation would become unavailable, leaving local instruments as the primary source for plant information, which affected the Ergonomics/Human Machine Interface (HMI) PSF.

Because of the importance of operator actions in mitigating strategies during external flooding events, the possible need for special treatment of some ex-control room actions, and the large uncertainties that may exist in HFE estimates, the contribution of HFEs on the risk may vary substantially depending on the assumptions. The PRA analyst may request assistance form NRR/DRA for subject matter expert to expedite this analysis by providing insights on adding or re-quantifying HFEs of high significance and possibly deviating from the SPAR-H guidance as necessary. The analyst should also consider the guidance in 9.4 of the Handbook, Volume 1 to account for dependencies between HFEs for operator actions during external flooding events.

In external flooding analyses, the Diagnosis component of HFEs could potentially be significance for some human actions. In particular, when the analyst must qualitatively consider recovery actions that licensees want the staff to consider when those actions are not proceduralized, careful treatment of the diagnostic component of the human error is critical. During the analysis of human actions for events or conditions associated with external floods, licensees may provide information to justify crediting various operator actions that could have been implemented using resources available. In some cases, the licensee attempted to demonstrate feasibility or reliability of human actions after an event has occurred and asked the staff to provide credit for such actions, even though procedures or training may not exist for those actions. As RIS 2008-15 (Reference 21) states, manual actions must be included in plant procedures and staff be trained to perform the actions in the context they are to be credited in order for the licensee to receive realistic quantitative credit in a risk assessment. The revision to RIS further states that, although quantitative credits for those actions are not warranted, the NRC will consider licensees' analyses for providing qualitative insights in cases where procedures for those human actions are under development or those human actions are included in other relevant procedures that could be reasonably identified and utilized for mitigating external flooding events. The NRC will rely more on historical evidence or supplemental inspections that demonstrate the successful feasibility and reliability of the actions that existed prior to the event, rather than information gathered after the event, and consider whether any credit may be given qualitatively in a risk-informed process using IMC-0609, Appendix M.

Appendix A: Examples of Deficiencies In Flood Protection Features

Example A.1

On January 9, 2014, St. Lucie Unit 1 was operating at 100 percent reactor power when the site experienced a period of unusually heavy rainfall. Although this event was below the design basis flood, St. Lucie declared an unusual event because of storm drain capacity degradation. Blockage in the site's storm drain system caused water to backup within the ECCS pipe tunnel outside of the Unit 1 reactor auxiliary building. Water entered the auxiliary building through two degraded conduits that lacked internal flood barriers. An extent-of-condition review identified four additional conduits on Unit 1 that lacked the required internal flood barriers. The modification that had installed the conduits had not considered the need for internal flood barriers for conduits installed below the design-basis flood elevation. Previous walkdowns performed in 2012 using the guidance contained in NEI 12-07, had failed to identify the degraded conduit or the missing conduit internal flood barriers. Additionally, St. Lucie determined that previous engineering evaluations used to assess the results of the walkdowns did not account for the site flood inundation times and therefore underestimated the volume of external flood leakage through degraded flood barriers. The licensee implemented corrective actions that included installing qualified internal water seals on all of the affected conduits. Additional information regarding this event is available in Licensee Event Report (LER) 50-335/2014-001-00, dated March 10, 2014, and in NRC Integrated inspection reports 05000335/2014009 and 05000389/2014009, dated September 24, 2014. In a letter dated November 19, 2014, (ADAMS Accession No. ML14323A786), the NRC issued the final significance determination the findings and characterized the finding as White, a finding of low to moderate risk significance.

Example A.2

On April 20, 2011, NRC inspectors at Brunswick identified that the EDG fuel oil tank chamber enclosure contained openings that would adversely impact the ability to mitigate external flooding of the oil tank chambers in the event of a probable maximum hurricane. The licensee subsequently performed extent-of-condition walk downs and identified numerous examples of degraded or nonconforming flood protection features, the majority of which were flood penetration seals. During walkdowns of flood protection features in accordance with NEI 12-07 in 2012, the licensee identified additional degradation in the reactor buildings and the EDG building, specifically degraded flood penetration seals, conduit seals, and a 3-inch gap in the weather stripping along the bottom of the Unit 2 reactor building railroad door. This gap would have allowed leakage into the reactor building during a PMH. The inspectors also identified an EDG rollup door that could have allowed water intrusion into the EDG building during a PMH. Additionally, the licensee identified unsealed shims under the base plates of the service water pumps, as well as leaking flood penetration seals and an unsealed conduit in the service water building that could have allowed flood water to enter the building during a PMH. The licensee also identified a potential flood pathway from the intake canal into the service water building through unsealed pump leak off hub drains, a condition that had existed since construction of the plant. These conditions were caused by a historical lack of a flood protection program. Multiple examples were identified where credited flood mitigation equipment had no established preventative maintenance program. Corrective actions included correcting the degraded seals, developing and implementing an engineering program to mitigate consequences of external flooding, and developing topical design basis for internal and external flooding. Additional information regarding this issue is available in NRC inspection reports 05000324/2014011 and

05000325/2014011, dated May 29, 2014. The NRC characterized the finding as White, a finding of low to moderate risk significance.

Example A.3
On December 12, 2012, the licensee at Sequoyah Nuclear Plant performed an inspection of an electrical manway and confirmed that inadequate electrical conduit penetration seals provided an in-leakage path into the essential raw cooling water (ERCW) pumping station. The licensee concluded that an external flooding event exceeding the elevation that would impact the conduits would inundate the ERCW pumping station, with impacts to both Unit 1 and Unit 2. The nonconforming seals would have allowed flood waters to enter the pumping station at a rate greater than the capacity of the sump pump and could have resulted in the ERCW system being unavailable to perform its design function during a flood event below plant grade. Although the electrical conduit penetration seals were meant to be the flood barrier, there was no clear identification of the flood barriers and their requirements. The licensee took corrective actions that included installing qualified conduit seals and revising design-basis documents and flood barrier drawings to identify flood boundaries and to include seal details. Additional information regarding this issue is available in LER 05000327, 328/2012-001-00, dated February 8, 2013, and in NRC inspection reports 05000327/2013011 and 05000328/2013011, dated June 4, 2013. The NRC characterized the finding as White, a finding of low to moderate risk significance.

Example A.4
On August 2, 2012, while observing the licensee flooding walkdowns at Three Mile Island Station in accordance with TI 2515/187, NRC inspectors noted degradation on several conduit couplings in the air intake tunnel. The air intake tunnel provides a source of air for safety-related ventilation systems and also contains both safety- and nonsafety-related electrical conduits. The couplings, which by design should have been injected with sealant to provide a barrier to design-basis flooding events, showed signs of exposure to wet environments, indicating that the sealant was missing. The licensee eventually determined that 43 conduit couplings were missing sealant. The original construction deficiency had not been identified by the licensee during a comprehensive review performed in 2010. Without adequate protection from flooding, flood water could have bypassed all flood barriers through the conduits and impacted the operability of decay heat removal equipment. The licensee implemented prompt compensatory actions, including staging extra sandbags and earth moving equipment to restore operability of the flood barriers. The licensee implemented permanent corrective actions that included sealing the conduits by injecting watertight qualified sealant material into the associated cable conduits. Additional information regarding this issue is available in NRC inspection report 05000289/2012005, dated February 11, 2013. In a letter dated April 30, 2013, (ADAMS Accession No. ML13120A040), the NRC issued the final significance determination the findings and characterized the finding as White, a finding of low to moderate risk significance.

Example A.5
On May 29, 2013, while performing flooding walkdowns in accordance with NEI 12-07, the licensee at R.E. Ginna Nuclear Power Plant discovered two penetrations that appeared to be unsealed leading to one of the battery rooms. Although the licensee determined that drains in the manhole would prevent the water level from reaching the unsealed penetrations, NRC inspectors raised questions about the operability of these drains, since they were not included in any maintenance or test program. In response to these questions, the licensee tested the drains and determined that they were not capable of draining enough water to prevent a design-basis flood from reaching the unsealed penetrations and flooding battery room B. Battery room A would also be flooded by a non-watertight fire door that connects it with battery room B. The potential existed to also lose offsite power leading to the loss of all alternating

current power to the site and an unrecoverable station blackout. In 1983, as part of the Systematic Evaluation Process, the licensee's design basis was changed to include additional external flooding events and the flood protection level was agreed to by the licensee at a level that was above the elevation of the manhole. The licensee did not evaluate the potential for flooding through the manhole and, therefore, did not seal the cable penetrations that were at an elevation below the new level. The licensee took corrective actions that included installing permanent hydrostatic seals in both penetrations between the manhole and the battery room. Additional information regarding this issue is available in NRC inspection report 05000244/2013005, dated February 14, 2014. In a letter dated April 17, 2014, (ADAMS Accession No. ML14107A080), the NRC issued the final significance determination the findings and characterized the finding as White, a finding of low to moderate risk significance.

Example A.6

On March 31, 2013, following the collapse of a temporary lifting rig carrying the Arkansas Nuclear One Unit 1 main turbine generator stator, a rupture in the fire water system resulted in water leakage past floor plugs in the auxiliary building and subsequent accumulation of water inflow in the safety-related decay heat removal room B through a room drain pipe. This event overlapped the timeframe in which the licensee was assessing flood mitigation features in response to Fukushima-related orders issued by the NRC. The extent of condition reviews by the licensee related to this event and those discrepancies identified during flood mitigation response efforts found numerous other pathways that were not effectively sealed against flooding in the auxiliary building and emergency diesel fuel storage buildings. The licensee's failure to design, construct, and maintain the Unit 1 and Unit 2 auxiliary and emergency diesel fuel storage buildings so that they would protect safety-related equipment during design-basis flood events caused the overall condition. The unsealed penetrations were not identified during the walkdowns because of incomplete information on flooding barriers, some information not being kept current, and inadequate oversight of the contractor performing the flood protection walkdowns. The licensee took corrective actions that included re-performing the reviews of essential flood protection features, identifying those features that were initially not identified, completing the missed portions of the walkdowns, and submitting corrected information to the NRC. In this event, an internal flooding event resulted in the licensee discovering external flooding vulnerabilities. Additional information regarding this issue is available in NRC inspection reports 05000313/2014009 and 05000368/2014009, dated September 9, 2014. In a letter dated January 22, 2015, (ADAMS Accession No. ML15023A076), the NRC issued the final significance determination the findings and characterized the finding as Yellow, a finding having substantial safety significance.

Appendix B: Examples of Factors Affecting Operator Actions to Flood Events

This Appendix provides a list of PSFs identified in Appendix C to JLD-ISG-2012-05 (Reference 16) adapted from SPAR-H methodology (Reference 20) and a generic description of circumstances related to external flooding events that could necessitate considering any of these factors as a performance drive or re-quantifying the HFEs. Reference 16 provides a more detailed discussion of these PSFs in the context of flooding.

B.1 Available time

Reviewing recent findings identified a number of instances in which available time to implement mitigating strategies was not sufficient because of variety of issues such as not accounting for particular steps in planning, not considering the sequential manner that some activities in the implementing procedures should be directed, underestimating the time to perform some of the more complex and coordinated work activities, etc. Following is an example for which the available time was either inadequate or barely adequate (Examples B.2 and B.4 are also related). For those actions with inadequate available time, the probability of failure is one.

Example B.1:
During an inspection from September 12, 2012, to May 15, 2013, NRC inspectors identified that the Monticello Nuclear Generating Plant site failed to maintain a flood mitigation procedure such that it could support the implementation of flood protection activities within the 12-day timeframe credited in the USAR to protect against a probable maximum flood (PMF) event. The licensee believed that flood mitigation actions for the protected area could be taken within the 12 days specified in the USAR by citing an independent engineering assessment performed in 2001. However, the licensee did not perform a verification walkthrough of the activities in the procedure and, therefore, did not identify vulnerabilities in its flood plan. The licensee took corrective actions, which included revising its procedure to add more detail, as well as pre-staging materials necessary to complete the bin wall in the timeframe cited in the USAR. Additional information regarding this issue is available in NRC inspection report 05000263/2013008, dated June 11, 2013. In a letter dated August 28, 2013 (ADAMS Accession No. ML13240A435), the NRC issued the final significance determination the findings and characterized the finding as Yellow, a finding having substantial safety significance.

B.2 Accessibility

Actions that must be performed in inundated areas or requiring operators and/or equipment to travel through inundated areas, should be considered infeasible unless it can be shown that elevated pathways or other means are available to enable movement through the inundated areas and significant hazards to operators (e.g., electrical hazards due to presence of water, low temperatures, etc.) are not present. Other accessibility issues include obstructions (e.g., charge fire hoses) and locked doors.

B.3 Environmental/Stress Factors

Stress refers to the level of undesirable conditions and circumstances that impede the operator from easily completing a task. Stress can include mental stress, excessive workload, or physical stress (such as that imposed by difficult environmental factors). During an external flooding event, environmental conditions could affect and impede completion of actions. The environmental conditions associated with flood events that could increase stress include:

adverse weather (e.g., lightning, hail, wind, and precipitation), temperatures (e.g., air and water temperatures, particularly if operators must enter water), conditions hazardous to the health and safety of operators (e.g., electrical hazards, hazards beneath the water surface, drowning), lighting, humidity, radiation, and noise.

B.4 Diagnostic Complexity, Indications and Cues

In the context of flooding, indications should be available to provide notification that a flood event is imminent if operator actions are required to provide protection against the flood event. Examples of indications include river forecasts, dam condition reports, and river gauges. Appendix C to Reference 16 states that any operator manual action initiated by the indication should be considered infeasible, if durable agreements are not in place to ensure communication from offsite entities and the plant does not have an independent capability to obtain the same information onsite. Consideration should be given to the quality of the agreements in place between offsite entities and operators at the nuclear power plant site as well as the potential for the communication mechanisms to fail.

In the context of mitigation actions, indications should be available to alert operators to the failure of flood protection features and presence of water in locations that are intended to be kept dry or otherwise protected from flood effects. For cases in which indications are not available, the evaluation can consider compensatory measures (e.g., local operator observations). If cues or indications are not available to operators, the mitigation actions should be considered infeasible.

B.5 Experience and training

This factor refers to the experience and training of the operator(s) involved in the task. Included in this consideration are years of experience of the individual or crew, and whether or not the operator/crew has been trained on the type of accident, the amount of time passed since training, and the systems involved in the task and scenario. As some licensees have not fully developed flood mitigation procedures or they have not been adequately trained on implementing those procedures, this factor could become a performance driver. The following are examples related to experience and training.

Example B.2:
In 2013, the licensee at Watts Bar identified that it could not demonstrate the capability to implement site external flood mitigation procedures in the time assumed between the notification of an imminent design-basis flood event and flood waters reaching the Watts Bar site. The design-basis flood event for Watts Bar would result in flooding above plant grade. Accordingly, the licensee relied on procedures used to reconfigure plant systems in preparation for site inundation to ensure the ability to safely shut down the reactor and remove decay heat. Examples of issues that challenged the assurance that the flood mitigation procedures could be implemented within the available time included: work activities in the implementing procedures were directed in a sequential manner, which added to the overall time required; piping interferences and the lack of suitable rigging locations for inter-system spool pieces; mislabeled or missing equipment was used in the implementing procedures; the time to perform some of the more complex and coordinated work activities was underestimated. The licensee took corrective actions that included revising the flood mitigation procedures to add more detail, increasing the frequency of the training for the procedures, and staging equipment and developing preventive maintenance activities to periodically validate that the equipment is in place. Additional information regarding this issue is available in NRC inspection report

05000390/2013009, dated June 4, 2013. The NRC characterized the finding as White, a finding of low to moderate risk significance.

B.6 Procedures

This factor refers to the existence and use of formal operating procedures for the tasks needed for mitigating an external flooding event. In evaluating the feasibility of an operator manual action, the quality of procedures should be assessed based on its ability to assist operators in correctly diagnosing an impending flood event (i.e., flood height and associated effects) or the compromise of a flood protection feature, to identify the appropriate preventative (or mitigation) actions and to account for prevailing current conditions, if applicable (e.g., high wind or lightning that makes it difficult for operators to work outdoors). The following examples illustrate cases where procedures were not available or incomplete.

Example B.3:
In August 2012, while observing licensee simulations at Dresden Nuclear Power Station, Units 2 and 3 for executing flood protection procedures as part of the NEI 12-07 walkdowns, NRC inspectors noted that the procedures did not account for reactor coolant system (RCS) inventory losses. The procedures assumed a flood duration of 4 days, during which time systems that provide normal and makeup capacity to the RCS would be flooded and unavailable. The licensee calculations accounted for the 5-gallon per minute (gpm) maximum technical specification allowance for unidentified RCS leakage, but it did not account for inventory losses from identified leakage, which could be as high as an additional 20 gpm. The licensee strategy did not originally provide for a method to maintain RCS inventory above the top of active fuel for RCS leakage rates that were allowable under technical specifications. The licensee took corrective actions, including modifying procedures to provide makeup capacity and to isolate the reactor recirculation loops during flood conditions when reactor vessel makeup capabilities are limited so that sources of identified leakage would no longer impact the reactor vessel level. Additional information regarding this issue is available in NRC inspection report 05000237/2013002, dated May 7, 2013. In a letter dated July 31, 2013 (ADAMS Accession No. ML13213A073), the NRC issued the final significance determination the finding and characterized the finding as White, a finding of low to moderate risk significance.

Example B.4:
In March 2013, inspectors found that the Point Beach Nuclear Plant licensee failed to establish procedural requirements to implement external wave run-up protection design features as described in the FSAR. Flood protection procedures directed installation of concrete jersey barriers to protect the turbine building and pumphouse from flooding. While performing the flooding walkdowns, the licensee discovered, among other issues, that when the barriers were installed, gaps were created and there were no provisions in the procedure for using sandbags to protect the openings in the jersey barriers or the gaps between the barriers and the ground. The licensee also had failed to consider the time that would be required to erect the barriers. The licensee took corrective actions, including modifying existing jersey barriers to eliminate openings, revising the procedure to direct the installation of jersey barriers in conjunction with sandbags, and pre-staging additional sandbags and jersey barriers. Additional information regarding this issue is available in NRC inspection report 05000266/2013002, dated May 13, 2013. In a letter dated August 9, 2013 (ADAMS Accession No. ML13221A187), the NRC issued the final significance determination the finding and characterized the finding as White, a finding of low to moderate risk significance.

Example B.5:
In September 2009, during a component design basis inspection at Fort Calhoun Station, NRC inspectors identified that the licensee failed to maintain adequate procedures to protect the intake structure and auxiliary building during external flooding events. These procedures described stacking and draping sandbags on top of installed floodgates to protect the plant up to the flood elevation described in the USAR. When inspectors asked plant staff to demonstrate this procedure, they were unable to complete the procedure as written because the cross section on the top of the floodgates was too small to accommodate enough sandbags to retain a 5-foot static head of water. The licensee took corrective actions that included revising the procedures. Additional information regarding this issue is available in NRC inspection report 05000285/2010007, dated July 15, 2010. In a letter dated October 6, 2010 (ADAMS Accession No. ML102800342), the NRC issued the final significance determination the findings and characterized the finding as Yellow, a finding having substantial safety significance.

B.7 Staffing

In assessing the feasibility and reliability of an operator manual action, the persons involved in performing the operator manual action should be qualified. The feasibility assessment should consider the availability of a sufficient number of trained operators without collateral duties during a flood event such that the required operator action can be completed as needed. In evaluating the reliability of an operator manual action, uncertainties in the number of operators onsite (or that can be brought in from offsite) should be considered.

B.8 Communication

Equipment may be required to support communication between operators to ensure the proper performance of manual actions (e.g., to support the performance of sequential actions and to verify procedural steps). Also because of the long durations of many flooding scenarios and because of the possible need of offsite support, communication with corporate and governmental organizations is important. Therefore, consideration of the causes of the floods impact on offsite communications must be considered. Consideration should be given to whether operators are trained to ensure effective communication and coordination during a flood event.

B.9 Human Factors Engineering

Human factors engineering refers to the equipment, displays and controls, layout, quality, and quantity of information available from instrumentation, and the interaction of the operator/crew with the equipment to carry out tasks. Many of the human actions anticipated for dealing with floods will be external to the main control room. As such, it is not the layout and design of the controls and annunciators in the control room that are of primary concern but instead those external to the control room. In Example B.2, one of the challenges in implementing flood mitigation procedures was the use of mislabeled or missing equipment in the implementing procedures.

Appendix C: Dam Failure Rates for External Flooding

Dam failure is well documented and can be characterized by type of dam. Table 2 is a summary of point estimate failure rates for dams that are broken down by large dams (>50 ft) and all sized dams. Characteristics of US dams and dam failures are available at the National Inventory of Dams, http://crunch.tec.army.mil/nid/webpages/nid.cfm and the National Performance of Dams Program, http://npdp.stanford.edu/index.html .

Of the 79,777 dams in the US, 72% are embankment type and 28% are concrete. Nineteenth century dams would fail at 5% in the first five years after construction but would settle out to a 1 to 4% additional failure by 20 years of life. This was reduced to 2% in the first 5 years for dams built after 1930. By 1960, dam failure rates were less than 0.01% due to better engineering. Whatever the era, half of all dams that ever fail, do so in the first five years. This high infant mortality is often due to piping in the soil around the dam or underneath it. Even concrete dams are not immune. However, dam construction dropped dramatically after 1980 so that nearly all dams are older than 5 years.

Dams as far up or downstream as 300 miles should be considered for both flood and loss of heat sink. It is noteworthy that all forms of dams have a failure rate between 1E-4 and 4E-4, even for blue sky events. Determining flood levels, however, is a complex matter. The US Army Corps of Engineers has software named HEC that when combined with GIS geographical data will model river flow and flooding in great detail.

Table 2a. Dam failure rates

All Dams	Failures	Dam-Years	apost	bpost	Mean	5%	50%	95%
Arch Dams	2	9101	2.5	12163.2644	2.055E-04	4.709E-05	1.789E-04	4.551E-04
Buttress Dams	2	9819	2.5	12881.2644	1.941E-04	4.446E-05	1.689E-04	4.297E-04
Concrete Dams	10	110227	10.5	113289.2644	9.268E-05	5.116E-05	8.976E-05	1.442E-04
Earth Dams	366	2240403	366.5	2243465.2644	1.634E-04	1.496E-04	1.632E-04	1.776E-04
Gravity Dams	28	122798	28.5	125860.2644	2.264E-04	1.615E-04	2.238E-04	3.004E-04
Masonry Dams	5	21692	5.5	24754.2644	2.222E-04	9.240E-05	2.089E-04	3.974E-04
Multi-Arch Dams	0	240	0.5	3302.2644	1.514E-04	5.954E-07	6.888E-05	5.816E-04
Rockfill Dams	7	73806	7.5	76868.2644	9.757E-05	4.723E-05	9.327E-05	1.626E-04
Stone Dams	2	11365	2.5	14427.2644	1.733E-04	3.970E-05	1.508E-04	3.837E-04
Timber Crib Dams	3	6536	3.5	9598.2644	3.646E-04	1.129E-04	3.306E-04	7.328E-04
Total	**425**	**2605987**	**0.5**	**3062.2644**	**1.633E-04**	**6.420E-07**	**7.428E-05**	**6.272E-04**

Table 2b. Dam failure rates for dams over 50 feet high

Dams Over 50 Feet High	Failures	Dam-Years	apost	bpost	Mean	5%	50%	95%
Buttress Dams	0	1876	2.4026	11970.7049	2.007E-04	4.410E-05	1.736E-04	4.497E-04
Arch Dams	2	5667	4.4026	15761.7049	2.793E-04	1.018E-04	2.585E-04	5.280E-04
Concrete Dams	0	19215	2.4026	29309.7049	8.197E-05	1.801E-05	7.092E-05	1.837E-04
Earth Dams	56	144810	58.4026	154904.7049	3.770E-04	2.997E-04	3.749E-04	4.617E-04
Gravity Dams	7	19542	9.4026	29636.7049	3.173E-04	1.683E-04	3.061E-04	5.044E-04
Masonry Dams	0	1987	2.4026	12081.7049	1.989E-04	4.370E-05	1.721E-04	4.456E-04
Multi-Arch Dams	0	77	2.4026	10171.7049	2.362E-04	5.190E-05	2.044E-04	5.293E-04
Rockfill Dams	4	20010	6.4026	30104.7049	2.127E-04	9.568E-05	2.017E-04	3.671E-04
Total	**69**	**213184**	**2.4026**	**10094.7049**	**2.380E-04**	**5.230E-05**	**2.059E-04**	**5.333E-04**

Notes:

Dams constructed with mixed materials are not counted; dams with no construction dates available are not counted.

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