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Lessons Learned from Missing Flooding Barriers Operating Experience

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ABSTRACT

Flooding hazard is highly significant for nuclear power plant safety because of its potential for common cause impact on safety related systems, and because operating experience reviews regularly identify flooding as a cause of concern. Source of the flooding could be external (location) or internal (plant design). The amount of flooding water could vary but even small amount might suffice to affect redundant trains of safety related systems for power supply and cooling. The protection from the flooding is related to the design-basis flood level (DBFL) and it consists of three elements: structural, organizational and accessibility. Determination of the DBFL is critical, as Fukushima Daiichi accident terribly proved. However, as the topic of flooding is very broad, the scope of this paper is focused only on the issues related to the missing flood barriers.

Structural measures are physically preventing flooding water to reach or damage safety related system, and they could be permanent or temporary. For temporary measures it is important to have necessary material, equipment and organizational capacity for the timely implementation. Maintenance is important for permanent protection and periodical review is important for assuring readiness and feasibility of temporary flooding protection. Final flooding protection element is assured accessibility to safety related systems during the flooding.

Appropriate flooding protection is based on the right implementation of design requirements, proper maintenance and periodic reviews. Operating experience is constantly proving how numerous water sources and systems interactions make flooding protection challenging. This paper is presenting recent related operating experience feedback involving equipment, procedures and analysis. Most frequent deficiencies are: inadequate, degraded or missing seals that would allow floodwaters into safety related spaces. Procedures are inadequate typically because they underestimate necessary time or they do not provide sufficient instructions. Most of the events are related to deficiencies discovered during walk-down, review, maintenance and sometimes to incidents. Perhaps these lessons learned from recent events could help filling the missing gap to have most complete flooding protection.

This paper presents results from the most recent activity related to the operational experience feedback for the nuclear power plant safety in the EC JRC Clearinghouse.

Keywords: *Flooding protection, missing flooding barriers, operating experience, lessons learned*

1 INTRODUCTION

Flooding hazard is substantial for nuclear power plant safety because it is usually happening and it has high potential for common cause failure of safety related systems. Source of the flooding could be external (e.g., river, lake, sea or precipitation) or internal (e.g., maintenance and failure of the service, cooling or fire water systems). The volume of flooding water may vary but even a limited amount might suffice to affect redundant trains of safety related systems for power supply or cooling. The protection from the flooding is related to the design-basis flood level and it consists of three elements: structural, organizational measures and accessibility (e.g. [1.] lists several regulatory and guidance documents). Determination of the design-basis water level is critical, as Fukushima Daiichi accident terribly proves (Figure 1). However the scope of this paper is limited to the issues related to the missing flood barriers.

Structural measures physically prevent flooding water to reach or damage safety related systems, and they can be permanent (i.e., water tight doors and barriers, sealed penetrations, drains and pumps) or temporary (i.e., pumps and barriers). For temporary measures it is important to have necessary material, equipment and organizational capacity for the timely implementation. Maintenance is important for permanent protection and periodical review is important for assuring readiness and feasibility of temporary flooding protection. Final flooding protection element is assured accessibility to safety related systems during the design base flooding level (DBFL).

Appropriate flooding protection is built on the right implementation of design requirements and proper maintenance. Nevertheless, operating experience is constantly proving how numerous water sources and systems interactions make flooding protection challenging. That is the reason why this paper is centered on most recent related operating experience feedback (OEF). Perhaps the specific lessons learned could help to fill the missing gap to have most complete flooding protection. The following section describes considered sources with short description for the most relevant events. Final section describes results from events analysis in a form of list of recommended actions with related purpose and example of potentially avoided consequences.

Figure 1 Example of Flood in Electric Equipment Room of Unit 6, pictured on 03.17.2011. (Source: TEPCO photo.tepco.co.jp/en/date/2011/201108-e/110810-01e.html)

2 SELECTED RELEVANT OPERATING EXPERIENCE

Operating experience is indispensable in finding the problems which went unnoticed during design, construction or maintenance. These events can also serve as motivation for additional checking and inspections. Hence this presentation contains selected most recent illustrative operating events and findings from related walk-downs and inspections. This experience is related to the external and internal flood protection failed to prevent or mitigate the effects because of deficiencies with analyses, procedures and equipment.

Two most comprehensive sources are consulted for operating experience: IAEA OECD International Reporting System (IRS) and US Nuclear Regulatory Commission (NRC). The IRS is closed event database system where all countries voluntary report important events. NRC provides open access to all US events. For this paper main source was NRC IN (information notice) 2015-01 ([4.]a) with recent relevant flooding issues. Selected list of older relevant INs ([4.]b-[4.]i.) illustrates different issue, e.g.: water leakages through conduits into buildings; unsealed concrete floor cracks and equipment hatch floor plugs; backflow through equipment and floor drain system.

Flooding protection related events from the rest of the world are described in several topical studies (TS) and could be also studied from the event reports in the IAEA OECD International Reporting System (IRS). Three relevant reports are consulted for this presentation: IRS Topical Study (TS) OEF External Flooding, [3.]a 2010; Joint Research Centre (JRC) TS on External events, [3.]b 2012; and Nuclear Energy Agency (NEA) Working Group on Operating Experience (WGOE) report on Fukushima Daiichi NPP Precursor Events, [3.]c 2014. Since all these reports are dealing with events mostly relevant from the external events perspective simple IRS search (i.e., free text "flood" in full report from 2010) was performed in order to find more relevant recent events. From total of twelve events, the four most relevant were selected and briefly presented here.

For this presentation priority was given to the most recent events because Fukushima Daiichi accident has motivated new consideration of the flooding protection issue in the last five years. All but two US events (i.e., E07 and E08) are taken from the NRC IN 2015-01. Four non-US events are described based on the respected IRS report. All these events are related to reduced ability to mitigate flooding. These are examples of flooding prevention and mitigation deficiencies with equipment, procedures, and analysis. They are frequently related to design and maintenance of flood barriers. Fifteen presented events are grouped in two groups: 1) Inadequate External and Internal Flood Protection Because of Missing or Degraded Flood Barriers; and 2) Inability to Demonstrate the Capability to implement Site External Flood Mitigation Procedures in Time. Short description for selected most relevant events follows (only title is provided for the other events).

2.1 Inadequate External and Internal Flood Protection Because of Missing, Inappropriate or Degraded Flood Barriers

E01 IRS#8311, Fuel oil tank room flooding caused EDG unavailability. On 15.05.2010, fuel oil pumps for emergency diesel generator (EDG) A were flooded with groundwater from malfunction of the wastewater pumps in the plant sewer system. This caused EDG A unavailability for about 30 h. EDG B and gas turbine were available as redundant power source. Even this is finding before Fukushima accident it is still included because it illustrates event outside US. The cause of the wastewater pumps failure was loss of the electrical cabinet. Operators failed to monitor and anticipate flooding. Finally leak tightness of the EDG room was insufficient (lack of civil engineering compliance). Corrective actions included rework of the leak tightness of buildings, alarms modification (in the EGD room and at the pumping station), and operation experience feedback distribution. This event demonstrates that several independent causes could result in safety system train loss and emphasize that redundancy has to be maintained.

E02 IRS#8316, Rainwater ingresses into the RB and TB due to heavy rainfalls[1]

[1] This event with some others is considered in the analysis but for brevity not described in the paper.

E03 IRS#8293, Flood in the containment of the Unit 2 (at power) from Unit 1 (in refueling) leading to controlled Unit 2 shutdown. The drainage piping of the spent fuel, refueling, and storage pools interconnects both units of the NPP. Reactor building of the Unit 2 was flooded and forced to controlled shutdown because Unit 1 refueling pools drainage failure. Flooding occurred on 06.09.2011 because of faulty check valve and open isolating valve for the Unit 2 storage and other pools. Even flooding was noticed early the source was uncovered 5 hours later because of the lack of communication between units. Faulty check valve was probably not properly assembled. It total 11 other causes contributing to the incident are identified, e.g.: poor post-assembly control, operational inspection miss after similar event, change of operating instruction which set isolation valves open for operating unit (with unclear reason and later questioned), refueling unit personnel did not verify amount of drained water into the auxiliary building tank, operators of flooded unit could not identify the source, slow sampling analysis, poor response from the plant shift engineer and the technical support group. The major lessons learned from this event are: importance of improved equipment configuration management for flooding protection; systematic review of similar check valves and other identified failures; improved event response procedures.

E04 IRS#8407, Potable water leak leading to controlled shutdown[1]

E05 St. Lucie Unit 1, Internal RAB heavy rain flooding due to degraded conduits lacking internal flooding barrier (IFB). On 09.01.2014, after heavy rainfall (below DBF) and storm drain capacity degradation water backup within Emergency Core Cooling System (ECCS) pipe tunnel and flooded Reactor Auxiliary Building (RAB) through two degraded conduits that lacked IFB, [5.]a. The extent of condition review (ECR) identified four additional conduits that lacked IFB. This event is important because Fukushima related walk-downs in 2012 (per NEI 12-07 guideline [2.]) were successful in finding similar issues (i.e., *Degraded manhole conduit seals bypassed external flood protection*, [6.]c) but clearly not all of them. Initial estimate of the 2012 finding was non-conservative with respect to site water hold up volumes. The problem is related to the permanent change modifications in 1978 (*Primary water degassifier and transfer pump*) and in 1982 (*Waste monitor tank addition*) when six power supply conduits were added without IFB in the ECCS pipe tunnel that penetrated the Unit 1 RAB (located below the DBF elevation). The design packages failed to perform an in-depth evaluation of the changes because items being installed were not safety-related. Further, failure to identify these during two walk downs (2009/10 when corrosion was identified and in 2012 related to Fukushima) highlights the importance of design control (to translate flood protection DB into specification, drawings, procedures and instructions) and need for related periodic inspections implementation. The St. Lucie Unit 2 also has had missing or degraded flood seals. This event and related findings are documented in several reports, e.g. [6.]d.

E06 Arkansas Nuclear One, Turbine generator stator collapse causing leakage and leading to identification of numerous MFB related deficiencies. On 31.03.2013, collapse of the temporary lifting rig carrying main turbine generator stator caused water leakage from the fire system to safety related Decay Heat Removal room through a room drain pipe, [5.]b. The valve was open due to incorrect safety classification and maintenance. Related licensee ECR identified numerous pathways in the auxiliary and emergency diesel fuel storage buildings not effectively sealed, [6.]b. Fukushima related flooding walk-downs earlier identified many other deficiencies. Walk-down was not more effective because of incomplete documentation and inadequate contractors' oversight. Finally, related NRC inspections identified even more deficiencies. Degradation of flood barriers was caused by inadequate design, improper construction, and insufficient maintenance. Findings in total have identified over 100 unsealed pipe penetrations, degraded penetrations seals, un-isolable floor drains, open ventilation penetrations and ductwork, non-water tight door and hatch, and abandoned pipes openings. Further NRC inspection with preliminary yellow finding provides additional details, [6.]a. The problems are related to configuration control, aging and rollout of seals. Corrective actions included: implementing compensatory measures, adding instructions and procedures, sealing penetrations, repeating essential flood protection reviews and completing the missed portions of the walk-downs. This is another example of findings after flooding occurred.

E07 Sequoyah NP, Unanalyzed condition affecting ERCW system due to external flooding[1]

E08 Vermont Yankee NPS, Potential to flood switchgear room due to missing conduit seal[1]

E09 Brunswick Steam Electric Plant Units 1&2, Inspection and walk-downs findings of degraded and nonconforming flooding protection. On 20.04.2011, NRC inspection has found EDGs fuel oil tanks chamber containing openings which would impact flooding mitigation in the case of PMF. This has led to the licensee walk-downs and finding of numerous examples of degraded or nonconforming flood protection features (mainly penetration seals). Further on during the Fukushima walk-downs additional degradations were identified related to the service water, reactor and EDG buildings (e.g., degraded flood penetration seals, conduit seals and gap in the weather stripping along the bottom of the Unit 2 RB railroad door). They also identified EDG rollup door seal deficiency, unsealed shims, leaking flood penetration seals and unsealed conduit (SWB). Together all findings resulted in over 450 work requests/orders and condition reports for degraded or nonconforming flood protection features. According to NRC IR [6.]g licensee failed to correct identified problems. Cause is historical lack of a flood protection program without established preventative maintenance program. These problems existed from 1995 till 2012. The Licensee also failed to develop engineering program to mitigate consequence of external events after NRC finding in 2011. Corrective actions were: repairing degraded seals, developing engineering program for mitigating external flooding, and developing topical design basis for internal and external flooding. This example is more interesting because of timeline and number of findings than because of safety relevance (white[2] NRC finding).

E10 Three Mile Island Station, Inspection and walk-downs findings of flood barriers deficiencies. On 02.08.2012, after Fukushima flooding walk-down observation NRC inspection noted degraded conduits couplings in the Air Intake Tunnel (AIT is the source for safety-related ventilation and it contains safety related electrical conduits). Inspectors also identified 13 unsealed penetrations through the Intake Screen and Pump House and multiple deficiencies to maintain the integrity of the flood barrier. This is an example of cross-cutting aspects: in the area of human performance, decision making, problem identification and resolution, and corrective action program (CAP). Licensee later, in the CAP and ECR, identified a total of 43 deficient external flood barriers (e.g., seals on the Crouse-Hinds Couplings). The plant failed to notice them during comprehensive review in 2010. These deficiencies could allow flood water to impact decay heat removal function. Prompt compensation was: sandbags and earth moving equipment. Permanent corrective actions included sealing the conduits by injecting watertight sealant. This is an example of licensee failure to identify external flood barrier deficiency during Fukushima walk-downs (e.g., they relied on design information instead on as built, etc.) as well as failure during previous review after increasing PMF level in 2011 after river discharge revision. Background and scope of the problem in this example is much more important than safety relevance. More is available in the related NRC IR, [6.]h.

E11 R.E. Ginna NPP, Fukushima flooding walk-down finding MFBs when draining insufficient[1]

2.2 Inability to Demonstrate the Capability to Implement Site External Flood Mitigation Procedures in Time

E12 Watts Bar NP Unit 1, Licensee identified inability to implement in time external flood mitigation procedures[1]

E13 Monticello NGP, NRC identified plant's failure to demonstrate implementation of flood protection against PMF during Fukushima flooding walk-downs[1]

[2] White US NRC finding represents low to moderate safety significance

E14 Fort Calhoun Station, NRC identified inability to protect the intake structure and auxiliary building during external flooding. Demonstration in Sep 2009, revealed that sandbags could not retain 1.5 m static head of water. Licensee failed to implement appropriate corrective actions based on new flooding information. Licensee's ECR revealed unsealed penetrations below the licensing basis flood elevation that could cause intake structure vulnerability during external flood. Corrective actions were: redesign and installation of flood protection features without need for sandbags; sealing affected penetrations; revising procedures. This is yellow[3] finding from NRC IR, [6.]e. Even this is finding before Fukushima accident it is still included because it demonstrates appropriate preventive inspection regarding later licensee's findings and later demonstrated capability to withstand major external flood on June 6, 2011, Figure 2. Licensee's findings include unsealed penetrations through outside wall of the auxiliary and chemistry and radiation protection buildings (below the DBF elevation); unsealed conduits, 2 leading to the auxiliary feedwater pumps and 1 leading to safety related electrical switchgear; drain path from chemistry and radiation protection room to ECCS pumps rom; weak flood protection strategy for raw water pumps. Root causes include: weak procedure revision process; insufficient oversight of work activities; ineffective identification, evaluation and resolution of external flooding protection performance deficiencies; and related "safe as is" mind-set, [6.]f.

E15 Point Beach NP Units 1 & 2, NRC identified failure to establish procedural requirements per FSAR during licensee Fukushima flooding walk-downs. In March 2013, NRC inspection has identified licensee's failure to establish procedural requirements to implement wave run-up protection per Final Safety Analysis Report (FSAR). This was observed during licensee Fukushima flooding walk-downs. There was not enough concrete jersey barriers to protect turbine building and pump house and erection time was not properly considered. They were also missing sandbags to fill barriers gaps. Corrective actions were to modify the jersey barriers to eliminate gaps, stock additional sandbags and jersey barriers and to revise related procedure. This was preliminary yellow with final white finding per NRC Inspection Report, [6.]i.

Figure 2 Fort Calhoun plant on 16.06.2011 during the Missouri River Floods; vital buildings were protected using water-filled perimeter "flood berms" (Source: OPPD Public pres., 04.04.2012)

[3] Yellow US NRC finding represents substantial safety significance.

3 LESSONS LEARNED AND CONCLUSIONS

Properly implemented and maintained flooding protection has potential to significantly increase safety at nuclear power plant because flooding can affect safety systems with common cause potential. The majority of findings presented here are the result of post-Fukushima walk-downs or related inspections. In the US, after Fukushima flooding walk-downs, about 90% of licensees entered an issue into its CAP, [9.]. Furthermore some examples clearly illustrate that even re-evaluation with this walk-downs (inspired by actual accident, supported with industry guidelines approved by regulator [2.] and therefore well planned) were not able to identify all deficiencies. Also all these findings are more reminding about known issues than discovering new insights from the industry wide OE feedback perspective. Evidently they are illustrating how challenging is to implement some of these insights and completely assure flooding protection. This all shows how pervasive flooding protection problem is and also how important are periodic maintenance and review.

Flooding protection related lessons learned are derived from comprehensive assessment of all presented events. The result is a list of actions with a potential to prevent flooding problems resulting in particular consequences. After aggregation, recommended actions are grouped based on potential purposes they could serve. There are four groups of lessons learned related to:

1) Configuration management and monitoring;
2) Non-safety systems interaction;
3) Timely identification of flooding protection problems; and
4) Flooding protection procedures validation.

Table 1 lists all four groups of lessons learned with respective actions (A1-12), purposes (P1-4) and consequences. In total twelve recommended actions are identified with four related purposes and twelve observed consequences (C1-12). Grouping is visible from the table in relations between actions, purposes and consequences/events. By judging from the number of related events and consequences following three recommended actions are standing out:

A4. Treat non-safety system in respect to potential safety impact (events: E02, E04 and E05).

A5. Systematically review a) identified failures for potential similar failures (events E03 and E08) and b) follow up on relevant operating experience (events E04 and E05).

A8. Assure more effective a) maintenance, b) review (events E08 and E10), and c) testing; (for a), b) and c): events E06 and E11).

Here proposed actions have potential to address all identified problems and help prevent specific consequences. However, flooding protection presents continuous challenge because even after all legacy issues are resolved there is need to continuously take care of aging, wear out and modifications related problems. In search for improvements EPRI has recently initiated a project to develop maintenance recommendations associated with flood seals with plan to publish them in the flood protection systems guide, [10.]. Therefore periodic maintenance and review are essential. Figure 3 and Figure 4 are illustrating some measures taken after Fukushima inspired review.

One way to emphasize the most important aspects of flooding protection challenges is perhaps this renaissance observation: "…*in the beginning of the malady it is easy to cure but difficult to detect, but in the course of time, not having been either detected or treated in the beginning, it becomes easy to detect but difficult to cure*." N. Macchiavelli, "The Prince", Chapter III

Table 1 Lessons learned groups, proposed actions, purpose and potentially prevented consequences

1. Lesson learned related to configuration management and monitoring

A1. **Install water level alarms for flooding monitoring (E01).**
P1.a Enable early identification (E01) and reduction (E03) of flooding.
C1. Water accumulation without early identification (E01, E03).

A2. **Assure safety buildings leak tightness water stops (E01).**
P1.b Enable prevention (E01) of flooding.
C2. Safety system flooded (E01, E02).

A3. **Improve flooding protection configuration management (E03).**
P1. Enable prevention (E01), early identification (E01) and reduction (E03) of flooding.
C3. Flooding through open/failed valve (E03).

2. Lesson learned related to non-safety systems interaction

A4. **Treat non-safety system in respect to potential safety impact (E02, E04, E05).**
P2. Better design of the non-safety system to prevent flooding: rainwater drainage system (E02), potable water system (E04), modifications (E05).
C2. Safety system flooded (E01, E02).

3. Lesson learned related to timely identification of flooding protection problems

A5. **Systematically review a) identified failures for potential similar failures (E03, E08) and b) follow up on relevant operating experience (E04, E05).**
P3.bcde Timely identification of potential internal flooding problems (E09, E10), i.e.: known check valve failure (E03), identified MFB (E05), applying learned from similar issues (E08), effective maintenance and review (E06, E07, E08).
C1. Water accumulation without early identification (E01, E03).
C5. Available similar relevant events not used (E04, E05).
C8. Numerous deficiencies discovered only after water leak (E08) or inspection (E09).

A6. **Improve event response (E03).**
P3.b Timely identification of potential internal flooding problems, i.e.: known check valve failure (E03).
C1. Water accumulation without early identification (E01, E03).

A7. **Improve documentation and configuration control (E06, E07).**
P3.ef Timely identification of potential internal flooding problems (E09, E10), i.e.: effective maintenance and review (E06, E07, E08), improved contractors' oversight (E06).
C6. Numerous flooding barriers deficiencies not identified after maintenance, review or walk downs (E06).
C7. Inadequate conduit seals installed (E07).

A8. **Assure more effective a) maintenance, b) review (E08, E10), and c) testing; (for all: E06, E11).**
P3.ade Timely identification of potential internal flooding problems (E09, E10), i.e.: sealing for insufficient drainage (E11), applying learned from similar issues (E08), effective maintenance and review (E06, E07, E08).
C7. Inadequate conduit seals installed (E07).
C8. Numerous deficiencies discovered only after water leak (E08) or inspection (E09).
C10. Drain adequacy disproved after inspection and testing (E11).
C11. Licensee identified problem but failed adequate response (E12).

A9. **Establish flood protection engineering program with maintenance (E09).**
P3. Timely identification of potential internal flooding problems (E09, E10).
C8. Numerous deficiencies discovered only after water leak (E08) or inspection (E09).

A10. **Perform thorough follow up on flooding related changes (E10).**
P3. Timely identification of potential internal flooding problems (E09, E10).
C9. Inadequate review after PMF increase with numerous deficiencies (E10).

4. Lesson learned related to flooding protection requirements validation

A11. **Improve analysis of ability to timely implement flooding mitigation procedure (E12, E13, E15).**
P4.a Fulfil flood procedure requirements: for PMF (E12, E13), and required by FSAR (E15).
C11. Licensee identified problem but failed adequate response (E12).
C12.a NRC identified problems during Fukushima flooding walk downs observation (E13, E15)

A12. **Improve flooding procedure revision process, work oversight and protection review (E14).**
P4.b Fulfil flood procedure requirements for new flooding information (E14).
C12.b NRC identified problems during inspection (E14).

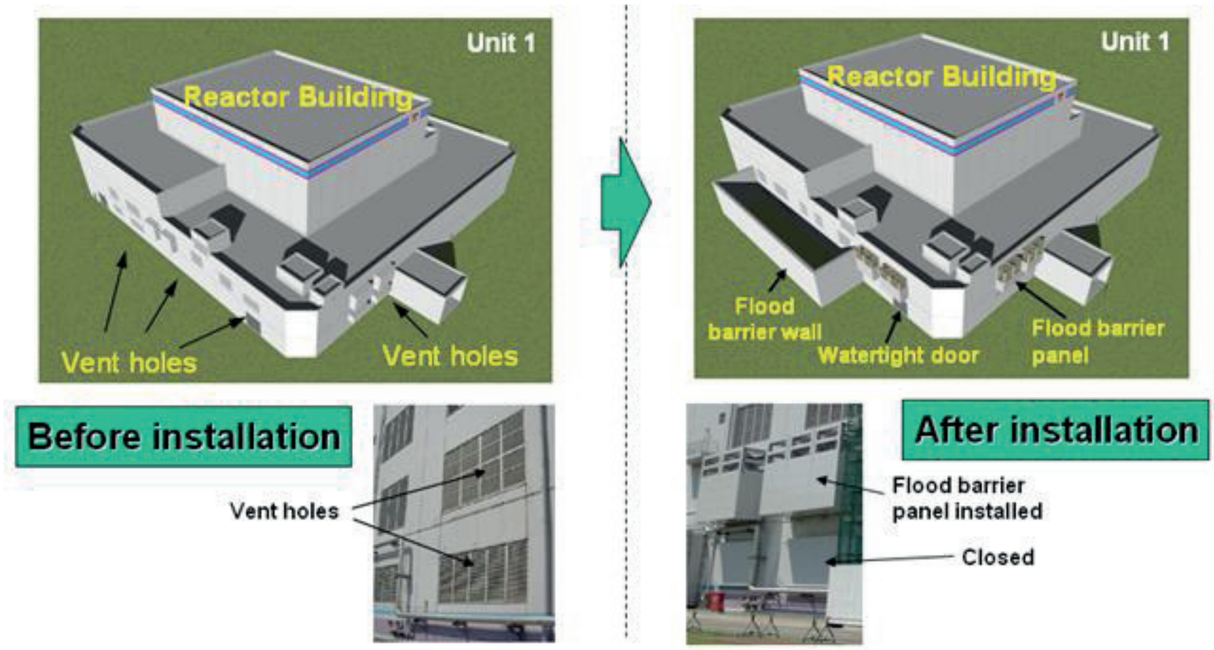

Figure 3 Example of measures to prevent flooding of the building: Kashiwazaki-Kariwa NPS. (Source: TEPCO www.tepco.co.jp/en/nu/kk-np/safety/flood-e.html)

Figure 4 Example of measures to prevent flooding of the critical equipment room and water tight cable conduits penetrations: Kashiwazaki-Kariwa NPS. (Source: TEPCO www.tepco.co.jp/en/nu/kk-np/safety/flood-e.html, tepco.webcdn.stream.ne.jp/…/201404-e.wmv)

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