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IAEA MISSION TO ONAGAWA NUCLEAR POWER STATION TO EXAMINE THE PERFORMANCE OF SYSTEMS, STRUCTURES AND COMPONENTS FOLLOWING THE GREAT EAST JAPANESE EARTHQUAKE AND TSUNAMI

Onagawa and Tokyo, Japan

30 July - 11 August 2012

IAEA MISSION REPORT

DEPARTMENT OF NUCLEAR SAFETY AND SECURITY
DEPARTMENT OF NUCLEAR ENERGY

INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA)
REPORT TO
THE GOVERNMENT OF JAPAN

Onagawa and Tokyo, Japan
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Mission date:	30 July – 11 August 2012
Regulatory body:	Nuclear and Industrial Safety Agency (NISA)
Location:	Onagawa and Tokyo, Japan
Organized by:	International Atomic Energy Agency (IAEA)

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EXECUTIVE SUMMARY

To strengthen global nuclear safety, the IAEA Action Plan on Nuclear Safety

(1) recommends the use of IAEA technical peer review services for plant safety, in the light of the accident at TEPCO's Fukushima Dai-ichi Nuclear Power Plant, and

(2) encourages that Member States promptly use IAEA review services to gather and disseminate information on the performance of their nuclear power plants (NPPs) and the performance of the designed protective measures against site specific extreme natural hazards and to utilize the lessons learned in the enhancement of NPP safety worldwide.

The Government of Japan and the IAEA have concurred to deploy a mission to Onagawa Nuclear Power Station (NPS), owned and operated by Tohoku Electric Power Co., Inc. (Tohoku EPCo), with the objective of gathering information, during the course of a two-week period on site. This included collecting data on the performance of the structures, systems and components of the Onagawa NPS, in the 11 March 2011 Great East Japan Earthquake (GEJE) and its major aftershocks, as well as compiling the information gathered in a seismic experience database for future use by the Member States to gauge the performance of their facilities against external hazards.

The Onagawa NPS has three boiling water reactors (units); with the first unit operating for the last twenty-eight years. Unit 1 began commercial operation in June 1984. Unit 2 began commercial operation in July 1995 and Unit 3 began commercial operation in January 2002. The three units have a combined electric generation capacity of 2,174 Megawatts.

Situated on the eastern coast of Japan facing the Pacific Ocean, the Onagawa NPS was the closest nuclear power station to the epicentre of the enormous M9.0 GEJE. Due to its proximity to the earthquake source, the plant experienced very high levels of ground motion –the strongest shaking that any nuclear power plant has ever experienced from an earthquake. The plant shut down safely.

The mission objective was to observe the response of the structures, systems and components to this high level of ground motion. The information gathered will be used to populate a database designed to capture the experience or performance of the structures, systems and components in strong earthquakes worldwide.

In addition, the Mission Team observed the impact of the tsunami which followed closely after the earthquake, and gained an understanding of the sequence of events that led to limited flooding at certain locations, which caused some system losses. The Mission Team also reviewed the recovery actions of the plant personnel in response to these events.

Information was delivered to the Mission Team through presentations by the Tohoku EPCo staff on the Structural Damages caused by 3-11 Earthquake and subsequent Tsunami; Investigation Results & Findings on Equipment's after Disaster; Tsunami Evaluation and Measures at Onagawa NPS and Observed Records at the NPS from 3-11 and the 4-7 Aftershock and the Evaluation of Major Equipment. Further information was also presented during discussions while conducting the walkdowns on site.

The Mission Team was divided into three teams:

1. Interview Team: to conduct interviews with the senior operating and technical staff to collect information to decide which systems of the plant the Mission Team should focus on during the subsequent walkdowns, as well as to gather information on the operators' work to date concerning systems operability during and after the GEJE.
2. Structures Team: to observe and collect information on the performance of the structural elements of buildings with different design criteria.
3. Systems Team: to observe the performance and collect field information on a representative sample of components of the plant, their structural integrity, anchorages and interaction with other components. The objective of this group was to gather information on the operability of systems to maintain critical safety functions during and after the earthquake and tsunami.

During the two weeks of walkdown, the Mission Team visited selected areas of Units 1, 2 and 3, coordinated by the staff of Tohoku EPCo. These areas included, but were not limited to, the reactor buildings (including the containments of all units); the turbine buildings and a variety of ancillary structures. The Tohoku EPCo personnel were very helpful in providing access to important areas of the plant and responding to the Mission member queries and requests.

Observations by the Structures Team indicated that the structural elements of safety related building systems (Class S) performed very well in all three of the Onagawa NPS units. Some minor level of cracking was observed in the walls of some of the facilities but the cracks were not indicative of any loss of overall structural integrity. In all safety related buildings walked down by the group no significant damage that would contribute to the degradation of structural performance was witnessed.

In the turbine buildings (Class B), which were designed for performance levels lower than the safety related buildings, some cracking of the walls at the upper levels was seen, along with deformation of isolated truss members. Given the high level of the earthquake ground and building motions, as well as the design considerations related to non-safety related structures, these observations were consistent with expectations for the performance of these building elements. Some of the bolts of the truss bottom chords in the Unit 2 and Unit 3 Turbine Buildings were sheared but these did not compromise the stability of the structure under normal conditions. In addition, the intermediate shaft bearing of the non-safety related turbine generator was damaged from the large load developed by the earthquake along the axis of the shaft in Unit 2.

The Structures Team concluded that the structural elements of the NPS were remarkably undamaged given the magnitude and duration of ground motion experienced during this great earthquake.

A significant quantity of instrumental data recorded by Tohoku EPCo at the Onagawa NPS was provided to the Mission Team. The records included actual motions in the buildings as well as those on the ground level and at deeper locations within a bore hole.

This data when processed will provide a valuable insight into the assessment of seismic margin and in establishing the fragility of structures, systems and components – information that is essential for safety analysis of the facilities.

In the case of the Systems Team, it reviewed the safety systems as classified by critical safety functions of criticality control, core heat removal, secondary heat removal and containment integrity. Each critical safety function is supported by systems and components which were assessed for operability during the earthquake and post-earthquake to the degree possible given the plant conditions. The Team also conducted a review of non safety-related systems to assess their performance to obtain a better understanding of the seismic capabilities of Class B and C systems and, particularly, to compare their performance to Class S (safety related) systems. Their work was supported by the Structures Team who conducted a review of the performance of the buildings.

The findings of the Systems Team indicate that the control rods were inserted, as required, during the earthquake shutting down all three reactors, satisfying the criticality control safety function. At the time of the earthquake, Unit 2 was just beginning to be restarted. In Units 1 and 3 core cooling was satisfied by the Reactor Core Isolation Cooling System and the operation of the safety relief valves to bring the core to lower pressure, allowing for the operation of the Residual Heat Removal System to bring the plants to a cold shutdown condition. Thus, the critical safety functions of core cooling and secondary heat removal were also satisfied in Units 1 and 3. Containment integrity was not challenged. Inspections of the containment to date do not indicate structural damage. Internal visual inspection, by Tohoku EPCo, of the bellows seal of Units 2 and 3 was conducted with no observed damage.

No emergency core cooling systems were needed since there was no loss of coolant accidents on any unit as a result of the earthquake. Post-earthquake functional tests of the High and Low Pressure Coolant Injection systems were made to the degree possible under given plant conditions, with no reported failure to function, i.e. pumps started, valves opened and closed as required.

The Systems Team also reviewed the seismic performance of the control room of the three plants and associated instrumentation. The team was told that no safety-related instrumentation or controls were lost on any of the units. Several light cover panels were reported to have fallen from the ceiling in each of the control rooms. Inspections of the control room cabinets were also made, with the general observation that the cabinets are well mounted with internal components securely attached.

The main steam stop valves performed their function as did the turbine bypass valves in the Class B turbine buildings. Inspections of components needed to shut down the turbines indicated that they were not structurally challenged and maintained their operability. Turbines (which are not safety-related) in Units 2 and 3 suffered damage to the blades and the intermediate shaft bearing support and baseplate during the earthquake. No damage to the Unit 1 turbine has been reported to date since it has not yet been inspected.

The Systems Team also reviewed the 61 identified (by plant personnel) damaged components or compromised functions, the most significant of which were the breaker fire at Unit 1 caused by the earthquake and the flooding of one of the two trains of the Reactor Closed Cooling Water System (RCW) at Unit 2 caused by the tsunami. The flooding was exacerbated by leakage past watertight doors (which were designed to keep water out of the room rather than retain it) and the presence of additional flooding paths. From there, adjacent plant areas were flooded resulting in loss of HPCW function and a threat to the second train of RCW. This created a situation that could have compromised the ability of the plant's ultimate heat sink. The tsunami also caused inundation of the TSW system on Unit 3, which is a non-safety related system.

The plant's electrical system was also reviewed. The site lost 4 of the 5 offsite transmission lines due to the earthquake or tsunami. On site, since the plant's tie lines are cross connected, from the initial stage there was no loss of off-site power. However, due to a over-current caused by a short circuit in a 6.9kV breaker, the startup transformer of Unit 1 tripped, causing a loss of offsite power directly to the unit. All emergency diesel generators started or stood by, although only Unit 1 diesels were needed to supply emergency power. The observation that all diesels started despite the earthquake is a significant positive finding. No water tanks, safety-related diesel fuel storage tanks (light oil) or associated piping failed.

The Class C fire protection system was also reviewed. The only failure noted was a section of buried fire pipe going to the light oil tanks of Unit 1. All other underground pipe and cables are located in concrete trenches. All safety-related piping and cabling trenches did not suffer damage or failures. Some non-safety related cable trenches were dislocated. Thus the water sources for emergency cooling were available if needed.

The Class S (Class B for the filtration and demineralization equipment) spent fuel pool cooling system was reviewed. Sloshing of the pool water caused a trip of the spent fuel cooling pump on all three units due to either a limit switch or pump pressure sensor. There was limited loss of water due to sloshing in all spent fuel pools (several liters). The spent fuel pool integrity was maintained, although some coming-off 's were reported in some bolts holding down the separation gates of Unit 3 but no loss of function reported.

A bearing failure in the reactor building overhead bridge crane was reported in Unit 1 which prevented reactor head off. The fuel handling machine suffered minor damage (instrumentation failure that was rectified by systems reset and sliding along the rails). Localized de-railing of the cable catenary was reported for the fuel handling machine in Unit 3, but without loss of electrical connection.

A small chip on a fuel channel that was removed from Unit 3 was reported and reviewed. The exact cause has yet to be determined but it is not thought to be due to the earthquake. It has been confirmed that there has been no fuel pin leakage in any of the reactors as a result of the earthquake.

The overall assessment of the Systems Team is that the plant’s safety systems functioned successfully during and after the earthquake. The plant’s non-safety and lower class seismic systems also functioned normally to shut the plant down indicating significant margins in the design. The team’s observation was that the tsunami caused more damage to the plant than the earthquake; in that it caused the degradation of the ability to utilize normal shutdown cooling systems of Unit 2. The most significant damage due to the earthquake was observed to the turbines of Units 2 and 3, which are non-safety-related equipment and are designed to lower seismic standards.

The interview team was responsible for conducting interviews with the senior operating and technical staff, and collected information. As a result, the team reviewed each unit's chronological plant conditions and operator actions, and summarized the process of reaching cold shutdown of all three units after the earthquake.

This first mission has demonstrated the value in observing real-life performance of structures and plant under extreme conditions. In the majority of cases it has been possible to learn from the successful performance of plant items and, in a small number of cases, from failures. It is anticipated that the information gathered during the Mission at Onagawa made available through the IAEA database will be utilized by the Member States in evaluating their operating facilities. Additional missions will be organized to collect information from other earthquake experience to expand the database. The Mission Team appreciated Tohoku EPCo’s quick turnover of the instrumental data for the completion of the database which will assist the future safety assessments made by the Member States of their own power plants. This database could be supplemented with experience data from other Japanese NPSs which have experienced varying magnitudes of earthquakes, as well as lower magnitude experience data from worldwide sources.

1. BACKGROUND, OBJECTIVES AND SCOPE OF THE MISSION

1.1 Background

To strengthen global nuclear safety, the IAEA Action Plan on Nuclear Safety encourages Member States to promptly undertake a national assessment of the design of nuclear power plants (NPPs) against site specific extreme natural hazards and to implement the necessary corrective actions in a timely manner, utilizing the lessons learned in the enhancement of NPP safety worldwide.

The Government of Japan and the IAEA have concurred to deploy an IAEA mission to Onagawa Nuclear Power Station (NPS), with the objective of gathering information, during the course of a two-week period on site.

Japan's energy needs have been largely fueled by electricity from nuclear power plants (29 per cent of total electricity). Nuclear electricity was generated from 54 nuclear power reactors at 17 plant sites, including 24 Pressurized Water Reactors, PWRs, 30 Boiling Water Reactors, BWRs and 2 under construction. Since earthquakes and tsunamis are common in Japan; nuclear power plant facilities are specially designed against such hazards.

The 2011 Off the Pacific Coast of Tohoku Earthquake occurred at 05:46 UTC (14:46 JST) on 11 March 2011. The magnitude (Mw) of the earthquake was 9.0. Extreme vibratory ground motion and tsunami were generated from this large earthquake. Due to the widespread disaster caused along the east coast of Japan, the earthquake is commonly known as the Great East Japan Earthquake (GEJE).

Onagawa NPS is located at about 125 km from the source of the earthquake. The hypocentre was located at 38.1N and 142.9E (130 km ESE off Ojika Peninsula) at a focal depth of 24 km on the subduction zone between the North American plate and the Pacific plate. The earthquake is estimated to have originated from the rupture of a subduction zone area having a length of more than 510 km and width of about 210 km.

The main shock was preceded by a strong motion foreshock and followed by a number of aftershocks extending over a long period; some of which has been recorded at by the seismographs at the Onagawa NPS. Large tsunamis which overtopped a limited area of the NPS were created by the earthquake.

The Onagawa NPS is located in both Onagawa-cho and Ishinomaki City, along the coast of the Pacific Ocean, approximately 60 km east of the central Sendai City in a straight line. The site area is about 1,730,000 sq. meters. The site was excavated to place the buildings of the station on deep rigid bed-rocks and artificial rocks. From the beginning, the main buildings of the Onagawa NPS, such as the reactor buildings, the turbine buildings and the control building, have been arranged in consideration of nature. The Onagawa NPS has been designed to cope with a tsunami height of O.P.[1] +14.8 meters. (Estimated tsunami height was not O.P. +14.8m but about O.P.+3m when unit 1 was designed). It was decided the site level with enough margin considering old time's tsunami (Jogan Tsunami in 869, Keicho Tsunami in 1611) which has unknown tsunami height.

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[1] O.P. (Onagawa Peil) is Onagawa NPS datum plane for construction, -0.74m below standard mean sea level of Tokyo Bay

The Onagawa NPS has three Boiling Water Reactors (units) built over eighteen years. Unit 1 began commercial operation in June of 1984. Unit 2 began commercial operation in July 1995 and Unit 3 began commercial operation in January of 2002. The plant has a total electric generation capacity of 2,174 Megawatts. Unit 1 and 3 of Onagawa NPS were in operation during the earthquake and were automatically shut down after the earthquake. After the earthquake, a tsunami strikes the Onagawa NPS. It was one of the largest tsunami that was generated around Japan. All three units have been safely shutdown and reached cold shutdown conditions. Currently at the Onagawa NPS detailed investigation and evaluations into facilities continuous until date.

1.2 Objectives

The sole objective of the mission was to collect earthquake experience data for inclusion into an earthquake experience database to be developed by the International Seismic Safety Centre (ISSC) at the International Atomic Energy Agency (IAEA), Ref. [1]. During this effort some information on the impact of the Tsunami was obtained and is also included in this report.

The historically earthquake experience information was collected and assembled into a database which contained data from small magnitude earthquakes and their effect on industrial and nuclear facilities mainly from the United States, commonly referred to as the EPRI Seismic Experience Database. Since nuclear facilities are inherently significantly more robust in comparison to industrial facilities the historic database does not provide the much needed data on the performance of nuclear "grade" SSC's during large magnitude earthquakes such as those experienced in Japan nor can reap the industry benefit from the vast quantities of test data that was generated during the heydays of the Japanese nuclear program.

The Onagawa NPP was among the few plants to date that has experienced a Magnitude 9.0 earthquake and being the closest to the hypocentre of the earthquake was selected as the best candidate for the initiation of data collection.

For the completion of the IAEA seismic experience database the data collected in this mission will be supplemented with additional data from Onagawa and other Japanese NPSs', that has experienced varying magnitudes of earthquakes, as well as, with data from worldwide sources to address the entire range of data needs .

It is anticipated that this effort to develop and disseminate a seismic performance database through the international reach of the IAEA will be carried forward with support from Japanese and other NPPs. The resulting database providing the real performance data of nuclear SSC's during a seismic event will be a significant asset as an input to "realistic" probabilistic risk assessments and as a tool for post-earthquake activities including restart.

1.3 Scope

The scope of this mission was limited to the establishment of the performance, through interviews and observation, of the SSC's of the Onagawa NPS, which is comprised of three reactor Units (1,2, & 3) and its supporting facilities, during the GEJE.

The performance of the SSCs' addressed the following specific areas:

- Performance of SSC’s with respect to their structural behavior, as observable from their damage state or lack thereof;
- Performance of SSCs’ with respect to their operability as established from the interviews, with the plant staff involved in the shutdown and on-going systems and component testing;
- For those SSCs’ that have or are undergoing repairs photographs and records of pre –repair and post repair actions were reviewed as a part of this data gathering effort.

The Mission use IAEA Safety Standards as reference where applicable Ref. [2], [3], [4], [5], [6], [7].

2. CONDUCT OF THE MISSION

The Mission was conducted in close cooperation with the Tohoku Electric Power Company (Tohoku EPCo) staff during discussions, presentations and walk downs, to observe the damage to the structures, systems and components(SSC's) in response to the Great East Japan Earthquake (GEJE) and Tsunami, at Onagawa Units 1,2 and 3.

In the initial briefing, background information was delivered to the Mission team through presentations by the Tohoku EPCo staff on the "Structural Damages caused by 3-11 Earthquake and subsequent Tsunami"; "Investigation Results & Findings on Equipment's after Disaster"; Tsunami Evaluation and measures at Onagawa NPS"; on observed records at the NPS from 3-11 and the 4-7 aftershock and the evaluation of major equipment.

Since the Units were all in a cold shutdown mode, the operability of the systems and components could not be verified visually. It was agreed with the counterparts that this confirmation would be made through interviews of the plant personnel involved in the post-earthquake shut down operations (See Appendix VIII).

Advised by the presented information the Mission team was divided into three smaller teams:

First- the Interview Team was responsible for conducting interviews with the senior operating and technical staff and collect information on 1) how the plant was operated during and after the earthquake; 2)how the plant systems performed during and after the earthquake; and 3) all testing of plant systems carried out since the March 11 event.

Second-the Structures Team was assigned to observe and collect information on the performance of the structural elements of buildings, with different design criteria. The team focused on the identification of damages along the load paths through the main structural members, in fill walls, anchorages and specifically at connections of structural elements.

The third and final team was the Systems Team dedicated to observe the performance and collect field information, on structural integrity, anchorage and interaction with other components, for a representative sample of the individual system components.

A team briefing was conducted by the staff of Tohoku EPCo prior to each walk down providing information on the route and the specifics of the SSC's to be encountered along the route.

Over the next few days, walk down of selected areas of Units 1, 2 and 3 were undertaken by the different teams coordinate by the staff of Tohoku EPCo. The information gathered by the walk downs was limited, as in many areas there were construction activities underway. However, all attempts were made by Tohoku EPCo staff to accommodate the mission team in spite of the on-going activities.

At the end of each walk down a briefing was made to the counterparts on the observations made and interpretation of the data gathered by the three Teams.

Experts attended different presentations as needed to address cross cutting issues. As much as possible information was exchanged with the counterparts to clarify issues and ensure a complete understanding of the plant response to the events, prior to finalization of the Mission Report.

Finally, in addition to the three technical teams noted above, the Reporting Team was composed of one IAEA documentation specialist for typing and drafting the report, one IAEA management specialist for logistics and a press officer for press interactions – of which there were many and photographers were embedded in both the structural and systems team to pictorially capture the team observations while keeping to the stringent security requirements.

3. CONCLUSIONS

Since the objective of the Mission was data collection on the seismic experience of the SSCs' of the Onagawa NPS, drawing conclusions was not a requisite for the Mission team. However, having collected the information on the performance of the Onagawa NPS in light of the GEJE, it would be an opportunity missed, if no conclusions on the observations were provided in this report. The IAEA staff members in the Mission team draw the following conclusions from the data collected:

- Despite prolonged ground shaking and a significant level of seismic energy input to NPS facilities the structures, systems and components of the Onagawa NPS performed its intended functions without any significant damage. The lack of any serious damage to all classes of seismically designed facilities attests to the robustness of these facilities under severe seismic ground shaking. It was concluded that the facilities of the Onagawa NPS remain "remarkably undamaged" given the magnitude, distance and duration of ground shaking.

- The instrumental data gathered in all the three reactor buildings of the Onagawa NPS indicate small to moderate exceedance of the seismic design basis that existed as of March 11, 2011. Using energy as a measure of the dynamic input to the plant the instrumental records indicate that significant shaking energy was imparted to the plant facilities. However, all three units were able to shutdown successfully in spite of some challenges posed by the tsunami inflicted disablement of a train of the residual heat removal system.

- The observed damages in the seismic design class S buildings are consistent with the moderate levels of exceedance of the design motion as recorded in the reactor buildings. Thus the current design basis is consistent with the potential of earthquakes, of at least in Magnitude, same as that of the GEJE. However the tsunami estimates in this region were developed with earthquakes along the same subduction zone of much smaller Magnitudes.

- It would be worthwhile to establish if the robustness was as a result of the design practices in Japan or was it gained by the progressive seismic upgrades made by Tohoku Epco to their facilities post prior earthquakes or was this, the original design basis. This information when established would be very valuable to the other NPS in Japan in establishing a measure of their robustness.

It will in addition help in make meaningful association of the Damage Indicating Parameters (DIPs) such as Japan Meteorological Agency Seismic (JMA) Intensity and Cumulative Absolute Velocity (CAV) to the Onagawa data collected during this Mission. The other conclusion that needs to be noted is that the most significant effects on the plant were in fact the direct or in-direct result of tsunami-induced flooding rather than earthquake shaking. Several layers of redundancy in safety systems remained even though Circulating Water (CW) for the main condensers were lost in all three units. CW pumps were tripped by flooding in Unit 2 & 3 and by startup transformer loss due to short circuit surge current in Unit 1) and in Unit 2 of the two trains of residual heat removal for the reactor was lost due to the flooding. The Onagawa experience highlights the importance of induced flooding as a credible common cause failure mode.

4. RECOMMENDATIONS

Tohoku EPCo already implements a crack mapping for structures. As with any severe earthquake aftershocks will continue to occur over a significant period. It is recommended that Tohoku EPCo continues to carry out a crack mapping program as in IAEA Safety Report 66 : Earthquake Preparedness and Response to ensure that the crack propagation as result of the aftershocks do not lead to the progressive loss in structural integrity of any structural element.

For seismic Class B and C buildings where the damages to SSCs' were more than those in seismic Class S building it would be beneficial to develop in structure response spectra in order to observe seismic performance of some components installed in these structures.

A follow–up mission to complete the data collection is essential to the success of the database and the establishment of the cause of the successful performance of the SSCs' at the Onagawa NPS.

5. STRUCTURES REVIEW

5.1 General Description of ONAGAWA NPS

The ONAGAWA Nuclear Power Station is operated by Tohoku EPCo. The NPS has 3 BWR reactors with a total installed electric power of 2174 Mw/h as presented in Table 5-1.

Table 5-1 Onagawa NPS Unit completion date

<table>
<tr><th>Unit</th><th>Onagawa 1
(Unit-1)</th><th>Onagawa 2
(Unit-2)</th><th>Onagawa 3
(Unit-3)</th></tr>
<tr><td>Capacity (MW)</td><td>524</td><td>825</td><td>825</td></tr>
<tr><td>Reactor Type</td><td>BWR4
Mark-I</td><td>BWR5
Improved
Mark-I</td><td>BWR5
Improved
Mark-I</td></tr>
<tr><td>NSSS</td><td rowspan="2">Toshiba</td><td rowspan="2">Toshiba</td><td>Toshiba</td></tr>
<tr><td>BOP</td><td>Hitachi</td></tr>
<tr><td>Start Commercial Operation</td><td>1984.06</td><td>1995.07</td><td>2002.01</td></tr>
</table>

5.2 Safety Classification for Seismic Design Basis

According with Pre-2006 regulatory guidelines there are four categories for seismic classification of SSCs according to their function and identifies typical equipment that fall into each category, see Table 5-2:

Class As Facilities, damage of which, may cause loss of coolant; facilities, which are required for emergency shutdown of the nuclear reactor and are needed to maintain the shutdown state of the reactor in a safe state; facility for storage of spent fuel; and nuclear reactor containment;

Class A Facilities, which are needed to protect the public from the radioactive hazard in the case of a nuclear reactor accident, and facilities, malfunction of which may cause radioactive hazard to the public, but are not classified as Class As;

Class B Facilities, which are related to the highly radioactive substance, but are not classified as Class As or A;

Class C Facilities, which are related to the radioactive substance, but are not classified in the above aseismic classes, and facilities not related to radioactive safety.

According to Ref. [8] revised NSC Regulatory Guide, specifies a new classification denoted Class S, which combines Class As and A SSCs. In addition, Class S SSCs will be designed to two earthquake ground motion levels designated Design Basis Earthquake Ground Motion (DBEGM) Ss, and Elastically Dynamic Design Earthquake Ground Motion (EDEGM) Sd.

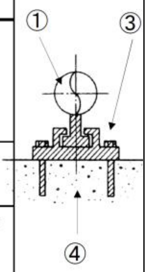
Table 5-2: Overview of the Classification Categories as per old and new NSC Regulatory Guide

Seismic Design Guide for Nuclear Power Plant　原子力発電所の耐震設計指針
Seismic Design Class　耐震重要度分類　2

Equipment is classified into 5. ※
①Main equipment, ②Auxiliary equipment,
③Direct supporting structures, ④Indirect supporting structures,
⑤Equipment which can influent on upper class one.]
※Shows the typical ones below.

設備は5つに分類される。※
①主要設備, ②補助設備,
③直接支持構造物, ④間接支持構造物
⑤波及的影響を考慮すべき設備
※以下に代表的なものを示す。

Seismic Design Class		① Main equipment	③ Direct supporting equipment	④ Indirectly supporting structures	
New Guide	Old Guide			Buildings	Structures
S	As	RPV, PCV, SFP, SF rack, Heat exch. Sea Water Pumps	RPV skirt	- R/B (Unit 2&3) - C/B (Unt2) - Hx/B(Unit3)	- Sea water pump pit (Unit 2) ： 2号海ポンプ室 - SGTS culvert ： 排気ダクト - Reactor auxiliary equipment cooling seawater culvert ： 補機冷却配管ダクト (Reactor auxiliary equipment cooling seawater intake ： 補機取水路)
	A	R/B, C/B(Unit1) Stack 排気筒			- Stack foundation： 排気筒基礎
B	B	Main steam sys. T/B (Unit1), Rw/B(Unit1), ・Rw	Main steam system's support	- T/B (Unit 2&3) - S/B (Unit3)	- Suppression pool water storage tank foundation： SPT基礎 - Condensate water storage tank foundation ： CST基礎
C	C	Circulating water sys.			



Tohoku Electric Power

Because of the newly revised NSC Regulatory Guide Ref. [8], the criteria for the generation of the Design Basis Earthquake ground motion in Japan can be classified as:

- Pre-2006: The basic criteria utilized in the design of the existing nuclear power plants;
- Post-2006: The updated criteria based on the newly revised NSC Regulatory Guide.

5.2.1 Pre-2006 criteria

- Two earthquake ground motion levels are defined: S1 and S2;
- S1 defines design ground motion for Classes As and A (return period = 10 000 years);
- S2 defines ground motion for Class As (return period = 50 000 years);
- S1 and S2 are defined on actual or hypothetical rock outcrop;
- Rock is defined by Vs > 700 m/s;
- Peak acceleration, velocity, and displacement are determined based on empirical relationships;
- The standard spectra are defined for Vs > 700 m/s with correction factors for stiffer rock properties up to 1500 m/s.
- Uncertainty is not explicitly treated;
- Duration and time variation of motions are based on empirical data;
- Only the hazard for the horizontal component is derived;
- Vertical component is derived from the horizontal component.

5.2.2 Post-2006 Criteria

The revised NSC Regulatory Guide Ref. [8] recognizes that there is the possibility of an earthquake producing ground motion at the site that exceeds the design basis earthquake ground motion. This possibility - termed "residual risk" - is to be minimized as practically possible.

The updated NSC Regulatory Guide specifies two earthquake ground motions for design:

- The Design Basis Earthquake Ground Motion (DBEGM) Ss, and
- The Elastic Design Earthquake Ground Motion (EDEGM) Sd.

The definition of the DBEGM Ss and Sd ground motions starts with a site and regional investigation to determine sources and their relevant parameters.

5.2.3 Design Basis Earthquake Ground Motion (DBEGM) Ss

The DBEGM Ss is defined by horizontal and vertical ground motions resulting from a deterministic assessment based on scenario earthquakes.
The DBEGM Ss is determined by evaluating the following two tasks, see Figure 5-2:

a) "Earthquake ground motion with site-specific earthquakes source location". This hazard is evaluated by taking into account the following:

- Consideration is given to past earthquakes (size, location, etc.), fault characteristics, active faults defined by evidence of activity, and other relevant information.
- The 120,000 – 130,000 year time frame corresponds to the late Pleistocene and is more conservative than the previous requirement of 50 000 years.
- Three types of sources are considered: interplate, oceanic (intraplate) and inland earth' crust earthquakes, see Figure 5-2.

The resulting set of candidate scenario earthquakes are termed "Investigation Earthquakes", see Figure 5-2. The site-specific "Investigation Earthquakes" for Onagawa NPS are listed in Table 5-3;

b) "Earthquake ground motion with no specific earthquake source location". This hazard results from sources of past earthquakes that cannot be identified. Response spectra in task are calculated based on near-source strong motion records and site-specific characteristics.

Year Regulation Event Action	～1978 In-house Guide	1978 Regulatory Guide	2005 Miyagi Offshore Earthquake(2005.8.16) Seismic Integrity Evaluation	2006 New Regulatory Guide Evaluation for all the existing facilities (Back-Check)	2011 3.11EQ/4.7EQ Seismic Integrity Evaluation(under way)
Unit1 Commercial operation:1984	【Design】 ・Design Basis Earthquake Ground Motion (DBEGM): 250Gal※ ・GM for Safety Check: 375Gal (=250×1.5) ※Taft, El Centro, Onagawa	【Back-Check】 ・DBEGM S1: 250Gal ・DBEGM S2: 375Gal (Evaluation of earthquake ground motions with response spectra)	・Observed Record at Onagawa NPPs ⇩ ・Ground motion A for Miyagi-oki earthquake expected: 302Gal(NS),308Gal(EW) (Evaluation of earthquake ground motions by the method with fault models) ・Ground motion B for Miyagi-oki earthquake expected: 370Gal (Evaluation of earthquake ground motions with response spectra) ・Earthquake Ground motion for Safety Check:580Gal	【Earthquake ground motion with the site specific epicenter】 ・Ss-D:580Gal(H), 387Gal(V) (Evaluation of earthquake ground motions with response spectra) ・Ss-F:445Gal(H),209GAL(V) (Evaluation of earthquake ground motions by the method with fault models) 【Earthquake ground motion with no specific epicenter】 ・Ss-B:450Gal(H), 273Gal(V) ⇩ Seismic Improvement Work by Tohoku's own decision. (Implemented in 2008 - 2009) Total:6600 points (approx.)	・Observe record at Onagawa NPPs 3.11EQ/4.7EQ ⇩ Seismic Improvement Work by Tohoku's own decision. (Started in 2012)
Unit2 Commercial operation:1995	－	【Design】 ・DBEGM S1: 250Gal ・DBEGM S2: 375Gal (Evaluation of earthquake ground motions with response spectra)			
Unit3 Commercial operation:2002	－				

Figure 5-1 History of Seismic Re-evaluation and Seismic Improvement Work on Onagawa NPS

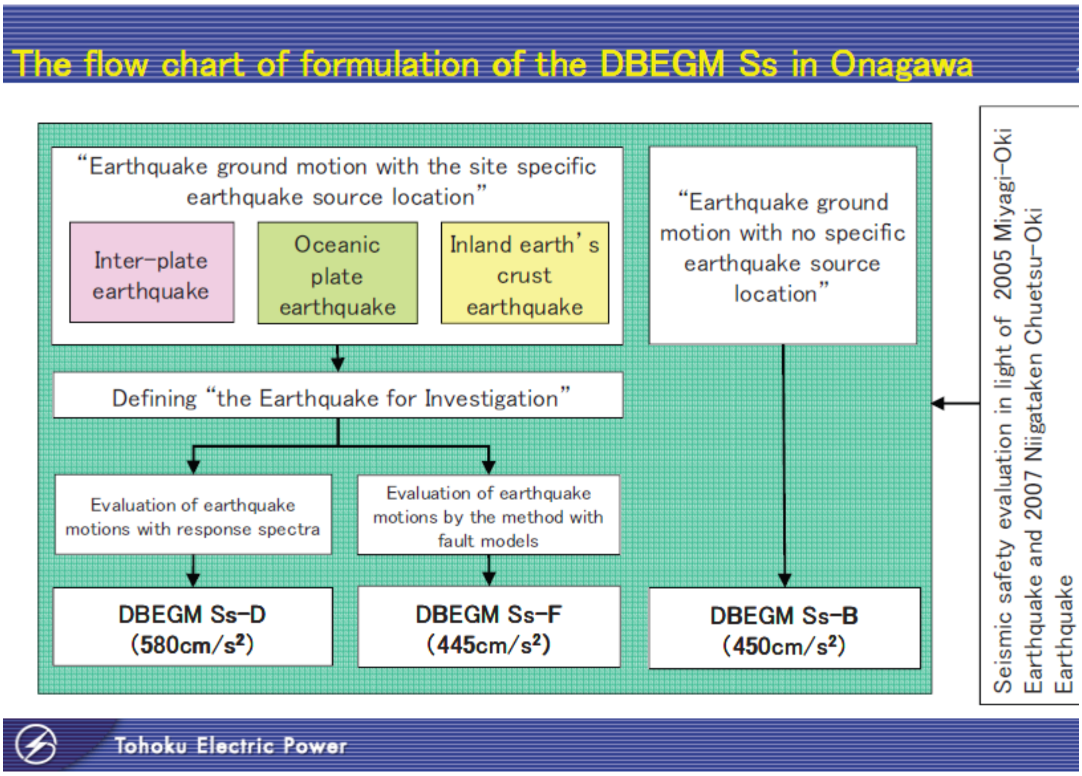


Figure 5-2 Evaluation of the Design Basis Earthquake Ground Motion (DBEGM) Ss

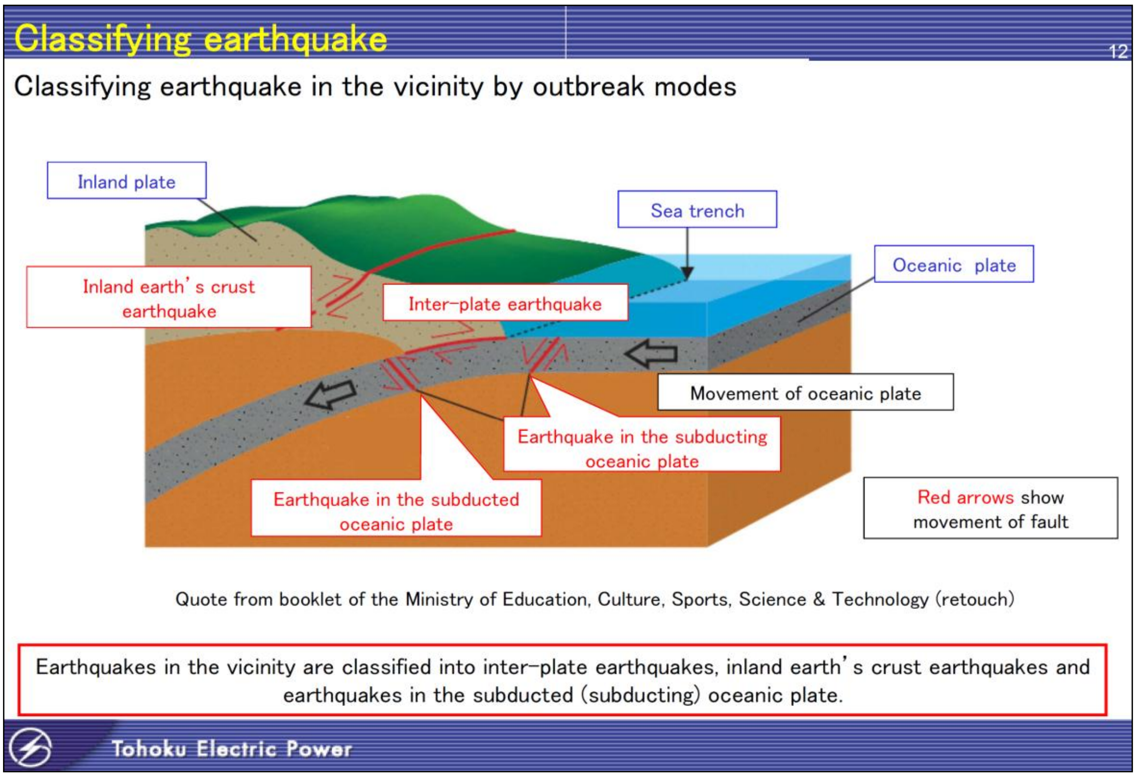


Figure 5-3 Types of earthquake sources considered in the evaluation of the he Design Basis Earthquake Ground Motion (DBEGM) Ss

Table 5-3 Site-specific "Investigation Earthquakes" for Onagawa NPS

Earthquakes for investigation of DBEGM S1-D, S2-D, S2-N, Ss 7

DBEGM	Earthquakes for investigation
S1-D	○The earthquake occurred off Sendai in 1897 (M 7.4, Epicentral distance 48km) ○The earthquake of the Sanriku occurred in 869 (M 8.6, Epicentral distance 201km)
S2-D	○The earthquake by active fault F-6 (Fault length 6.4km,M 6.2, Epicentral distance 12.1km) ○The earthquake by active fault F-7 (Fault length 9.2km, M 6.5, Epicentral distance 21.0km) ○The earthquake by active fault F-15 (Fault length 14.2km, M 6.8, Epicentral distance 36.1km) ○The inter-plate earthquake of the sea near Miyagi (M 7.6, Epicentral distance 20.0km, Hypocentral depth 45km)
S2-N	○ The earthquake located just below the site (M 6.5, Hypocentral distance 10km,)
Ss	○Miyagi-ken Oki Consecutive Earthquake (Mw 8.2), that is the largest Inter-plate Earthquake that is assumed to occur off Miyagi Pref. and links with the faults. ○Oceanic plate Earthquake located just below the site, that is 2003 Miyagi-ken Oki earthquake (Mj 7.1) which is the largest in Tohoku district, and is located just below the site, considering uncertainty ○The Earthquake by Active fault F-6 ～ F-9 (Mj 7.1), that is the largest in the area near the site from relationship with distance and magnitude

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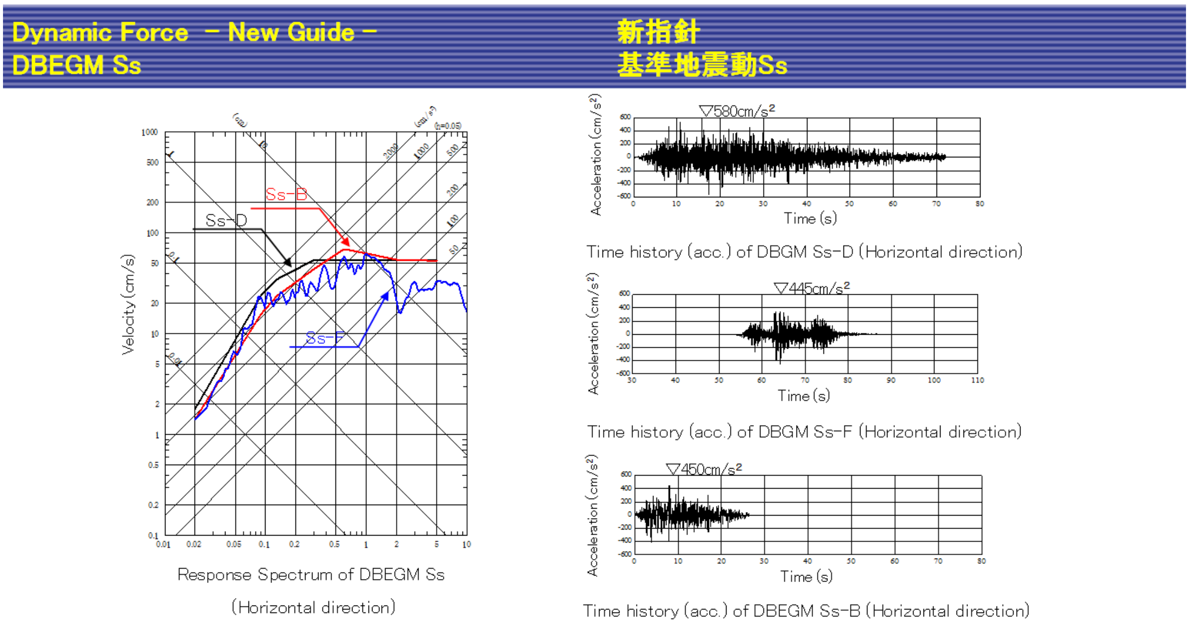
Other key elements of the Design Basis Earthquake Ground Motion (DBEGM), Ss, are:

• Uncertainty – appropriate methods should be applied taking into account the cause of uncertainty and its impact on the determination of DBEGM Ss. Probability concepts should be considered with emphasis on determining the probability of exceedance of the DBEGM Ss;
• Control point – the ground motion is defined on "the free surface of the base stratum", i.e. on an actual or hypothetical outcrop surface. The base stratum is to be a solid foundation material defined with Vs ≥ 700 m/s;
• Site specific characteristics - as e.g. the soil profile - should be taken into account;
• Both horizontal and vertical ground motion are to be determined.

The site-specific "Investigation Earthquakes" for Onagawa NPS are listed in Table 5-3. The site-specific Design Basis Earthquake Ground Motion, Ss, for the horizontal component is defined by PGA values, ground response spectra and time-histories in
Figure 5-4. An enlarged plot of the horizontal component of the ground response spectra is given in Figure 5-5.

The vertical response spectrum of DBEGM Ss-F is obtained directly from the time-history resulting from the fault model simulation.

The time histories compatible to the ground response spectra of DBEGM Ss-B and DBEGM Ss-D are generated artificially.



DBEGM Ss			Horizontal	Vertical
Earthquake ground motion with the site specific epicenter (敷地ごとに震源を特定して策定する地震動)	Evaluation with response spectra (応答スペクトルに基づく手法)	Ss-D	580	387
	Evaluation by the method with fault models (断層モデルを用いた手法)	Ss-F	445	209
Earthquake ground motion with no specific epicenter (震源を特定せず策定する地震動)		Ss-B	450	273

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Figure 5-4 Onagawa NPS site-specific the Design Basis Earthquake Ground Motion (DBEGM) Ss- horizontal direction

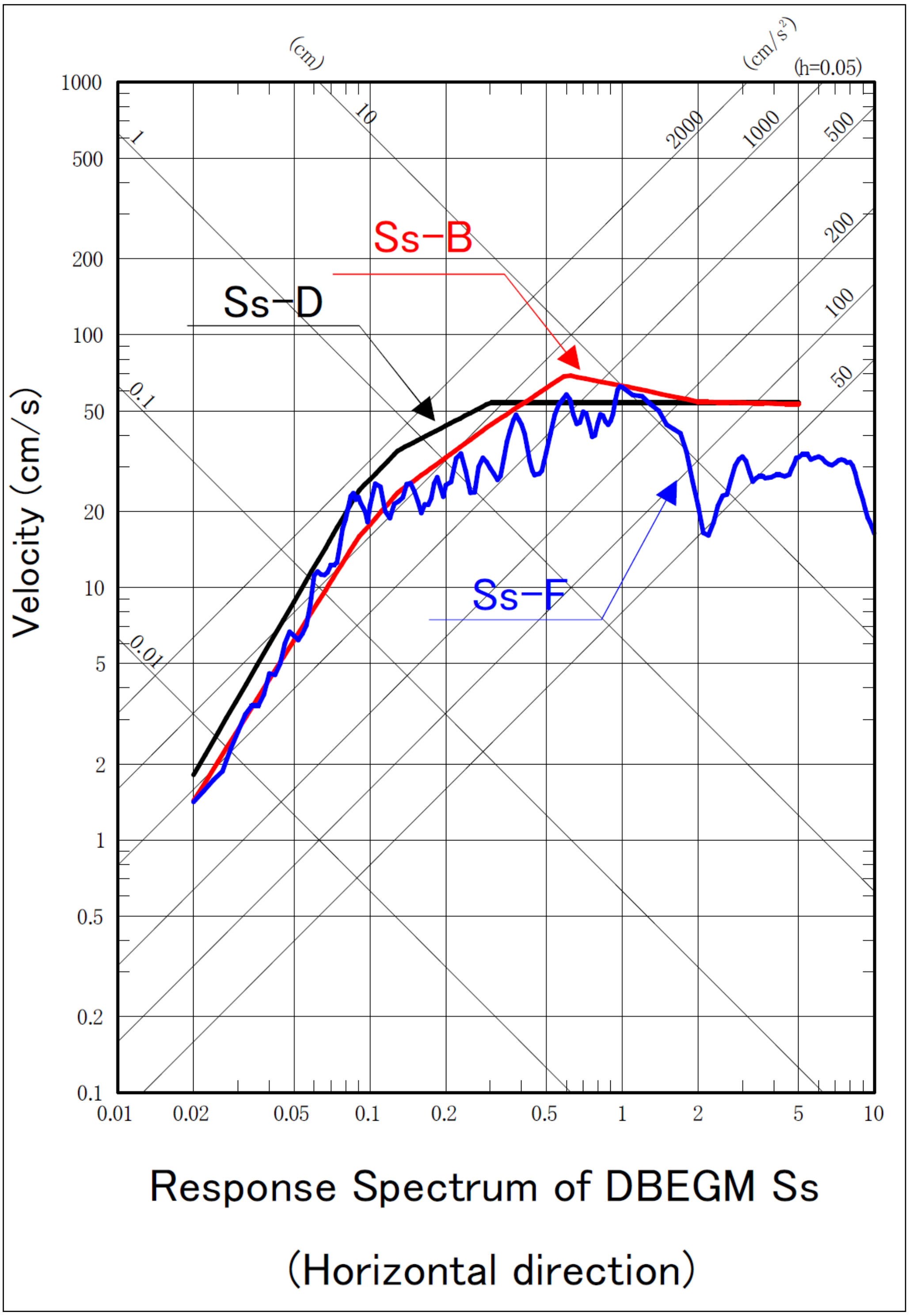

Figure 5-5 Response Spectra for Onagawa NPS site-specific the Design Basis Earthquake Ground Motion (DBEGM) Ss

5.3 Design requirements for SSCs

As discussed in the previous section the new NSC Regulatory Guide Ref. [8] criteria combines Classes As and A into Class S and defines a new set of design basis earthquakes: DBEGM Ss andEDEGM Sd.

In general, Class S SSCs should be designed to remain elastic when subjected to the maximum of the static calculated values and the dynamically calculated responses due to the EDEGM Sd earthquake ground motion.
Class S SSCs are further evaluated to the DBEGM Ss with the requirement that these SSCs remain functional. Table 5-4 summarizes the requirements for seismic forces in nuclear power plant buildings

The dynamic analyses are assumed to be two sets of analyses, one for each horizontal direction including the vertical ground motion. The maxima are then used for structure design or evaluation.

For the static analyses, additional considerations are:

- The story shear coefficient Ci is further defined as a function of a seismic zone where the structure is located, soil conditions, the vibration characteristics of the structure, a parameter related to vertical force distribution, and finally the standard shear coefficient (Co = 0.2g).
- Kv (vertical seismic coefficient): Value determined with Kv = 0.3 taken as the basic value, and the dynamic characteristics of the structure, soil conditions, etc. are considered.
- A reduction in the horizontal force for portions of the structure below plant grade is permitted. Significant detail is provided in NSC Regulatory Guide Ref. [8] as to how to modify the static coefficients for below grade portions of the structure.

The design of the Class S SSCs is dominated by the static force 3 × Ci or dynamic force, see Table 5-4 Class B and C SSCs are designed by an equivalent static procedure.

Table 5-4: Overview of the Design Seismic Forces as per old and new NSC Regulatory Guide

Seismic Design Guide for Nuclear Power Plant **原子力発電所の耐震設計指針**
Design Seismic Force **設計用地震力**

Class	Design Seismic force（設計力）		
	Static force （静的）	Dynamic force （動的）	
	New and Old Guide（新旧指針）	New Guide （新指針）	Old Guide （旧指針）
S (As)	3.0 Ci : horizontal （水平） Kv= 0.3 : vertical （鉛直） Ci :story-shear coefficients（層せん断力係数） Ci= Rt･Ai･C0 C_0 :standard shear coefficient（標準せん断力係数）=0.2 Rt :characteristic coefficient（振動特性係数）=0.8 Ai :distribution coefficient towards the height of the shearing force（高さ方向の層せん断力の分布係数）	Design Basis Earthquake Ground Motion (DBEGM), Ss. （基準地震動Ss） : horizontal and vertical motions respectively （水平・鉛直動） Elastically Dynamic Design Earthquake Ground Motion (EDEGM), Sd. （弾性設計用地震動Sd）	S2 : horizontal （水平） ½ S2 : vertical （鉛直）
A	As same as Class As （Asクラスと同じ）		S1 : horizontal （水平） ½ S1 : vertical （鉛直）
B	1.5 Ci : horizontal （水平）	½Sd*	½ S1* : horizontal （水平）
C	1.0 Ci : horizontal （水平）	-----	-----

Note: * Class B structures which can be resonate are required dynamic design.
共振のおそれのあるBクラス構造物は動的設計が要求される。

Horizontal maximum acceleration（水平最大加速度）
Ss-D: 580 gal, Ss-B: 450 gal, Ss-F: 445 gal
S2-D: 325 gal, S2-N: 375 gal, S1-D: 250 gal

Occurrence period considered	考慮した発生期間
Ss : the latter period of Pleistocene	後期更新世
S2 : 50 thousand years	5万年
S1 : 10 thousand years	1万年

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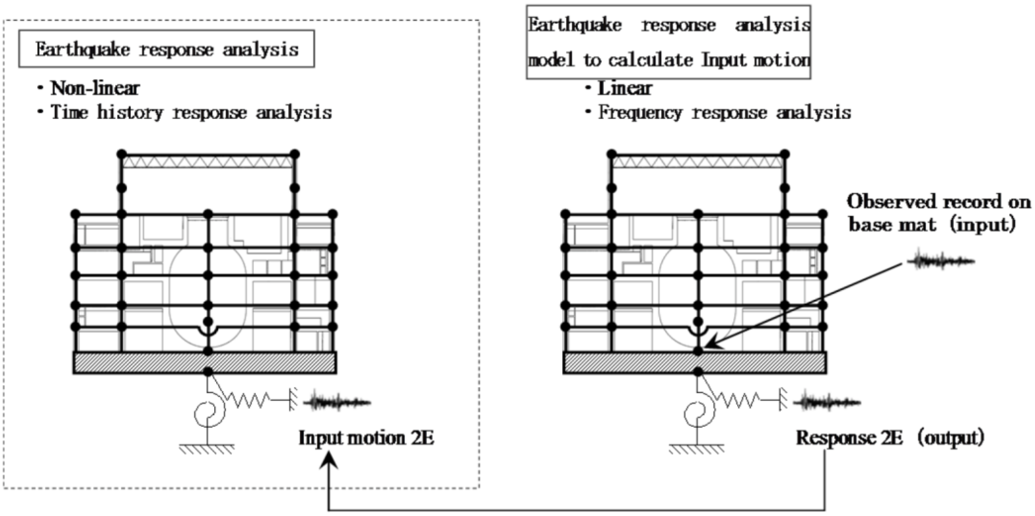
5.4 Structural Response to GEJ

Table 5-5 contains an overview of the Tohoku EPCo' approach for nonlinear analysis of the structural response of reactor building to GEJ earthquake.

Table 5-5 Tohoku EPCo' Approach for Nonlinear Analysis of the Structural Response of reactorbuilding to GEJ Earthquake

		Earthquake response analysis model	Earthquake response analysis model to calculate Input motion
Response calculation method		Non-linear time history response analysis	Linear frequency response analysis
Input motion		Calculated wave(Earthquake response analysis to calculate Input motion	Observed record on base mat
Input Location		Outoside the bottom spring	On base mat
Physical property values of concrete (design values)	Fc	Unit1 : 22.1 N/mm² (225 kgf/cm²) Unit2 : 32.4 N/mm² (330 kgf/cm²) Unit3 : 32.4 N/mm² (330 kgf/cm²)	←
	Ec	Unit1 : 2.06×10^4 N/mm² (2.10×10^6 tf/m²) Unit2 : 2.65×10^4 N/mm² (2.70×10^6 tf/m²) Unit3 : 2.65×10^4 N/mm² (2.70×10^6 tf/m²)	←
Damping	Reinforced concrete	5%	←
Analysis model	Soil-structure interavtion	Sway-rocking model	←
	model	Multi-cantilever and multi-lumped mass system with the rigid basemat slab and main earthquake-resisting walls substituted by equivalent bending-shear beams	←



• Seismic response (time history) at outcropping base rock in the free-field is calculated in frequency domain (linear analysis) from the recorded signal (time history) at the base mat of each reactor building;

- The calculated signal is used as an input for a nonlinear analysis of the coupled soil-structure system;

- The base mat is assumed as rigid body, .i.e. the soil impedances of the 6 global degrees of freedom are concentrated at a master node in the center of the foundation base mat;

- The nonlinear behavior is restricted to only material (elasto-plastic) nonlinearity of the structure and geometric nonlinearity at the soil-structure interface, i.e. foundation uplift and sliding;

- The structure is modeled by stick model with concentrated masses;

- The energy is dissipated only in designated numerical macro stick elements with elasto- plastic behavior. These macro elements are established empirically for a particular type of structural system, e.g. shear wall. They should be able to properly represent the hysteretic behavior (energy dissipation) of this system under the expected strain amplitude and number of stress cycles of the earthquake;

- Capacity curve of seismic wall is set for each seismic wall based on the JEAC(Japan Electric Association Code) 4601.

- The capacity curve is a function of the drift of seismic wall vs. shear force of seismic wall. Division through height and shear area, respectively, can normalize both quantities.

- The nonlinear dynamic time history analysis due to the GEJE excitation will produce a pair of data (drift of seismic wall vs. shear force of seismic wall);

- If we plot this data point in the same graph with the capacity curve, then we check the performance of the structures for this particular earthquake. If the data point of the earthquake were within the linear range of the curve, then we would not expect any damage. If it is beyond the linear range (assuming both analysis are correct) and depending on how far beyond the elastic limit, then we should expect damage;

The family of curves in Figure 5-6 is representing the capacity curves for the different floors in the reactor buildings (Unit 1 to 3). We can also see in this figure a few circles representing the results of the nonlinear dynamic time history analysis due to the GEJ earthquake. Most of the circles are within the elastic range of the curves. Some like the CFR data for Unit1 and 2 are slightly beyond the elastic limit. The data for 3f of Unit 3 is significantly beyond the elastic limit.

It should be noted, however, that damage is a very local phenomenon. It cannot be well captured by a global performance criteria as the story drift ratio. Local performance criteria as e.g. exceedance of material stress in both concrete and reinforcing steel or concrete crack width, should be used as well.

Hence, a more sophisticated model (e.g. 3D finite-element model) is needed in order to capture the performance of the structures under the strong shaking of the GEJ earthquake.
Figure 5-7 demonstrates in a very global fashion the adequacy of the built-in reinforcement quantity vs. the quantity required by the GEJ earthquake. Again, local damage may take place

because of extreme local demand on the reinforcement; however, the model cannot predict such anomaly.

3. Evaluation of erthquake response of R/B

The shear strain of seismic wall in R/B (3.11EQ.)

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Maximum shear strain (3.11EQ.)

		Analysis result		allowable strain	shaer strain by DBEGM Ss
		shear strain	Part		
Unit1	Direction NS	0.36×10^{-3}	BLD.G CRF	2.0×10^{-3}	0.65×10^{-3}
	Direction EW	0.35×10^{-3}	BLD.7 5F		0.56×10^{-3}
Unit2	Direction NS	0.49×10^{-3}	IW-C CRF		1.15×10^{-3}
	Direction EW	0.28×10^{-3}	IW-4 3F		0.55×10^{-3}
Unit3	Direction NS	0.81×10^{-3}	IW-B 3F		0.99×10^{-3}
	Direction EW	0.18×10^{-3}	IW-2、4 3F		0.41×10^{-3}

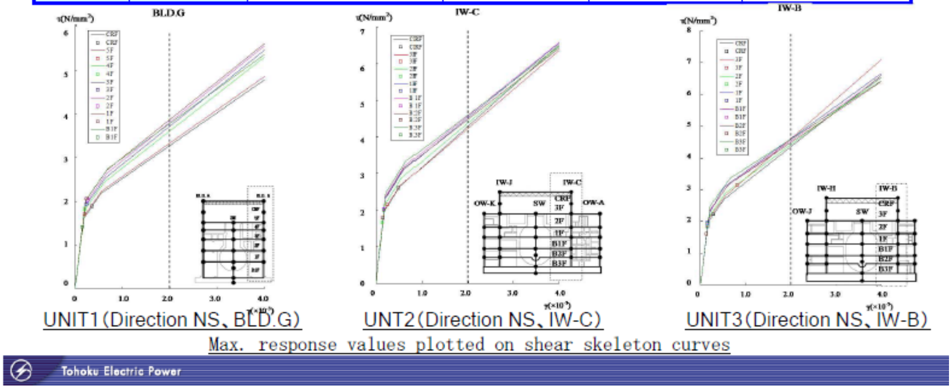

Figure 5-6 Tohoku EPCo' Results from Nonlinear Analysis of the Structural Response of reactor building to GEJ Earthquake

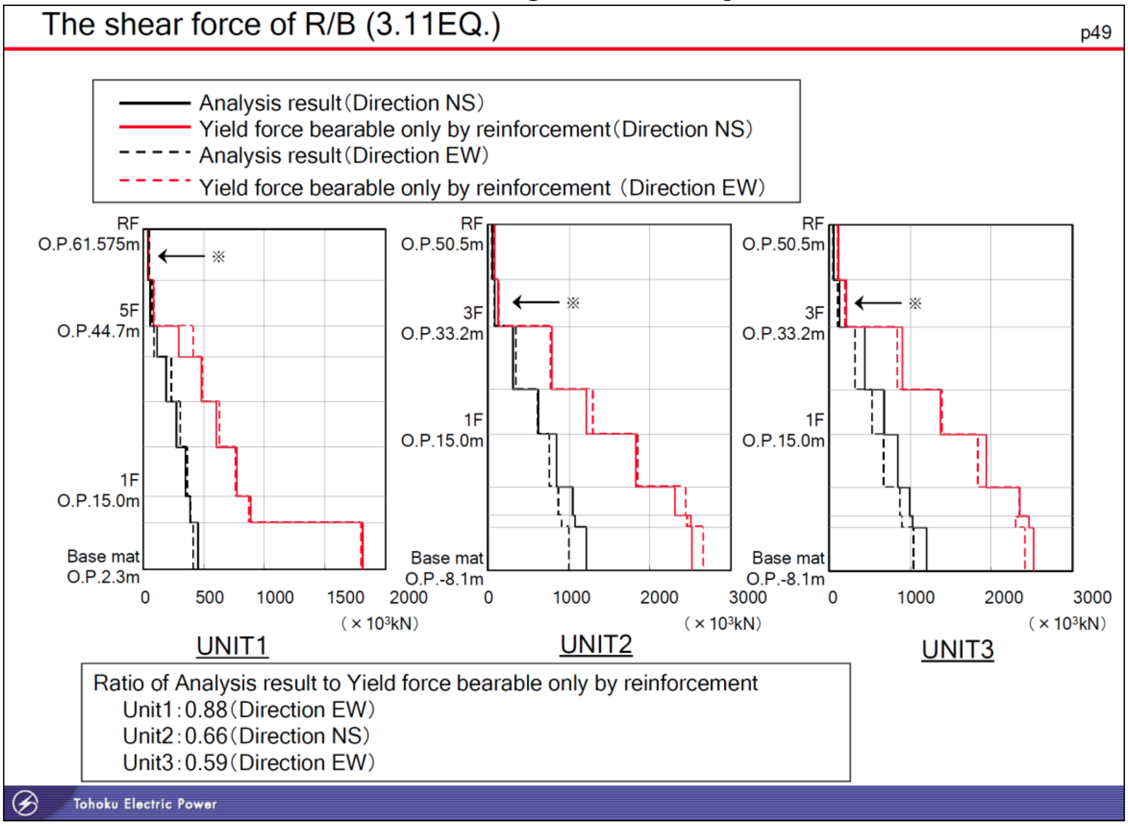

Figure 5-7 Tohoku EPCo' Results from Nonlinear Analysis of the Structural Response to GEJ Earthquake

5.5 Recorded Seismic Response on March 11, 2011

Tohoku EPCo provided seismic records at Onagawa NPP of Great East Japan Earthquake on March 11, 2011 and the aftershock on April 7,2011 [4]. The records are available for free field, different elevation in the bore hall and for significant elevations of reactor buildings of units 1 to 3. Seismic records have been processed by calculating:

- Peak acceleration
- Duration of the strong motion
- Damage indicators Cumulative Absolute Velocity (CAV) and Arias Intensity
- Fourier and Power spectra
- Elastic Response Spectra for 5% damping ratio

All these are presented in Appendices IV to VI and are used together with other information obtained from design review, interviews of operators and seismic walk downs to assess seismic performance of Selected Structure Systems and Components (SSCs).

5.6 Comparison between Recorded Response and In-Structure Response

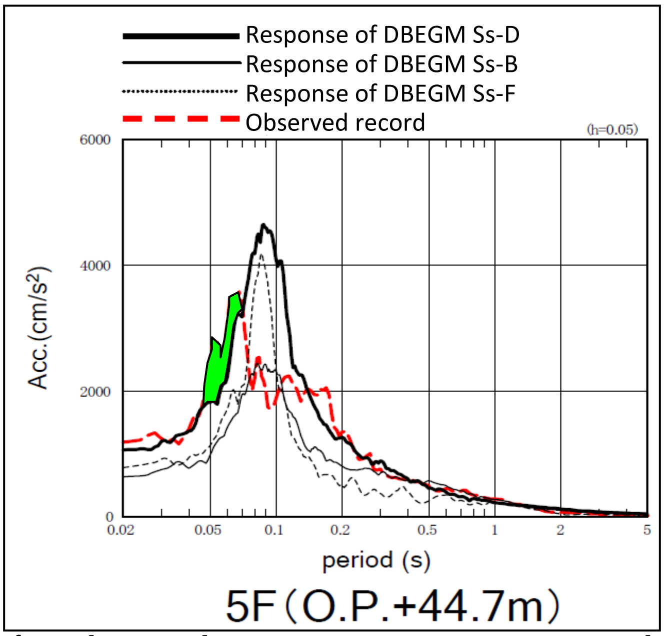

Figure 5-8 Exceedance of Acceleration Floor Response Spectra in R/B Unit 1 due to 3.11 EQ in direction UD - Exceedance in the range 14 to 22 Hz. For example, 1.40-times exceedance (1830 cm/s² vs. 2580 cm/s²) at 20 Hz.[2]

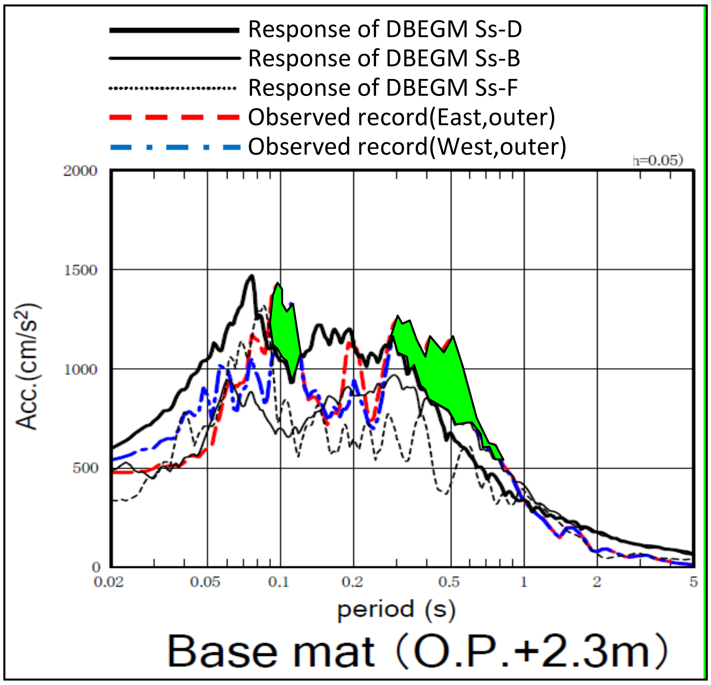

Figure 5-9 Exceedance of Acceleration Floor Response Spectra in R/B Unit 1 due to 3.11 EQ in direction NS – Exceedance in the ranges 8 to11 Hz and 1.3 to 3.6 Hz For example, 1.33-times exceedance (1045 cm/s² vs. 1395 cm/s²) at 10 Hz and 1.50-times exceedance (770 cm/s² vs. 1155 cm/s²) at 2 Hz.

•

[2] Figure 5-8 to Figure 5-15 were originated by Tohoku EPCo, IAEA added colored area to show the exceedance of the design. * cf.Ref [11]

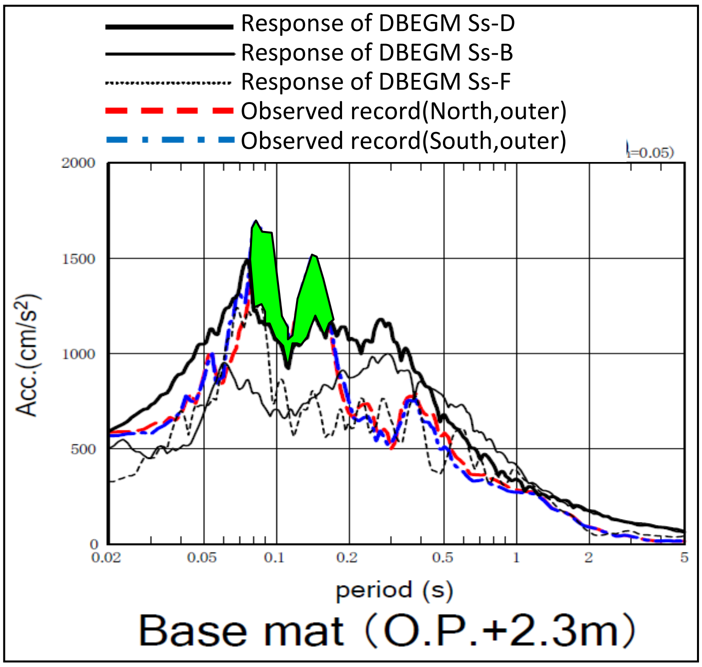

Figure 5-10 Exceedance of Acceleration Floor Response Spectra in R/B Unit 1 due to 3.11 EQ in direction EW – Exceedance in the ranges 6 to 13 Hz. For example, 1.37-times exceedance (1230 cm/s² vs. 1690 cm/s²) at 12.5 Hz and 1.25-times exceedance (1155 cm/s² vs. 1450 cm/s²) at 6.7 Hz.

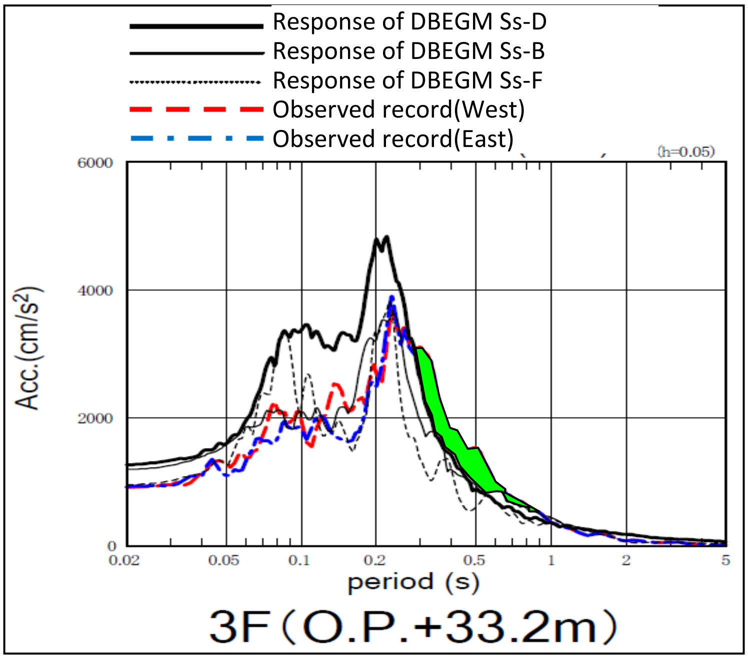

Figure 5-11 Exceedance of Acceleration Floor Response Spectra in R/B Unit 2 due to 3.11 EQ in direction NS – Exceedance in the ranges 1.1 to 3.5 Hz. For example, 1.63-times exceedance (950 cm/s² vs. 1550 cm/s²) at 2.0 Hz and 1.20-times exceedance (2575 cm/s² vs. 3100 cm/s²) at 3.3 Hz

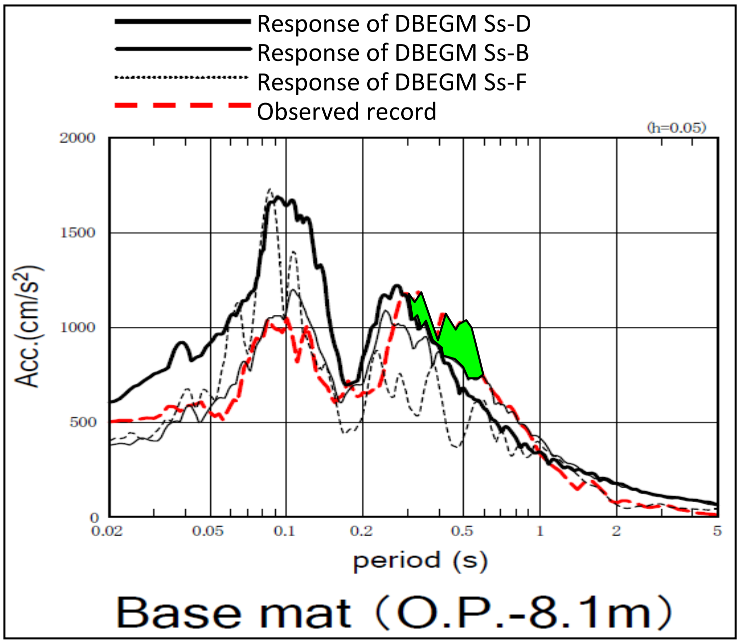

Figure 5-12 Exceedance of Acceleration Floor Response Spectra in R/B Unit 2 due to 3.11 EQ in direction NS – Exceedance in the ranges 1.7 to 3.3 Hz. For example, 1.32-times exceedance (775 cm/s² vs. 1030 cm/s²) at 2.0 Hz

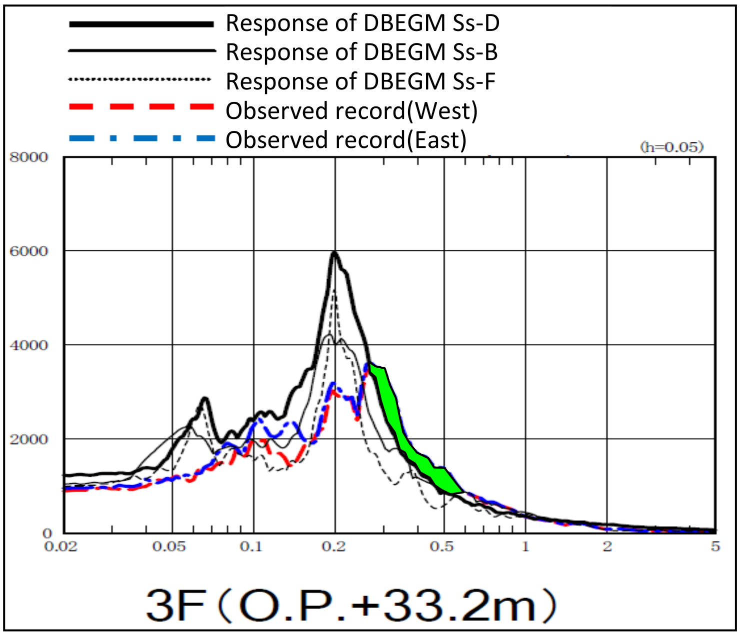

Figure 5-13 Exceedance of Acceleration Floor Response Spectra in R/B Unit 3 due to 3.11 EQ in direction NS – Exceedance in the ranges 1.7 to 3.7 Hz. For example, 1.54-times exceedance (910 cm/s² vs. 1400 cm/s²) at 2.0 Hz

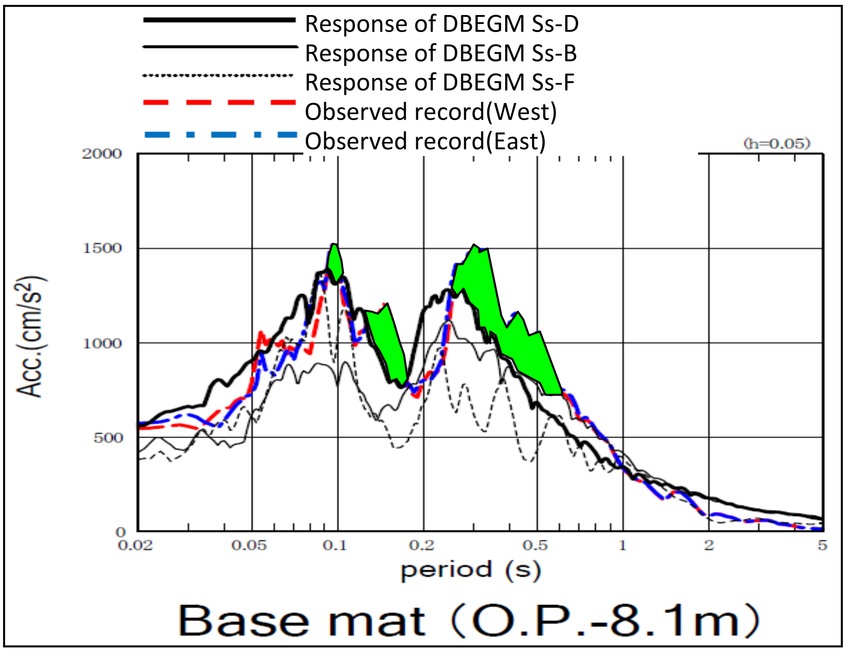

Figure 5-14 Exceedance of Acceleration Floor Response Spectra in R/B Unit 3 due to 3.11 EQ in direction NS – Exceedance in the ranges 1.7 to 11 Hz. For example, 1.40-times exceedance (1060 cm/s^2 vs. 1495 cm/s^2) at 3.0 Hz and 1.40-times exceedance (855 cm/s^2 vs. 1210 cm/s^2) at 6.8 Hz and 1.15-times exceedance (1340 cm/s^2 vs. 1525 cm/s^2) at 10.5 Hz.

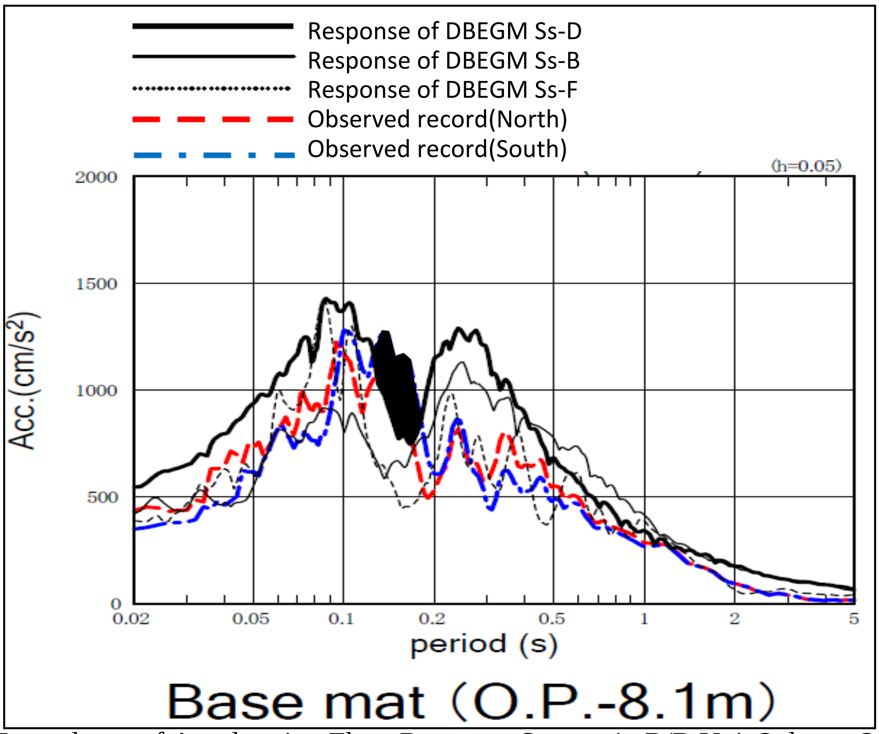

Figure 5-15 Exceedance of Acceleration Floor Response Spectra in R/B Unit 3 due to 3.11 EQ in direction EW – Exceedance in the ranges 5.6 to 8 Hz. For example, 1.46-times exceedance (785 cm/s^2 vs. 1145 cm/s^2) at 6.2 Hz.

5.7 Findings of Class S Structures

5.7.1 Reactor Buildings for Units 1, 2 & 3

5.7.1.1 Summary

The structures team walked down much of the three Reactor Buildings to observe the effects of the earthquake and aftershocks on the structure, including embedments and anchorages of equipment and systems. As safety-related buildings, these structures were designed to seismic class S. Based on the collective observations of the structures team, the overall integrity of the structures was not compromised. Damage was limited to fine cracking, none of which affected the structural integrity of the buildings. Illustrative pictures of RB units 1 to 3 from the structures' walkdown are presented in Appendix VII.

5.7.1.2 Unit 1

5.7.1.2.1 Background information

Date of commissioning:	1984
Outer dimensions:	53.3m x 43.8m
Total height:	63.67m
Embedment depth:	16.0m
Foundation type:	3.5m-thick raft foundation founded on bedrock
Type of construction:	Reinforced concrete shear wall with steel truss supporting reinforced concrete roof (15cm)

Table 5-6 Acceleration records at Onagawa NPP (in gal) from 3/11 and 4/7 earthquakes:

	3/11 Earthquake ('main shock')			4/7 Earthquake ('aftershock')		
	N-S	E-W	Vertical	N-S	E-W	Vertical
Rooftop	>2000 (2202)	1636 (2200)	**1389** (1388)	>2000	1494	1212
Operating Floor (5F)	**1303** (1281)	998 (1443)	**1183** (1061)	1280	901	724
1F	573 (660)	574 (717)	510 (527)	403	513	385
Base Mat	**540** (532)	**587** (529)	439 (451)	378	373	381

Numbers in bold are design basis values that were exceeded by the earthquake. Design data based on DBEGM in brackets.

5.7.1.2.2 Walk-Down and Detailed observations

At 44.7m elevation, the top floor of the Reactor Building was subject to the maximum acceleration during the earthquake. Based on the team's observations, the earthquake did not affect the structural integrity of the walls.

Previous repair works unrelated to the earthquake, for instance repairs due to shrinkage effects, were highlighted and were typically observed at higher levels of the walls. The team generally ignored these things because they were not earthquake related. However, it would be instructive to understand whether further cracking propagated from previously existing damage due to the earthquake.

On the 5th floor the team observed several cracks in walls, mostly insignificant hairline cracks, many of which Onagawa NPS personnel had already identified and marked. In the lower bays the team only reviewed cracks that were easily observable from the floor. The cracks in the walls were minor, typically <0.3mm in width, with some measuring up to 0.6mm. According to the Onagawa NPS internal standards, the maximum allowable crack width for the comprehensive purpose of structural integrity, shielding and so on is 1mm. Neither the team nor Onagawa NPS staff observed any cracks exceeding this limit. Some of the minor cracks observed were close to or passed through embedded parts and anchorage plates on the walls, but this is not likely to impact their performance in any way.

Shear cracks ('cross' or diagonal cracks at 45 degree angles to the vertical) were evident in the west wall of the building. This is probably because the acceleration of the floor was higher in the N-S direction than in the E-W direction. According to Onagawa NPS staff, the overhead bridge crane was parked near the wall on the west side, therefore imposing a larger shear load on the west wall than on the east wall.

The team believes that many of the observed cracks are from previous earthquakes and normal concrete shrinkage. Other than the 3/11 earthquake, the M7.2 Miyagi-Ken-oki earthquake of 2005 also affected the plant, to name one of the most significant examples.

Overall, the Onagawa NPS staff's efforts to date to identify and catalogue cracks appeared to be diligent. In some places plaster or paint covered the concrete surface, so it was not possible to observe the precise extent of the cracking within the concrete itself without removing the covering.

According to NPS staff, immediately after the earthquake plant staff inspected the structure for integrity. Next, more detailed inspections (which are on-going) catalogued any observed damage and the extent of any cracking in the building. The team reviewed some of this mapping of cracks, including what plant staff stated were the highest concentrations of cracks and crack widths. According to NPS staff, typical earthquake related cracks were in the walls on the 5th floor, as well as on other floors.

Due to the unavailability of the RB overhead bridge crane, NPS staff has not carried out any detailed inspections of the steel roof truss, other than visual inspections from the operating floor. After the earthquake, NPS staff inspected the crane and found that bearings were damaged, so they considered the crane to be non-functional.

In brief reviews of the lower levels of the RB, going down to the 1st floor, the team observed less cracking. This was in line with the findings of the more detailed reviews by NPS staff.

5.7.1.3 Unit 2

5.7.1.3.1 Background information

Date of commissioning:	1995
Outer dimensions:	77.0m x 84.0m
Total height:	64.6m
Embedment depth:	28.9m
Foundation type:	6m thick raft foundation directly on bedrock
Type of construction:	Reinforced concrete shear wall with steel truss supporting reinforced concrete roof (15cm)

Table 5-7 Acceleration records at Onagawa NPP (in gal) from 3/11 and 4/7 earthquakes

	3/11 Earthquake ('main shock')			4/7 Earthquake ('aftershock')		
	N-S	E-W	Vertical	N-S	E-W	Vertical
Rooftop	1755 (3023)	1617 (2634)	**1093** (1091)	1975	1657	**1386**
Operating Floor (3F)	**1270** (1220)	830 (1110)	743 (968)	1173	686	**1002**
1F	605 (724)	569 (658)	330 (768)	465	516	426
Base Mat	**607** (594)	461 (572)	389 (490)	387	388	373

Numbers in bold are design basis values that were exceeded by the earthquake. Design data based on DBEGM in brackets

5.7.1.3.2 Walk-Down and Detailed observations:

As at Unit 1, the team observed minor cracks and the presence of diagonal shear cracks in Unit 2.

The team observed the Operating Floor (3rd level) from the mezzanine fuel exchange operating room. The reactor head was removed, so the team did not enter the Operating Floor itself due to higher dose rates. The glass windows of the operating room broke during the 3/11 earthquake.

The earthquake did not affect the overhead bridge crane nor the fuel handling machine.

Onagawa NPS staff mentioned that in the roof truss, certain steel members used for construction support had deformed in the earthquake. From its vantage point in the operating room, the team observed only very minor deformations.

On the 2nd floor, the team observed minor diagonal cracks (wider than 1mm) in the floor at the corners of a large floor opening (at structural gridlines RF-RH/R8-R10).

5.7.1.4 Unit 3

5.7.1.4.1 Background information

Date of commissioning:	2002
Outer dimensions:	80.5m x 77.0m
Total height:	64.6m
Embedment depth:	28.9m
Foundation type:	6m thick raft foundation directly on bedrock
Type of construction:	Reinforced concrete shear wall with steel truss supporting reinforced concrete roof (15cm)

Table 5-8 Acceleration records at Onagawa NPP (in gal) from 3/11 and 4/7 earthquakes

	3/11 Earthquake ('main shock')			4/7 Earthquake ('aftershock')		
	N-S	E-W	Vertical	N-S	E-W	Vertical
Rooftop	1868 (2258)	1578 (2342)	1004 (1064)	1959	1775	963
Operating Floor (3F)	956 (1201)	917 (1200)	888 (938)	750	1019	**1333**
1F	657 (792)	692 (872)	547 (777)	420	688	477
Base Mat	**573** (512)	458 (497)	321 (476)	396	398	311

Numbers in bold are design basis values that were exceeded by the earthquake. Design data based on DBEGM in brackets.

5.7.1.4.2 Walk-Down and Detailed observations:

As in Units 1 and 2, damage was limited to minor cracks, including diagonal shear cracks, in Unit 3.

The team walked down the 2nd and 3rd basement floors, as well as the 1st and 2nd Floors. As at Unit 2, the reactor head was removed, so the team did not enter the Operating Floor itself due to higher dose rates. Given the similarity of the overall structures between Units 2 and 3, and the similar accelerations experienced by the two Reactor Building structures during the earthquake, the team felt that it was not necessary to perform a specific review of the Unit 3 Operating Floor.

In general, reinforced concrete walls had crack widths less than 0.3mm, although at some locations there were cracks of approximately 0.8mm. These minor cracks do not affect the overall integrity of the structure. The team also observed only minor cracks at certain embedded parts supporting the anchorages of components.

On the 1st floor, at structural gridline RG/R7, a wall area of approximately 2m X 2m had cracking along the perimeter of an infilled concrete block wall (a former wall opening which was filled in with concrete masonry,) but the cracking was determined to be insignificant because such infilled concrete block wall was not counted as strength member. No safety related components were observed in the vicinity of the wall.

On the 2nd Floor along structural gridlines RB and R10 the team saw minor cracks with a width of approximately 0.3mm at the junction of the reinforced concrete slab to the wall.

5.7.1.5 Anchorages & support

The team observed numerous wall anchorages (typically employing embedded steel plates), supports, and braces for piping, conduit, ducting, equipment, etc. Most supports for piping, HVAC and cable tray rack are welded on pre-anchored plates. Some supports that were installed after the original construction are fixed on the concrete structure within chemical anchorages. The team did not see any damage to anchorages.

5.7.1.6 Unit 2 Sea-Water Intake Structure and Pump Pit

The structures team examined the full length of the Unit 2 Sea-Water Intake Structure and Pump Pit in order to observe the effects of the earthquake and aftershocks on the structure and joints. This safety-related structure was designed to seismic class S. Based on the collective observations of the structures team, the overall integrity of this structure was not compromised. Illustrative pictures of the Intake Structures' walkdown are presented in Appendix VII.

5.7.1.6.1 Background information

Before the 3/11 earthquake and tsunami, the sea-water intake structures for all three units had been inspected approximately every 13 months, with each inspection lasting 2-3 months. Inspectors reviewed the development of any existing cracks in concrete structures, and any new cracks were also identified and catalogued. During every second inspection, the intake was painted in order to prevent biological growth on the exposed concrete surfaces. This painting did not conceal the cracks that inspectors had identified. During inspection, cracks greater than 0.4 mm in width were repaired. According to Onagawa NPS staff, no cracks greater than 0.4 mm in width were observed during inspections after the 3/11 earthquake.

The entire intake structures, including waterway and pump pits, are founded either on mass concrete which extends down to the bedrock, or directly on the bedrock. The Unit 2 structures are embedded to a depth of approximately 20m at the Reactor Building side and about 11m at the Intake side. The main waterway structure is one cellular concrete box with 13.4m width x 5.5m height having two cellular inside channels with 5m width x 3m height.

The intake structures have expansion joints, including omega-type waterproof joints in certain places, with 2cm-thick rubber seals within the joint to limit the flow of water. In front of the intake, a modular concrete curtain wall system blocks debris from entering the intake and causing damage, and acts as a breakwater.

The team selected the Unit 2 intake for inspection because the entire waterway and pump pit had already been drained for further seismic resistance reinforcement works. The team believes this structure is representative of what Onagawa NPS staff has already identified in earlier inspections in the Unit 1 and 3 intakes.

5.7.1.6.2 Walk-Down and Detailed Observations

The team reviewed the curtain wall in front of the main seawater intake, including the original curtain wall and the newer one that is further out to sea.

The original curtain wall structure is no longer in use, but the original walkway above is still in place. One of the junctions between disused curtain wall support beams and a pier walkway was damaged, but no damage was observed at support piers. However, the team suspects that the damage resulted from earthquake and/or tsunami loads.

The new operational curtain wall structure experienced the same 1m of tectonic subsidence as the rest of the site. Retrofits to increase the wall height are visible, which include new steel brackets and concrete panels above the water surface. The only visible damage from the 3/11 earthquake was a section of retaining wall on one end that moved approximately 40cm.

The concrete plugs in the intake structure appeared to be functioning well, with very little ingress of water and no sign of any differential movement that would impede operation of the gates.

Within the waterway structure, cracks that had been identified and catalogued during routine inspections were clearly marked and appeared to match inspection records. Many of the cracks identified were present prior to the 3/11 earthquake, mostly as a result of contraction and thermal stress and so on. The largest cracks due to contraction and thermal stress were about 0.2-0.35mm in width. Onagawa NPS staff informed the team that cracks above 0.4 mm in width would be repaired, but none had been identified so far during post-3/11 inspections. Discussions with the Onagawa NPS staff indicated that the 3/11 earthquake and tsunami had either very limited or no effect on widening the cracks previously identified.

At expansion joints, there were some very limited differences in alignment across the joints. The differences were inconsequential, and it is not clear if they were direct result of the earthquake and tsunami. In order to monitor any potential differential movements in the future, Onagawa NPS staff have installed markers on either side of the expansion joints.

At the entrance to the sea-water pump pits, Onagawa NPS staff is currently retrofitting some of the internal dividing walls by adding transverse steel reinforcement to prepare for expecting review and strengthen the Onagawa NPS's DBEGM. But the walls did not appear to suffer any earthquake damage.

There was no significant evidence of cracking at the base of the intake structures, nor was there any indication of differential movement between the bedrock and mass concrete foundations.

5.7.1.7 Units 2 & 3 Stack

The structures team inspected the lowest three levels (platforms) of the tubular steel support structures of the Stack for Units 2 & 3. This safety-related structure was designed to seismic class S. At the time of the earthquake, the stack's strengthening works, in accordance with the revise of NSC Regulatory Guide, was under way. So certain works were completed after the 3/11 earthquake. The structures team observed no earthquake damage to the structure in any of the areas visited. Illustrative pictures of the Stacks' walkdown are presented in Appendix VII.

5.7.1.7.1 Background information

Outer dimensions (at base):	38.0m x 38.0m
Total height:	160m (stacks), 147m (supporting space frame structures)
Embedment depth:	18.8m
Foundation type:	5.0m raft foundation founded on bedrock (infilled with mass concrete up to ground level just before 3/11 earthquake)
Type of construction:	Tubular structural steel space frame

The stack support structure is a space frame structural tubular steel tower. Currently, five platforms have dampers to reduce movement of the stack during earthquakes. At the time of the earthquake, only the lowest platform had dampers installed.

The concrete foundation was originally designed as a frame structure comprising groundbeams and columns connected to a base slab. Just before the 3/11 earthquake, the 'voids' in this box structure were completely filled with mass concrete.

5.7.1.7.2 Walk-Down and Detailed Observations

No structural damage of any kind was observed during the walk-down of the Stack.

At each damping location four elasto-plastic dampers are positioned at equal spacing around each stack. Each pair of dampers (located on opposite sides of the stack to each other) allows free translational movement in one direction only.A 20cm clearance was originally designed and exists between the edge of the stack and the edge of the space frame to allow for differential movement between the structures. There was no sign of any contact having occurred between the space frame and the stacks at the lowest platform level where the dampers had already been installed prior to the earthquake.

The elasto-plastic dampers that were installed were basically thick circular structural steel rods with square pads located at the base to enable the dampers to be guided along the direction of freedom. These dampers are connected to the space frame and are designed to dissipate energy in the event of differential movement between the space frame and the stacks through a combination of elastic and plastic deformation of the rods.

At the lowest level, the circular steel dampers were significantly thinner than those at upper levels. According to Onagawa NPS staff, the dampers at the lowest level were replaced after the 3/11 earthquake. The team inspected the original dampers that had been in place during the earthquake and observed no deformation of the steel rods, which suggests that any damping effects during the earthquake were predominantly limited to elastic deformations of the dampers. This also implies that the combined response of the stacks and the structural steel space frame was stiff, without significant differential movement between the structures during the earthquake.

The team observed additional strengthening works consisting of additional steel plates welded to the main legs of the space frame. These retrofits were started to add before the 3/11 earthquake in order to increase the safety margin of the structure.

5.7.1.8 Unit 2 SGTS Culvert

The structures team walked the full length of the Unit 2 Standby Gas Treatment System (SGTS) culvert in order to observe the effects of the earthquake and aftershocks on the structure and joints. This safety related structure was designed to seismic class S. Based on the collective observations of the structures team, the structure was essentially undamaged by the earthquake. Illustrative pictures of the STGTS Culverts' walkdown are presented in Appendix VII.

5.7.1.8.1 Background information

Roughly two thirds of the Unit 2 SGTS culvert is a drilled tunnel within bedrock and one third is founded on bedrock. This structure is approximately 190m long and connects the Unit 2 Reactor Building and the Unit 2 Stack. The culvert structure is embedded to a depth of approximately 25m at the Reactor Building side and 15m at the Stack side. It was designed to seismic class S.

5.7.1.8.2 Walk-down and Detailed Observations

At the entrance to the staircase to access the SGTS culvert, the team saw a retrofitted steel door with sealing earthquake for tsunami protection.

The culvert consists of segments that are each approximately 7m long. Inspection of the interfaces between these segments showed minor differential movements towards the Stack side of the culvert (where it is closer to the ground level) in both the longitudinal and vertical directions. Most of the cracks observed by the team were typically less than 0.3mm in width and had already been identified by the Onagawa NPS staff. Many of these are likely due to shrinkage and other effects that are typical of reinforced concrete. Some longer and wider cracks were observed in local areas, (e.g. crack 276-3 which was 0.5mm in width and 7.8m long) however there was no evidence of leakage beyond insignificant moisture seepage from the surrounding soil. The team did not observe any significant damage due to the earthquake. The team was not able to inspect the floor of the culvert because a steel walkway covers the full length of the culvert.

The culvert structure is separated from the Stack foundation and the Reactor Building with omega waterproof joints. The team saw no damage in these joints.

5.8 Walk-downs of the Seismic Class B Structures

5.8.1 Turbine Buildings for Units 1 & 2

The structures team walked down much of the Unit 1 & 2 Turbine Buildings to observe the effects of the earthquake and aftershocks on the structure, including embedments and anchorages of equipment and systems. The Turbine Buildings are non-safety related structures designed to seismic class B, or about one half of the requirements for seismic class S safety-related structures. In accordance with Japanese nuclear standards, no vertical accelerations were considered in the seismic design. Based on the collective observations of the structures team, the overall integrity of the structures was not compromised. No location was observed where remedial works would be required and in some cases a few repair works had already been undertaken. Illustrative pictures of the Turbine Buildings' walkdown are presented in Appendix VII.

5.8.1.1 Unit 2

5.8.1.2 Background information

Outer dimensions:	96.0m x 57.7m
Total height:	49.5m
Embedment depth:	17.0m
Foundation type:	3.0m raft foundation founded on bedrock
Type of construction:	Reinforced concrete shear wall with steel truss supporting reinforced concrete roof (17cm). Upper bay lateral stability provided by steel frame supporting the roof truss.

5.8.1.3 Walk-Down and Detailed Observations

The Structures team did not observe any damage to the Turbine Buildings for Units 1 and 2 that compromised the overall structural integrity of the buildings.

The walk-down started on the Operating Floor, on the 2nd Floor, which is the highest level of the Turbine Building at a level of OP +24.8m.

As in the Reactor Buildings, the team observed numerous small cracks at lower levels in the external shear walls and the internal columns. Many of these cracks had already been identified during the post-earthquake inspections by the Onagawa NPS staff. Some of the minor cracks observed were close to or passed through embedded parts and anchorage plates on the walls. There was no visible displacement of the baseplates, and the minor cracks are very unlikely to have any affect on their performance.

The upper level wall bays will be inspected by the Onagawa NPS staff for cracking shortly. However, about 1mm width longitudinal cracks were observed in the waterproofing coating to the external walls, and now are scrutinized from the view point of the effects on seismic resistance. The Onagawa NPS staff found that these cracks had a width of about 1mm and extended for approximately 5m adjacent to the steel columns supporting the steel roof truss structure above. The team was not able to see these cracks close up in order to verify these details from the Operations Floor level.

The team observed an isolated instance of cracking at the location of a joint of a perimeter primary beam members with the supporting column at grid location TG-T1 (operating gridline G-1). This crack did not appear to impact the structural integrity of the joint connection under normal conditions, however it may be worthwhile investigating the extent of this cracking in further detail.

Overall, very limited cracking was observed in the slab, although not all of these cracks appeared to have been recorded as part of the inspections undertaken by the Onagawa NPS staff.

The main steel truss structure, which supports the roof along its shorter axis, had no visible damage to its structural members. In the sub-truss, which supports the roof along its longitudinal axis, the team observed one diagonal member, adjacent to the gridline T1 perimeter wall, which had buckled.

The team also observed some buckling in the lateral bracing members connected to the bottom chord of the structural truss, which the Onagawa NPS staff explained were "temporary" for construction. No damage was visible from the Operations Floor to the gusset plates connecting the individual steelwork members.

At four support connections of the columns to the bottom of the sub-truss, the connecting bolts had sheared. The team considers that these member buckling and bolt shear issues may have resulted from the lack of consideration of seismic force for the class B structures.

Due to the high level of inherent redundancy, the roof truss appeared to have maintained its overall structural integrity. It would however be prudent to replace the bolts that had sheared. The Onagawa NPS staff confirmed that they would repair this damage premeditatedly.

During the team's visit the turbine was disassembled and under repair. While the team was unable to inspect this area in detail, because repairs had already been undertaken, the team learned that some bolts in the foundation of the turbine were damaged, as well as the surface of the concrete adjacent to the turbine support. The bolts apparently bent as a result of the earthquake, however they have since been replaced as part of the remedial post-earthquake works.

Discussions with the Onagawa NPS staff indicated that there was a 25mm gap between the turbine pedestal and the surrounding floor. However, there did not appear to be any damage as a result of impact between these elements due to the earthquake. This indicated a stiff combined response with limited differential movement between the turbine and the surrounding operating floor.

While descending through the stair cores, the team saw a number of insignificant smaller cracks, some of which were located between embedments.

At the B1 floor level, (OP +7.6m) minor cracking was observed in line with other locations. However none of these appeared to be significant.

Throughout the building there are infilled concrete block masonry walls. For infilled walls less than 3m in height, they appear to be made of continuous blockwork. However, for larger infilled walls, some of which were up to 6-7m in height, the masonry is split with a beam/column system to avoid a potentially dangerous earthquake hazard.

5.8.1.4 Unit 1

5.8.1.5 Background information

Outer dimensions:	93.8m x 61.1m
Total height:	38.65m
Embedment depth:	20.0m
Foundation type:	2.5m raft foundation founded on bedrock
Type of construction:	Reinforced concrete shear wall with steel truss supporting reinforced concrete roof (15cm).

5.8.1.6 Walk-Down and Detailed Observations

General observations recorded above for Unit 2, especially with respect to minor cracking and the presence of diagonal shear cracks, were also applicable to the walk-down for Unit 1. However, the team observed no buckling in the roof truss of the building.

Within bay T5/T6-TB, there was vertical cracking caused by shrinkage in the middle of the span in the perimeter beam of the external wall, along the full depth of the beam. It was not possible to measure the width of the crack, but given that it was visible from the Operating Floor, it was probably about 1mm at the base of the beam. At gridpoint T5-TB, there was vertical separation (again about 1mm) between the column and the shear wall. Within bay T2/T3-TB, the team observed a long diagonal shear crack in the perimeter wall. None of this cracking affected the structural integrity of the overall structure.

5.9 Walk-downs of the Seismic class C structures

5.9.1 Radioactive Solid Waste Storage Building

The structures team examined the three areas of the Radioactive Solid Waste Storage Building in order to observe the effects of the earthquake and subsequent aftershocks on the structure and joints. This non-safety related structure was designed to seismic class C. Based on the collective observations of the structures team, and despite some damage due to a poor detail at an expansion joint, the overall integrity of this structure was not compromised.

Illustrative pictures of Solid Waste Storage Building walkdown are presented in Appendix VII.

5.9.1.1 Background information

	Area A	Area B	Area C
Date of commissioning:	1982	1993	1999
Outer dimensions:	Areas A & B combined	95m x 36m	32m x 36m
Total height:	13.7m	10.3m	15.3m
Foundation type:	Pile foundation on bedrock		
Type of construction:	Reinforced concrete shear wall construction with internal beam and column frame.		

The Radioactive Solid Waste Storage Building was built in three phases, comprising Areas A, B and C, which are separated by expansion joints. Areas A and B are two storeys tall and Area C is three storeys tall. At certain locations the live loading conditions on the floor are very high, up to 30kN/m2. The external perimeter wall is 60cm thick and the roof slab 40cm thick for radiological shielding.

5.9.1.2 Walk-Down and Detailed Observations

The only visible damage due directly to the earthquake is on the joint between Areas A and B. The expansion joint between the walls was undamaged. However, the joint did not continue into the floor, where differential movements of the buildings during the earthquake caused some damage and exposed the reinforcing bars within the floor slab. This damage also extended into the base of the wall, however there was no visible evidence of loss of integrity of the load-bearing column adjacent to the joint. The damage was the result of poor detailing of the joint in the slab, which should have allowed for differential movement between the slabs on either side.

The team observed full height cracks within some of the main beams supporting the first floor level. These were typically evenly spaced, suggesting that they originated from shrinkage effects. There was minor cracking elsewhere around the structure, but nothing that would affect its stability.

At the 3rd Floor of Area C, the team was shown a number of radioactive waste storage barrels that had been stacked up to three levels high. The restraint of the barrel loosened by the earthquake, so two of them fell to the floor, and other two of them turned over on the spot. There did not appear to be any damage to the structure from these falling objects and the barrels did not open. The Onagawa NPS staff estimated that there was slight movement in a part of the barrel system as a result of the earthquake. The movement was observed to be about 5cm.

Outside, the backfill around the building subsided during the earthquake, exposing many of the footing foundation on pile supporting building. No structural damage was observed.

5.10 Walk-downs of the Tsunami wall

The original raised ground level protecting the plant was 14.8m above sea level. During the 3/11 earthquake, part of the east coast of Japan subsided approximately 1m with respect to sea level. As a result, the raised ground level had an effective height of 13.8m above sea level at the time of the tsunami. Since the earthquake, Tohoku EPCo constructed 3m high embankment up to 17m from sea level. The structures team did not observe any damage, settlement or failure in the sea side part of the raised ground and the slope reinforcement structure. Illustrative pictures of the tsunami wall walkdown are presented in Appendix VII.

5.10.1 Background information

Tohoku EPCo recognized tsunami measures to be an important issue and took tsunami measures of Onagawa NPS.
In planning of the Unit 1, the estimated tsunami height at the site was around only 3m according to the past tsunami records. But considering the argument results by the experts, Tohoku EPCo planned the site ground level as 14.8m including the margin for the tsunami height.
In planning the Unit 2, Tohoku EPCo carried out a paleoseismological survey on A.D. 869 Jogan tsunami for the first time in Japan.
The site ground of the Unit 2 and 3 were designed to be the same level as the Unit 1 (14.8m), after estimating the tsunami height as 9.1m by the numerical simulation.
In 2002, based on the JSCE method, Tohoku EPCo internally calculated tsunami height as 13.6m and confirmed the safety of the site. The tsunami height of the GEJE was 13.0m (tide gauge), and it was almost the same level as the calculation result by the JSCE method.

Outer dimensions (at base):	Full length of plant perimeter exposed to sea
Total height:	14.8m original design 13.8m (after 3/11 earthquake due to 1m subsidence of the peninsula) 17.0m (after addition of 3.2m wall post-3/11)
Type of construction:	Original raised ground (14.8m) - earth embankment with concrete reinforcement Post 3/11- Soil mixed with cement (100kg/m3) embankment

Table 5-9 Outline of Tsunami Evaluation at Onagawa NPS

1.The process of Tsunami evaluation and measures of Onagawa NPS

	Contents	Outlines	Tsunami height*1	Measures	Notes
1970.5	Unit1 Installation License Application	1. Literature search & Interview survey 2. Tsunami measures were argued by a internal committee by specialists. (1968～1980)	About 3m —	-The site height (O.P.+14.8m) -Layout of structures(O.P.+15.0m) -Tide gauge	Literature search & Interview survey
1987.4	Unit2 I.L.A.	1. Vestigial investigation of Jogan Tsunami(A.D.869) in Sendai Plain 2. Numerical simulation of tsunamis	O.P.+9.1m	-Slope protection (O.P.+9.7m)	Evaluation by the reproduction calculation of the biggest historical tsunami
1994.5	Unit3 I.L.A.	1. Numerical simulation of tsunamis	O.P.+9.1m		
2002.2	Tsunami evaluation technique(JSCE)	1. Numerical simulation based on evaluation technique by Japan Society of Civil Engineers.	O.P.+13.6m	- Tsunami height is below the site height.	Estimation by the virtual tsunami considering indeterminacy
2006.9	Revision of the Regulatory Guide *2	1. Tsunami evaluation compared with a new guideline is being carried out based on directions from the government (Sep. 20th , 2006).	Now under evaluation	—	
2010.3	Tide gauge for backup	1. A tide gauge was added for prevention of data missing.	—	-Tide gauge for backup	—
2011.3	The 2011 off the Pacific coast of Tohoku Earthquake	1. Reproduction analysis of the tsunami which attacked Onagawa N.P.S.	O.P.+13m (Tide gauge)	Relocation of devices to a high place	—

*1 : O.P. is Onagawa N.P.S. datum plane for construction, and is the height of the-0.74m from standard mean sea level of Tokyo Bay (T.P.)
*2 : Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities (The Nuclear Safety Commission of Japan (NSC))

5.10.2 Walk-Down and Detailed Observations

The structures team did not observe any damage, settlement or failure in the sea side part of the raised ground and the slope reinforcement structure.

At present, there are no design criteria for tsunami walls, however the original Onagawa NPS tsunami wall was designed partly based on JEAG4601 & 2008. Based on JSCE methods (Tsunami Assessment Method for Nuclear Power Plants in Japan, 2002), a theoretical tsunami height of 13.6m had been calculated for the Onagawa site. The observed height of the 3/11 tsunami was 13m. In order to provide additional margin in the interim, a new 3m embankment was built on top of the existing raised ground after the 3/11 earthquake. Additional height may still be added depending on the results of an ongoing evaluation.

According to Onagawa NPS staff, a settlement survey of the tsunami wall will be carried out once a year, on top of a monthly visual check.

6. OPERATORS AND PLANT TECHNICAL STAFF INTERVIEWS

In order to independently assess the performance of systems used to shutdown the plant and maintain it in a safe shutdown condition, interviews with NPS operators and shift supervisors who were on duty on March 11, 2011 were conducted. Each unit's chronological plant conditions and operator actions were reviewed. The following is a summary of the conditions for each Unit. At the time of the earthquake only one out of five transmission lines was operable due to earthquake damage off the site. This one line (Matsushima) was able to provide power to all three plants due to a common bus for AC power. All units tripped on seismic signal at 14:46. The details of the control room actions for each unit are found in Appendix VIII.

Unit 1:

Both emergency diesel generators started in standby mode. At 14:55, there was a failure in the 275 kV startup transformer due to a failure in the high voltage circuit breakers caused by the earthquake. This created a loss of power on Unit 1 at which point the diesels were used to provide emergency AC power to the Unit. At 14:59 the operators started the RCIC system to cool reactor and used the safety relief valves to control reactor water level and pressure. To achieve cold shutdown, the operators manually depressurized the reactor and the RHR system was manually started at 15:00. At 0:58 on March 12th the reactor achieved cold shutdown. During the seismic event, the control room experienced significant shaking (hand rails and hard hats were needed) but the operations were conducted without incident in terms of safety function and operability of equipment in a loss of the offsite power situation. There was no loss of control room instrumentation needed to shutdown the plant and maintain it in safe shutdown conditions. The startup transformer was restored to service on March 12th at 2:05.

Unit 2:

Unit 2 was in the beginning of a startup sequence and reactor was not critical when the earthquake occurred. Offsite power was available. Unit 2 achieved cold shutdown by 14:49. Unit 2 however experienced flooding in the seawater pit due to the tsunami. This is described in detail in Section 5.8. The tsunami began to arrive at 15:21. Unit 2 CWP tripped at 15:23 on erroneous low water level signal. From an operational point of view, due to leakage through piping penetrations of reactor auxiliary area outside wall, the train B RCW Hx and pump room and the adjoining HPCW Hx and pump room were flooded causing a trip of the train B RCW and HPCW pumps at 15:34 and 15:41 respectively. The HPCW pump is installed on lower base. From an operational point of view, due to leakage through piping penetrations of reactor auxiliary area outside wall, the train B RCW Hx and pump room and the adjoining room HPCW Hx and pump room were flooded causing a trip of the B RCW and HPCW pumps at 15:34 and 15:41 respectively. The HPCW pump is installed on lower base. Once train B RCW and HPCW pumps tripped, the emergency diesel generator train B tripped at 15:35 and the emergency diesel for the HPCS tripped at 15:42 due to a lack of cooling water. The offsite AC power was available for Unit 2. Because the reactor was just started up, the reactor coolant temperature was approximately 78 degree Celsius (172 degree Fahrenheit). Then operators used reactor coolant clean-up system (CUW) by reducing controlled temperature of un-regeneration heat exchanger, to cool reactor core. Train A

RCW/RSW were employed for cooling CUW un-regeneration Hx. Train A systems, such as RHR was used to provide core cooling on March 12 by 12:12.

Unit 3:

Unit 3 was operating at full power at the time of the earthquake. The sequence of events at Unit 3 started with the SCRAM signal from seismic instrumentation followed by automatic reactor shutdown and turbine trip. The emergency diesel DG (3A) had completed its monthly functional test before noon on the day (before the earthquake). The offsite AC power remain available during and after the earthquake. The turbine steam bypassed to condenser was initially used to remove heat from the core. With the arrival of the tsunami at 15:21, the Turbine Seawater Pumps tripped at 15:22 due to flooding of the seawater pit area. The circulating water pumps tripped a minute later due to the ground fault of ultrasonic sensors caused by flooding of the Unit 3 seawater dust screen pit. However with the loss of the circulating water pumps, the operators manually closed the Main Steam Isolation Valves at 15:26 and then started the RCIC system to provide core cooling. RPV was depressurized and the RHR system was started at 23:51. The reactor achieved cold shutdown at 1:17 on March 12^{th}.

The operators of Unit 3 also used other systems during this event demonstrating their functionality after the earthquake.

There was insufficient time to review all of the details with the operators but the necessary functions were performed to bring the plant to a safe shutdown condition indicating no apparent earthquake damage of these systems or controls.

6.1 Design Changes Review

A joint meeting with Structures and Systems Teams was held with the Tohoku EPCo design engineers. The objective of this review was to understand the design standards used in the design and construction of the Onagawa plants. The reference code of seismic design is called JEAC developed by Japan Electronic Association. Even though max acceleration of 3-11 earthquake and 4-7 after shock exceeded the design basis (DBEGM Ss) at some elevations of reactor buildings and some spectra period of it exceeded design basis (DBEGM Ss), the values of seismic integrity evaluation for major equipment did not exceed JEAC criteria. As an example of seismic integrity evaluation to 3-11 earthquake, the engineers presented an analysis of the Main Steam system at Onagawa Unit 3 and identified the maximum stress occurred in the piping system. The maximum stress occurred at a “T” joint (junction of Safety Release Valve and the Main Steam piping). The calculated stress value was 240(N/mm2). That is less than JEAC allowable criterion of 375(N/mm2), and indicate considerable margin. If this is representative of other components and systems, despite exceeding the ground motion spectrum, it is possible to say the plant design margins were quite high. And it is possible to explain the reason that there is no damage to the structures, systems and components that are designed by Seismic Design Class S standards.

After Miyagiken-oki earthquake happened near Onagawa NPS on August 16, 2005, Tohoku EPCo increased the design ground motion of Onagawa NPS (Max acceleration: 580Gal), and carried out the evaluation and confirmed the integrity.

Based on the revised regulatory guide in 2006 and the knowledge obtained from the Niigataken Chuetsu-oki Earthquake in 2007, Tohoku EPCo carried out the Seismic Safety Evaluation (Seismic back-check) and confirmed that the calculated stress value of each SSC of the three plants satisfied the allowable value determined in JEAC. However, decided to carry out the upgrade work to enhance the seismic reliability more. It was implemented from 2008 through 2009 for 6,600 points in total (see below). The table shown below summarizing the number of improvement work to supports implemented in order:

	Number of modifications	Piping	Cable Tray	Instrumentation	Order
Unit 1	3,600	800	2300	500	1
Unit 2	900	300	500	100	3
Unit 3	2,100	500	1500	100	2

Number of unit 2 improvement works was fewest applying the test results (ex: strength test of Cable Tray Joint Element).

6.2 Summary of the Post-Earthquake Shutdown

The primary effects of the earthquake and subsequent tsunami that struck the Onagawa nuclear plant on March 11, 2011 can be summarized as follows-

- The earthquake did not affect the capacity of the units to safely shutdown or cause damage to key safety systems. The demanded safety related systems operated as designed and the emergency diesel generators provided the plant with the power needed maintain core cooling and achieve cold shutdown conditions. Only Unit 1 needed the emergency diesel generators since one offsite power was available for Units 2 and 3.

- The major impact on the plant was not due to the direct effect of the tsunami waves since the plant itself was 15 meters above sea level but tsunami induced flooding in the seawater pits did occur which impacted some plant systems.

- Flooding occurred in all three trains of the Unit 2 reactor building auxiliary area basement, named RCW/RSW heat exchanger and pump rooms, and HPCW/HPSW heat exchanger and pump room. Flooding reached sufficient height to trip the pumps in the RCW/RSW train B and HPCW/HPSW train.

- Loss of train B of the Unit 2 reactor building service water system due to flooding eliminated cooling water to two out of three diesel generators operating on standby. Because the unit continued to be supplied from the off-site grid, loss of the two diesels did not impede Unit 2 reactor shutdown.

- Flooding through the seawater intake ultrasonic level sensors caused some ground faults at the sensors to shut down of the main condenser circulating water pumps for unit 2 and 3. Flooding also occurred in the Unit 3 seawater pit containing the three pumps for the turbine building service (sea) water. Main condenser circulating water pumps for unit 1 tripped due to the shutdown of startup transformer for unit 1. Operation of the main condensers was thus lost; however the main condensers are not used for shutdown following an abnormal event such as an earthquake.

- A short circuit occurred in a 6.9 kV switchgear breaker, resulting in an over-current surge that tripped off-site power supply to Unit 1. However the two diesels serving Unit 1 started automatically on turbine generator trip and closed circuits to supply emergency AC power.
- The process of bringing all three units to cold shutdown following the earthquake is summarized Appendix VIII based on discussions with the plant operators and on an English translation of the operating logs for the three units.

7. SYSTEM' REVIEW

7.1 Objective of Systems Team Review

The objective is to produce a report that assesses the safety performance of the selected system's components of Class S, B and C (seismic design classes) for operability during and after the March 11, 2011 earthquake and tsunami; to identify issues that need further exploration, or assessment based on IAEA Safety Standards, and to compile the findings in a seismic experience database.

The plant identified 61 instances of damage and/or malfunctions to safety and non-safety related items. Each was reviewed for seismic performance and safety significance when applicable. Additionally, to gain an insight into the challenges faced by the operators during the earthquake and subsequent tsunami, operator interviews were conducted. Detailed operator actions were reviewed (as described in Section 6) on all three units, one of which experienced a loss of offsite power requiring the use of emergency diesel generators. In order to gain a better understanding of the seismic performance, a sample review of the seismic analysis was made with the design engineers as well as the preliminary seismic probabilistic safety analysis results.

The team also reviewed tsunami damage to the site due to flooding. Since the site was located 14.8 meters above sea level protecting against a tsunami, there was no direct damage from the tsunami wave on the nuclear plant but there was flooding reported through the Unit 2 seawater pit into the Reactor Cooling Water System Room and the Unit 3 seawater pit affecting the Turbine Service Water System. The sea level docks and shore facilities including a non-safety related oil storage tank at the port were damaged by the tsunami.

7.2 Areas of review

<u>-Class S Systems</u>

In order to identify principal components performing the main safety functions and their supporting systems the review covers:

Criticality and Reactivity Control

Systems and components include the control rod drive system the standby liquid control system and associated instrumentation and control functions.

Core Cooling

Systems and components include the Reactor Core Isolation Cooling system (RCIC); High and Low Pressure Coolant Injection Systems (HPCI and LPCI); Main Steam Safety Relief Valves (SRV); Station DC batteries; Emergency AC power, instrumentation and control functions, associated water tanks and piping systems.

Heat Removal

The key systems are associated with the Residual Heat Removal System (RHR); seawater cooling systems combined with the component cooling (RHRS/RSW/RCW).

Containment

Key systems include the dry containment; downcomers; bellows seals; suppression chamber; main steam isolation valves; standby gas treatment system and hardened vent.

Spent Fuel Pool Cooling System (Unit 1)

Class B Systems

Class B systems perform lower safety functions and are designed to lower seismic standards as compared to Class S systems. It is important to understand the seismic capabilities of these systems since they are less robust than Class S systems. Class B systems include the turbine and generator; spent fuel pool cooling system (Unit 2 and 3), and the Radioactive Waste Storage System etc.

Class C Systems

Yet another measure of margin is the seismic behavior of Class C systems which are designed to normal industrial codes and are of the lowest seismic standard. Class C systems include the Fire Protection System and Start-up Transformers as representative systems.

Review of Seismic Design Basis for Systems

A brief review was presented of Onagawa's approach to design for systems so as not to exceed design limits. A sample of design margins was presented which is reported in Section 5.2.

Operator Interviews

To gain an insight into operator actions during the earthquake and tsunami, operator and supervisor interviews were conducted to review the sequence of events and operator actions at each unit. Questions about systems and instrumentation operability were discussed to confirm the finding in this report. A summary is provided in Section 6 of this report.

Review of 61 Identified Damage

This review entailed a discussion of each item identified in Ref. [9] as prepared by Tohoku EPCo to understand the damage condition and impact on plant safety. This review also provided the team with needed areas of site inspection. Section 7 of this report summarizes our findings.

Review of Tsunami Impact

While the plant's elevation protected the plant from the direct tsunami waves, portions of the plant's seawater systems were flooded by the water coming into the sea water pits disabling the circulating water pumps and flooding one sea water pit on Unit 2 causing internal flooding of the RCW room and adjacent rooms as well as Unit 3 flooding of the seawater pit. A detailed review was conducted as to the causes of this flooding. Flooding at the areas installed seawater level sensors caused ground faults which resulted in condenser water circulation pumps' trip for unit 2 and 3. This event was also reviewed and reported in Section 7.8.

Review of Fuel Channel Damage of Unit 3

It was reported that a Unit 3 fuel assembly channel was chipped when inspected in the spent fuel pool after being removed from the reactor.

7.3 Findings of Class S Systems

7.3.1 Reactivity Control

All units were automatically shutdown by seismic automatic trip systems which initiated control rod insertion. All control rods were inserted and the plants achieved sub-criticality and subsequently cold shutdown conditions. Shown below are the hydraulic control units showing the seismic supports provided to adequate seismic capacity to ensure functionality during an earthquake see Figure 7-1.

Figure 7-1 Hydraulic Control Units

7.3.2 Core Cooling

Given the circumstances on each unit, the plant's core cooling functions were met differently. Each plant's response is summarized below:

Unit 1:
After the initial shutdown, the plant lost off site AC power due to failure of the high voltage breaker and start-up transformer requiring the use of the emergency diesel generators which picked up the load as required. Operators used the Reactor Core Isolation Cooling system to provide core cooling until the pressure was reduced to allow for the operation of the low pressure residual heat removal system. The water for core cooling came from the condensate storage tank. All systems functioned as designed with

no reported failures. There were no major water leaks reported in piping systems or storage tanks containing safety related water. Control room functions and monitoring of important systems was maintained despite numerous alarms.

Unit 2:
Since Unit 2 was just beginning its startup sequence the core was not critical. It was confirmed in cold shutdown within three minutes of the reactor trip signal. Unit 2 was able to maintain offsite AC power through the plant cross connect of the electrical system. Train B of the RCW was disabled by the tsunami induced flood.

Unit 3:
Unit 3 was also able to maintain offsite AC power. This allowed for a normal shutdown sequence until tsunami disabled Turbine Service Water (TSW) system and Circulation Water (CW) system. Due to the ground fault of ultrasonic sensors caused by flooding of the Unit 3 seawater dust screen pit, the plant lost the use of the circulating water pump preventing the use of the condenser to remove heat from the core. The operators then manually used the RCIC system and RHR for cooling the reactor. All systems worked as designed with no loss of water due to the earthquake from piping systems or water tanks see Figure 7-2, Figure 7-3, Figure 7-4 and Figure 7-5.

Figure 7-2 RCIC Steam Driven Pump (upper left), Low Pressure Core Spray Pump (A) (upper right), and Motor Operated Valves for these systems (lower)

Figure 7-3 High Pressure Core Injection Pumps (left) and its pipe support (right) in Unit 1

Figure 7-4 Condensate Storage Tank (left) and #2 Suppression Pool Water Storage Tank (right)

Figure 7-5 Sample of Cable Tray Supports (left) and Emergency Diesel Generator (right)

7.3.3 Heat Removal

Unit 1:
The reactor was depressurized allowing the use of the Residual Heat Removal System which was operated as one of the component cooling systems. The reactor service water and component cooling (RHR, ECW and ECW) systems functioned normally.

Unit 2:
Even though the plant was not operational at the time of the earthquake, cooling of the core is still required. Due to the flooding of the Reactor Component Closed Cooling Water system (RCW) Heat Exchanger B & D room and adjacent rooms (discussed in Section 7.10), the Train B RCW pumps tripped causing the Emergency Diesel Generator B tripped. A short time later the HPCW pump tripped as did the EDG for High Pressure Core Spray system due to flooding in the adjacent room. This left only one train of RCW in Train A to provide cooling for the pumps to support the Residual Heat Removal System. These events were not directly seismically induced but were caused by flooding of the seawater pits leaking in the auxiliary rooms described more fully in Section 7.8.

Unit 3:
The operators started up the RCIC to feed coolant to the reactor core and upon sufficient depressurization, core cooling was maintained by the RHR system (Train A). No evidence of any seismic damage on any system was observed see Figure 7-6.

Figure 7-6 RHR Pump and RHR Motor Operated Valve

7.3.4 Containment Integrity

The containment integrity was not affected by the earthquake on any of the units. The plants did not experience a loss of coolant accident or steam line break inside of the main steam isolation valves. Inspections were made of the bellows seals on Units 2 and 3 with no indication of damage see Figure 7-7. The suppression chamber (torus) did not experience any leaks. Pressure tests to check complete containment integrity will not be performed until the plant resumes pre-operational testing. Main steam isolation valves appeared to hold pressure.

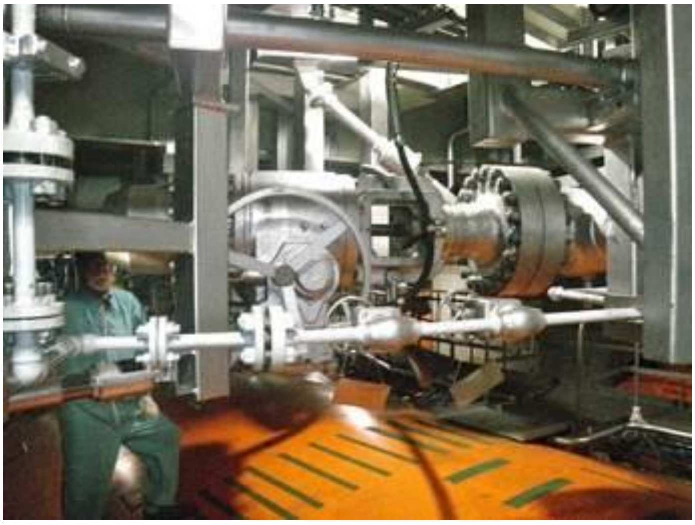

Figure 7-7 In Containment Above Torus – showing seismic supports

7.3.5 Position Switch Relocation (Main Steam Safety Relief Valve)

A false indication was displayed in the Unit 1 control room showing that the main steam pressure relief Valve C was both open and closed. Apparently vibration of the lever atop the piston actuator slightly moved the close-side switch downward, which caused the switch unable to detect proper close position of the valve and to indicate both an open and closed position for the valve on the main control room panel. But the operator easily confirmed that the steam relief valve actually remained closed according to the trends of the exhaust pipe temperature and reactor pressure vessel's pressure. Later maintenance engineer confirmed its relocation issue, see **Figure 7-8.**

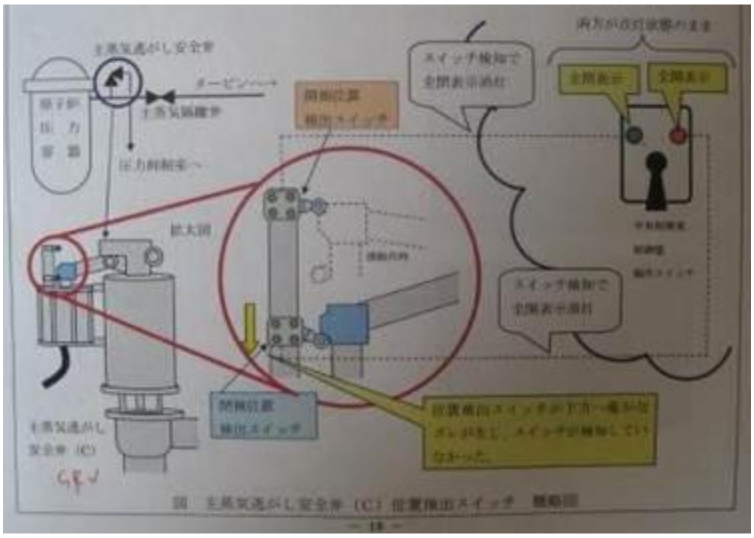

Figure 7-8 The piston actuator linkage atop the main steam safety relief valve

7.3.6 Tilt of Swivel Attachment (Stainless Steel Water Gates)

On the refueling floor of the Unit 3 reactor building, an anomaly was observed in the vertical stainless steel watertight gates that form a lock between the spent fuel pool water and the normally dry canal to the reactor well, and to the spent fuel cask pit (see illustration below). According to the maintenance engineers' explanation, a set of large bolts is screwed down against the top of the gate, to prevent lift of the gates by buoyancy when the both side of gates were filled with water. At the two locations the tightening bolt atop the gate was found to have loosened, but the gate was still in proper position by the L-shape retainers welded on the pool wall and the cylindrical bars welded on right and left sides of the gate at 4 elevations. The bolts were found tilted to one side on their swivel attachment. In neither case was the bolt or its attachment to the gate noticeably damaged, nor was the gate seal leaking. The drawing of the gate attachment to the fuel pool side in the illustration shows a series of hooked-shaped supports for the gate that push the gate against its lift from the proper position as the bolt is tightened down - see **Figure 7-9.**

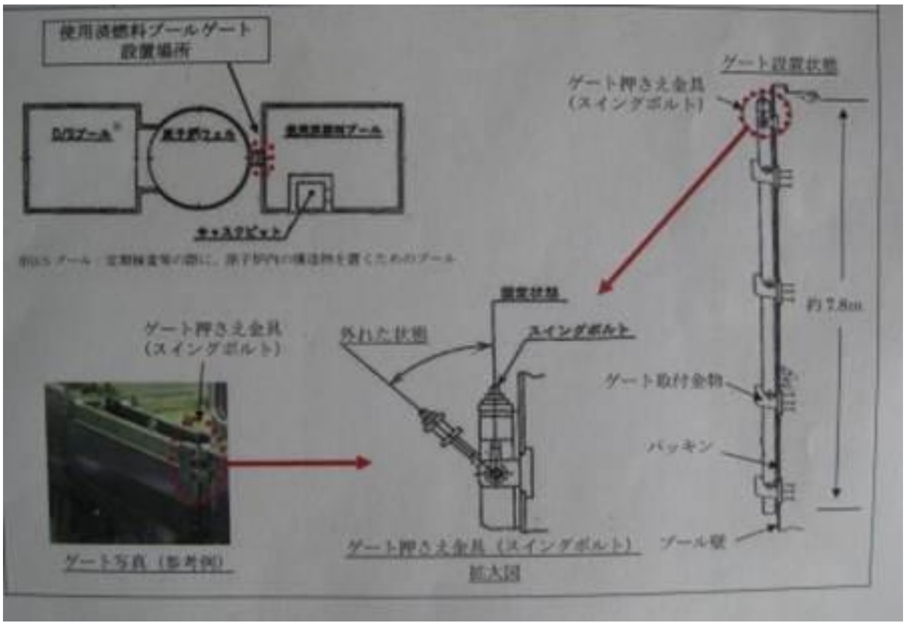

Figure 7-9 Gate of the spent fuel pool

7.3.7 Ground faults (DC125V Circuits)

Ground faults in certain 125-volt DC circuits caused over-currents, but circuit breakers in DC distribution panels housed in various cabinets in the Unit 1 Control Building, the Unit 2 Control Building and the Unit 3 Reactor Building still connected, that were consistent with breakers' specification. Ground faults were caused by sea water contact with live conductor in various devices that were inundated in the areas flooded by the tsunami. Unit 1 DC ground faults were apparently caused as a secondary effect of the arc and fire in the Train A 6.9-kV switchgear, which contains DC circuits for protective relays.

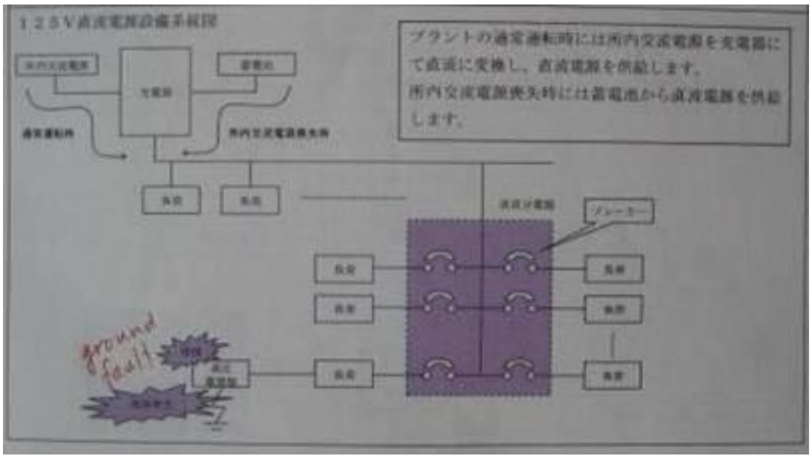

Figure 7-10 The simplified diagram illustrates ground fault failures

The simplified diagram illustrates ground fault failures in 125 volt DC panel boards. The apparent cause was contact of sea water with conductor in devices located in the flooded areas of the auxiliary buildings see **Figure 7-10.**

7.4 Findings of Class B Systems

Class B systems are safety related systems with lower role than Class S system and designed to a lower seismic standard. While a detailed review of Class B systems was not made, those systems that suffered damage are reviewed below. In general it can be said, that the only major equipment that suffered damage were the steam turbines. The systems supporting the balance of plant did not suffer damage including the turbine bypass and turbine stop valves since they operated after the earthquake. These findings show the margins available in the design of these systems and structures.

7.4.1 Blade Wearing & Intermediate Bearing Damage (Steam Turbine)

The Unit 2 turbine generator was rotated at low speed by turning gear in preparation for startup at the time of the earthquake. The spinning turbine rotor essentially floats on a film of oil while spinning. After earthquake Intermediate bearing (thrust bearing) were dismounted to be inspected and renovated at the factory. Axial bearings were reported as showing wear but did not require replacement. At the base of Intermediate bearing housing between the high pressure and low pressure turbine A, the concrete surface (grout) of the base spalled, but steel bar reinforced concrete (strength member) showed no damage at all according to the inspection after the grout removed. Bolts securing the base plate of the bearing housing were also slightly bent. Scoring was noticed where the rotor blades contacted the surrounding nozzles on the low pressure turbines. The contact damage did not require blade or nozzle replacement on the Unit 2 turbine.

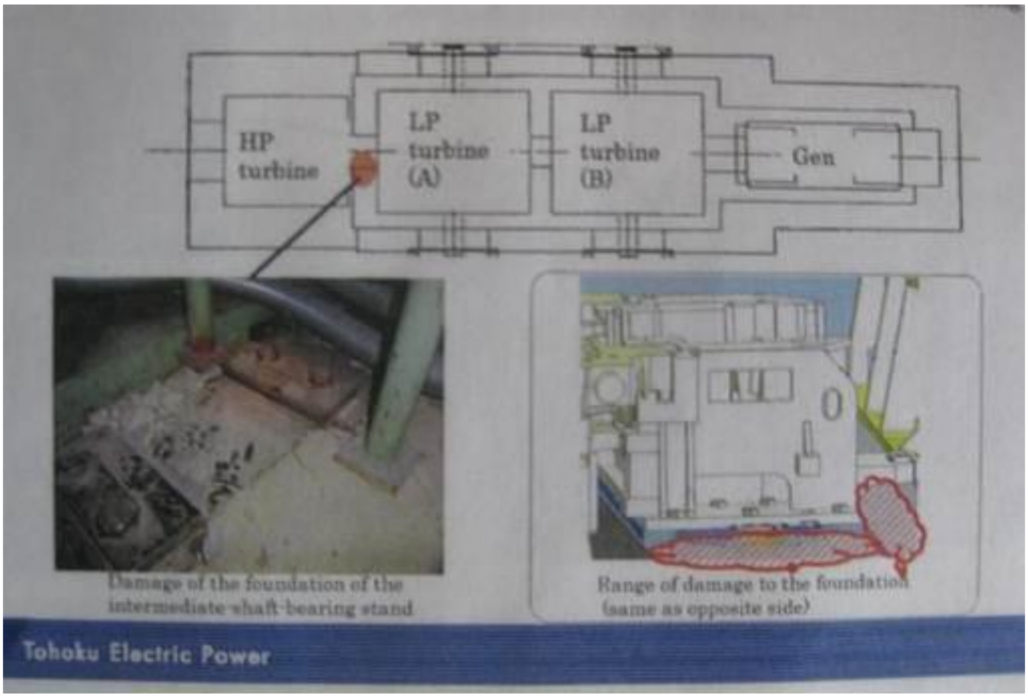

Figure 7-11 Spalled Concrete Grout Under Intermediate Shaft Bearing Base Plate Unit 2

The drawing shows the location of spalled concrete at the base of the Unit 2 bearing housing between the high pressure and first stage low pressure turbine see Figure 7-11.

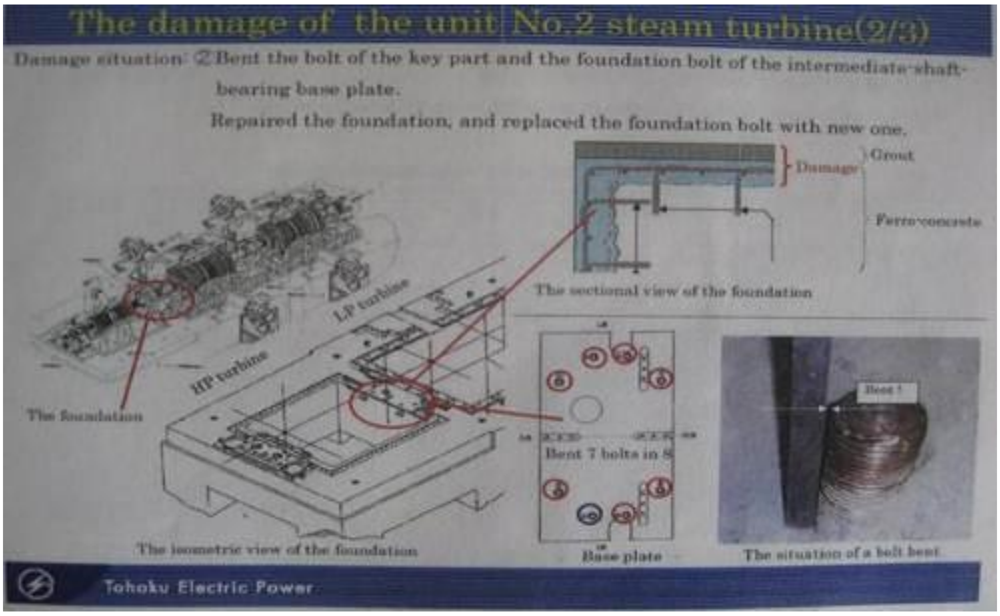

Figure 7-12 Slightly Bent Bolts of Intermediate Bearing Base Plate Unit 2

The photos illustrate bent bolts in the base plate of the Unit 2 bearing housing see **Figure 7-12.**

More extreme damage was observed in the Unit 3 turbine which was spinning at normal operating speed (1500 rpm) at the time of the earthquake. Here again Intermediate bearing for the Unit 3 turbine were renovated at the factory. The bearing housing base plate between the high pressure turbine and low pressure turbine A stretched the bolts by 3 – 6 millimeters. And the blades embedded on the spinning rotor contacted surroundings, such as nozzles, and wore. From the view point of generated steam efficiency (thermal efficiency), considered necessary period for the seismic resistance improvement work and the blade replacement work, a part of turbine blades were decided to be replaced.

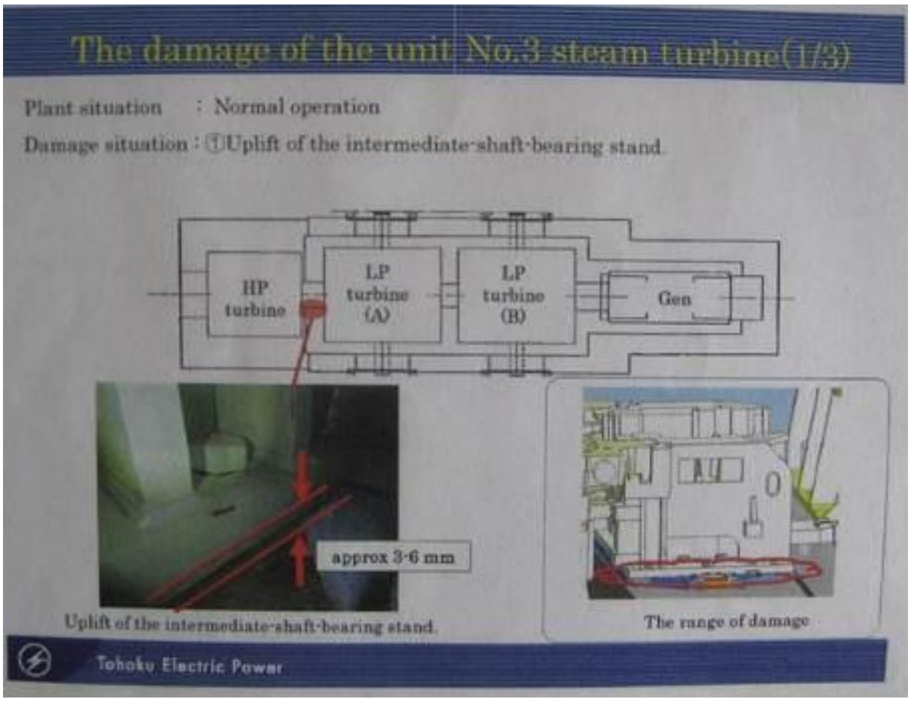

Figure 7-13 Uplift of Base Plate of Bearing Housing Unit 3

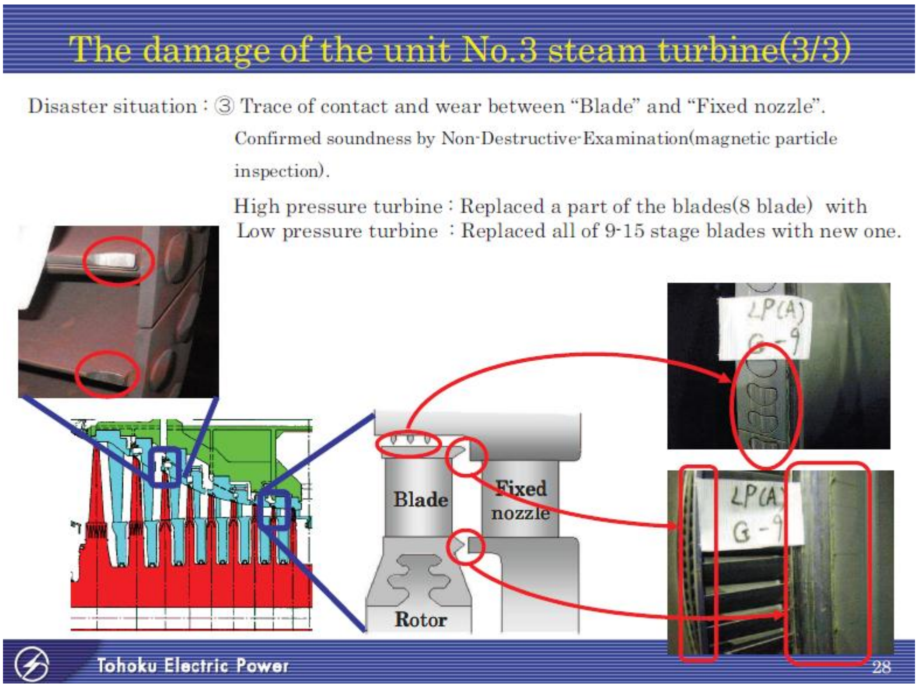

Figure 7-14 Wearings on the Unit 3 steam turbine blades

Contact of the spinning turbine blades with the static nozzles resulted in damage of a blade on both the high pressure and low pressure turbine in Unit 3 see **Figure 7-13.** and **Figure 7-14.**

The operators reported that the Unit 1 turbine has not yet been inspected.

7.4.2 Damage of Shaft Bearings & Operation Cab Flame (Overhead Bridge Cranes)

Yielding and cracking occurred in the part of the steel support frame supporting the operator’s cab on the Unit 1 and on the Unit 2 reactor building overhead bridge cranes. At both locations the cab (or cockpit) is cantilevered beneath the frame. The level of motion at the crane rail level apparently incurred sufficient cantilever sway in the cab to initiate cracking in the steel. Had failure in the support frame reached the point of cab detachment, the falling cab could have been a serious interaction hazard for the refueling floor fixtures, therefore Tohoku EPCo considers the countermeasures, such as frame reinforcement below see **Figure 7-15.**

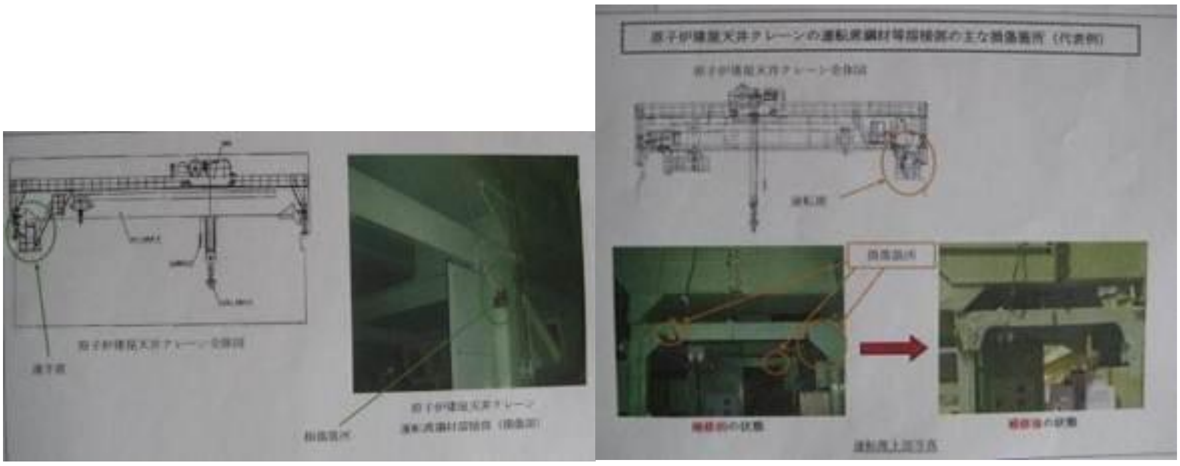

Figure 7-15 Overhead Bridge Cranes

The cab or cockpit of the Unit 1 and Unit 2 overhead bridge cranes are cantilevered from a steel frame attached to the main bridge of the crane. Sway of the cab during the earthquake cracked the steel members on both units, requiring weld repairs.
After the earthquake Unit 1 reactor building overhead bridge crane was found to be squeaking on its moving of the bridge. But this June one of 4 driving shaft bearings in the gear drives for the crane wheels was found to be broken. Crushed bearing debris was found in the oil tray within the crane wheel housing as illustrated in the drawing see **Figure 7-16.**

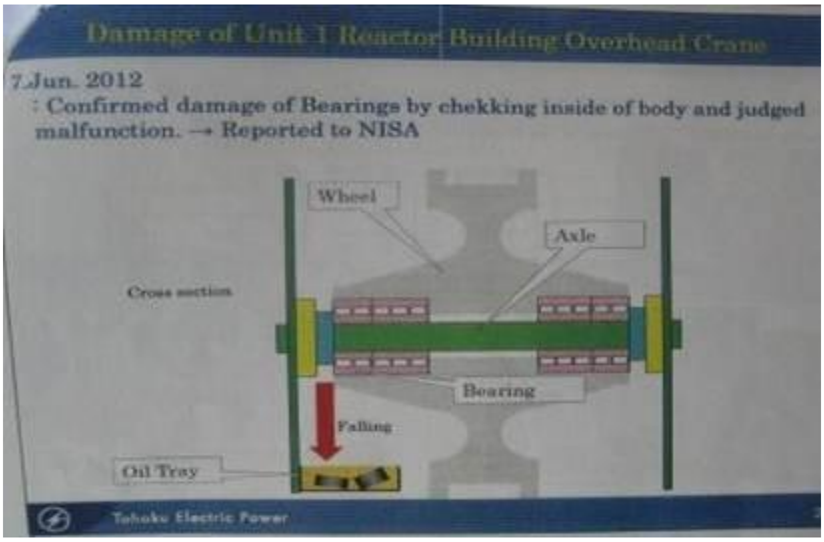

Figure 7-16 Crushed bearing debris were found in the oil tray of the rail wheel assembly of the Unit 1 overhead bridge crane.

The overhead bridge crane over the Unit 3 reactor building operating floor apparently slide along its rails during the earthquake as indicated by scratch marks on the surfaces of rails and driving wheels.

7.4.3 Cable Holding Caterpillar Dislodgement (Refueling Machine)

A caterpillar for holding cables of the Unit 3 reactor building refueling machine dislodged from the rails, presumably due to transverse torsion of the cable holding caterpillar see **Figure 7-17.**

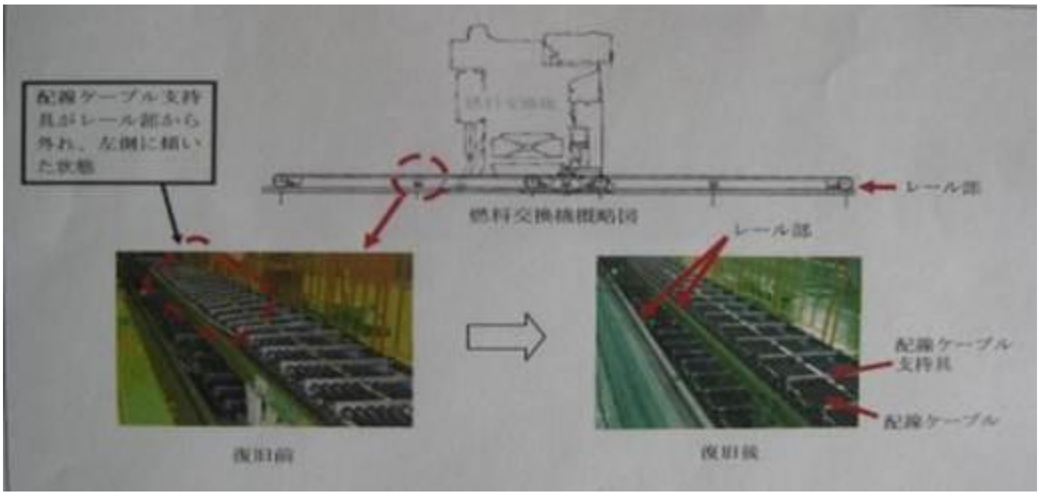

Figure 7-17 A cable holding caterpillar dislodged from the rail of the Unit 3 refueling machine

7.5 Findings of Class C Systems

Class C systems are designed to a seismic standard about 3 times lower than that of Safety Class systems. As a general finding, all Class C systems maintained function with limited damage again demonstrating significant seismic margin in the plants. This section summarizes the findings of the Systems Team. The damage reported is relatively minor.

7.5.1 Pressure Relief Valve Actuation (Transformers)

At the time of the March 11 earthquake, main transformers for all three units, startup transformers for Unit 1 & 2, house & auxiliary boiler transformers for Unit 2 experienced oil pressure relief valve actuations and corresponding over-pressure alarms due to sloshing of insulating oil in the transformer tanks. At the time of the biggest aftershock on April 7, main & house transformers for all three units, startup, auxiliary boiler & exciter transformers for Unit 2 experienced the same events as above. Activation of pressure switches in oil-insulated transformers due to sloshing is a common earthquake effect.

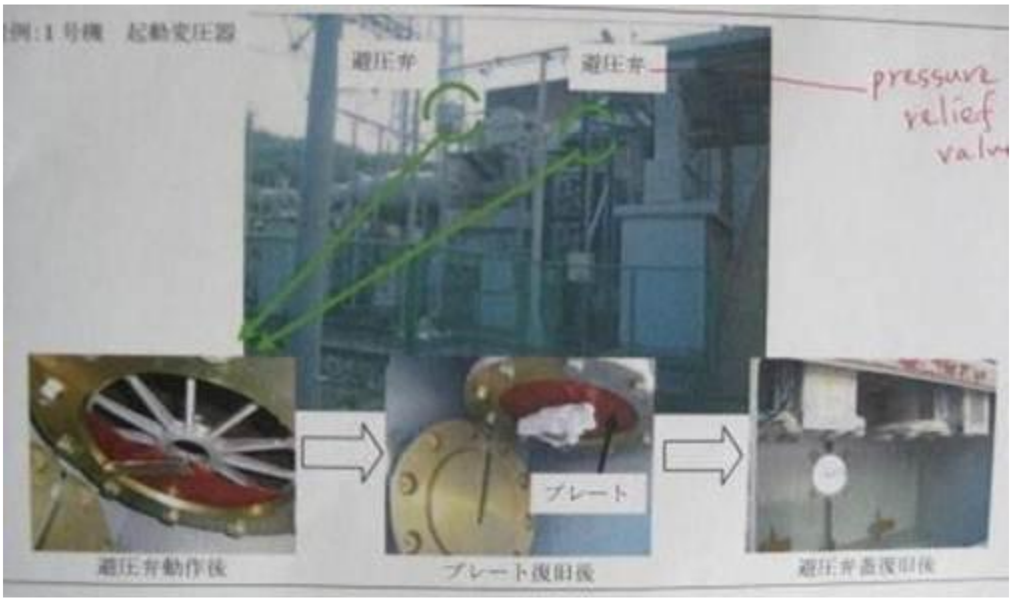

Figure 7-18 Activated pressure relief valves for unit 1 start-up transformer (example)

The photos illustrate the location of the pressure relief valves and the valves with the seal popped open see **Figure 7-18.**

7.5.2 Transformer Radiator Leak (Startup Transformers)

A crack occurred in a fin of the radiator for the Unit 2 startup transformer, leaking a small amount of oil. Oil leaks are common in transformer radiators, but usually occurring at the flanged connection of the cantilevered radiator mass. The fact that the leak occurred in a fin rather than the radiator pipe attachment may indicate an impact of the radiator against adjacent steel see **Figure 7-19.**.

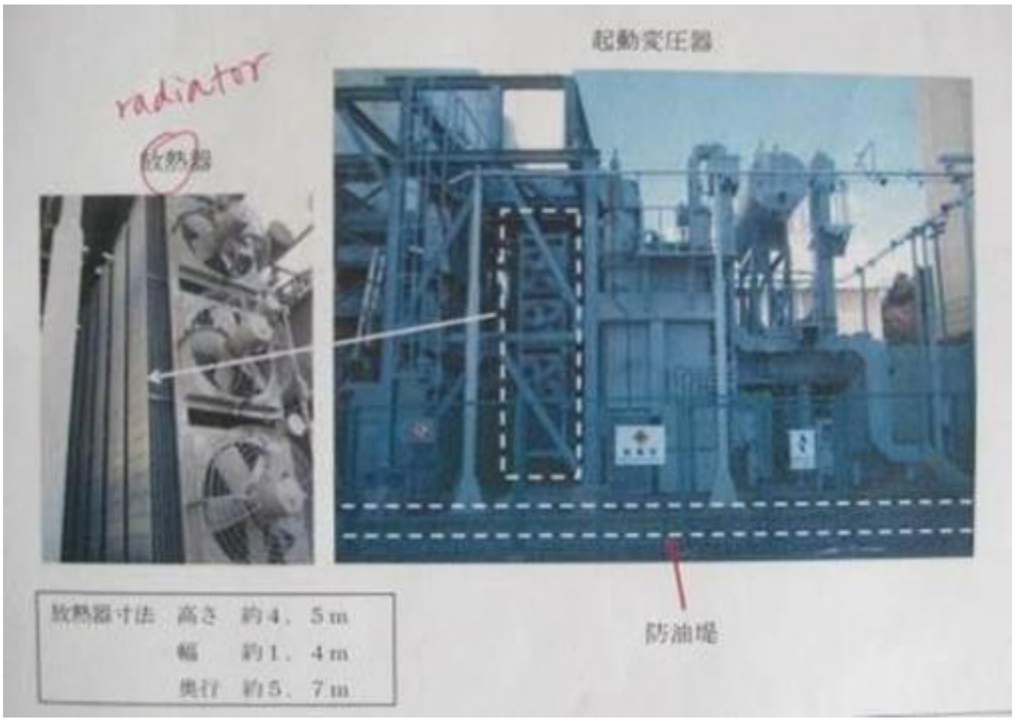

Figure 7-19 the radiator fin of the Unit 2 startup transformer

A leak occurred in the radiator fin of the Unit 2 startup transformer, possibly due to impact of the radiator against the adjacent structural steel.

7.5.3 Partial Burnout (Lightning Arrestors)

Partially burnout occurred in two over-current surge (lightening) arrestors in the sulfur-hexafluoride (SF-6) switchgear on the 275-kilovolt lines. The sudden over-current was apparently caused by reduction of insulting gap between an energized part, voltage distribution shield, and arrestor elements, zinc oxide, due to sway of lightning arrestors connected to the two Oshika lines. The surge arrestors have since been replaced by seismic resistance improved model that have a less moment arm and rigid seismic supports, see **Figure 7 20.**

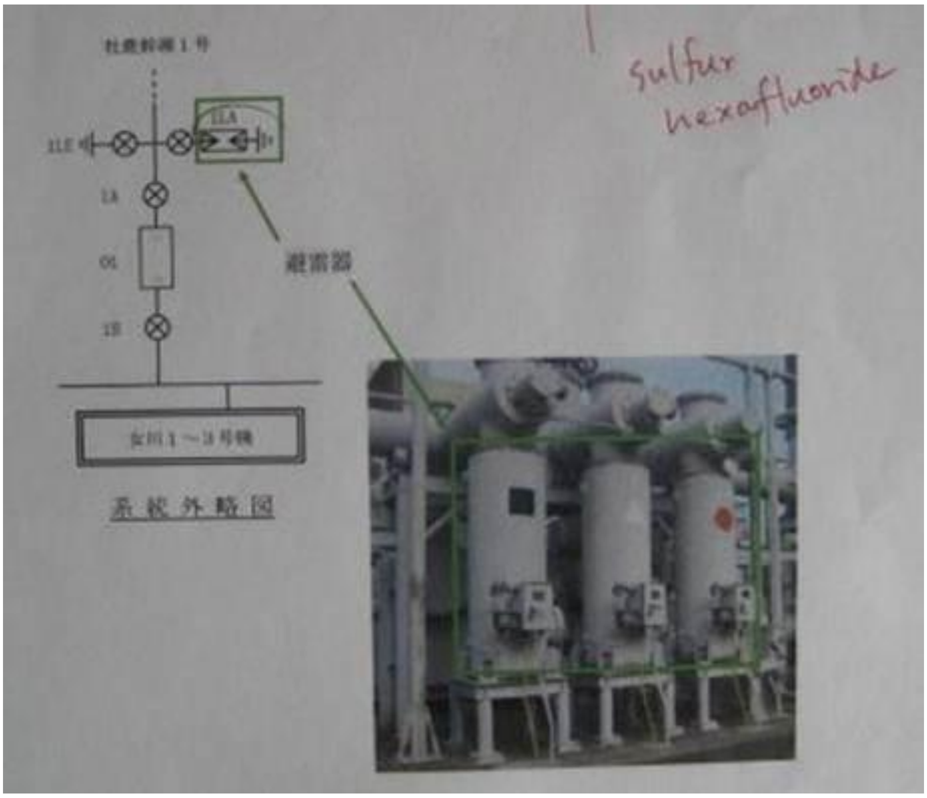

Figure 7-20 Simplified diagram and photo of the surge arrestors in the SF-6 system for the 275-kV lines

7.5.4 Over-Current Burnout (Power Train at 6.9kV)

The Unit 1 power train at 6.9-kilovolts (the voltage for large motors) includes five switchgear assemblies (refer to the one-line diagram below for all three units). The Unit 1 non-safety-related power supply Train A consists of vertically-racked circuit breakers, unlike the horizontally-racked breakers in safety-related switchgear. Rocking of a vertically-racked breaker apparently fractured the insulators enclosing the bus clamps at the top of the breaker, allowing bus contact with the cabinet sheet metal. The resulting ground fault and short circuit flash started a small fire in the cabinet, consuming the cable insulation and the few other flammable materials in the cabinet. The arc and fire damage took the A switchgear assembly out of service. The activation of the protecting relay for start-up transformer caused the loss of offsite power in Unit 1 see **Figure 7-21.**, **Figure 7-22.** and **Figure 7-23.**

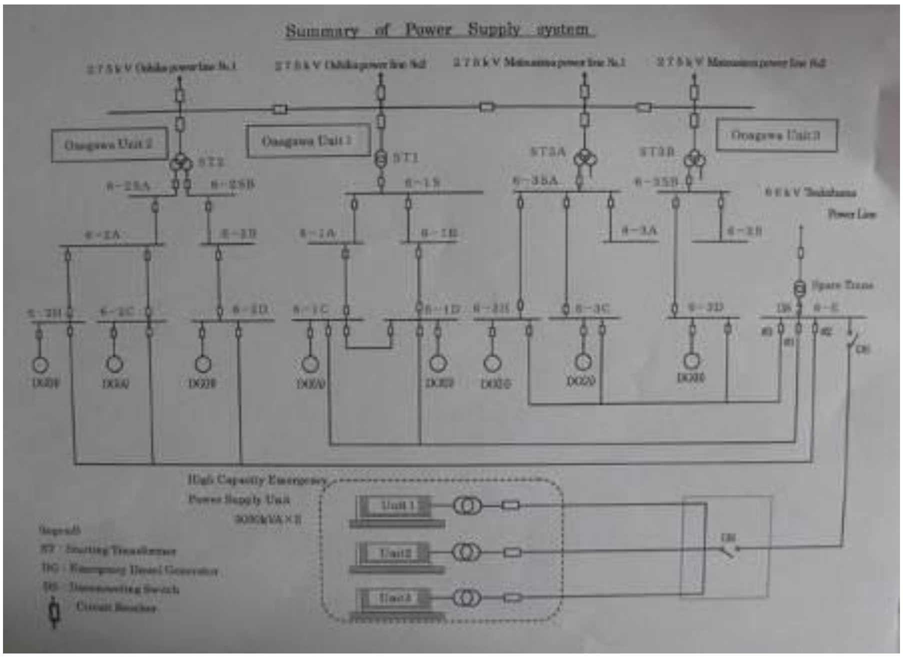

Figure 7-21 Electrical one-line diagram of power flow into the Onagawa Power Plant, including the damaged 6.9-kV Train A on Unit 1

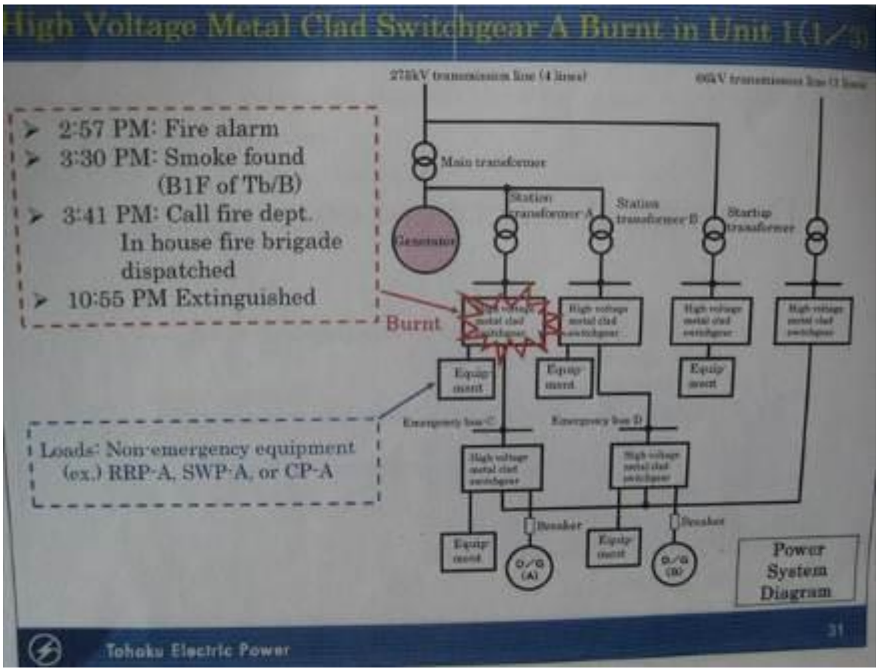

Figure 7-22 Simplified one-line diagram and sequence of events in suppressing the fire from the ground fault in the Units Train A 6.9-kV circuit breaker

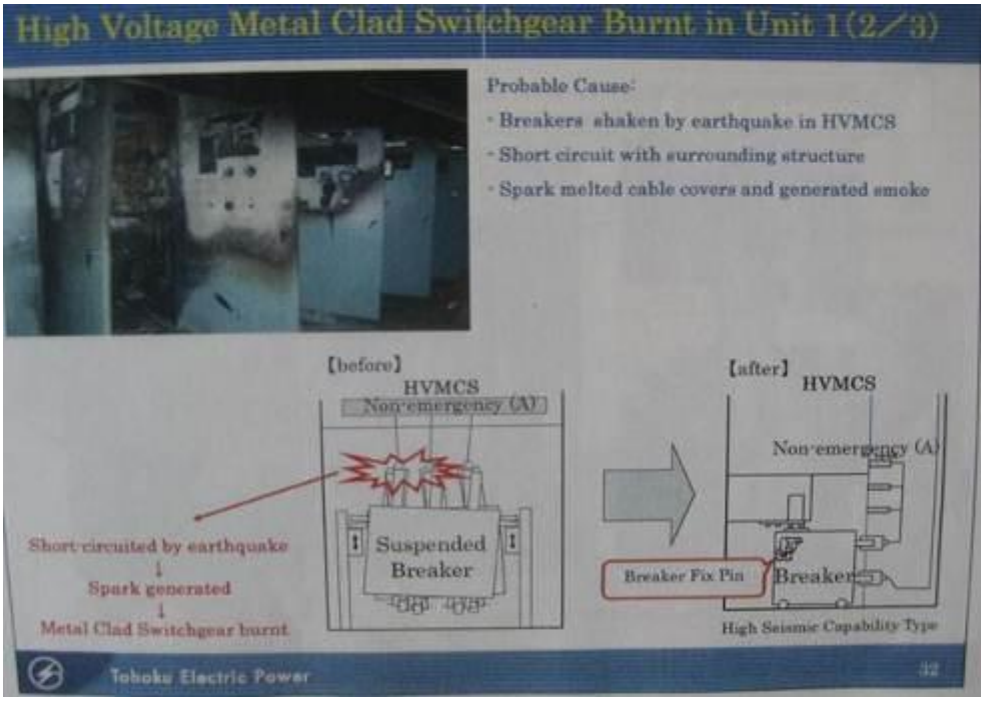

Figure 7-23 Photos & illustrations of the ground fault damaged vertically racked breaker provided by Tohoku EPCo

7.5.5 Fuse Burnout (120V AC Circuit)

A fuse burned out in a main control panel of Unit 1 in the 120 volt AC circuit supplying a signal converter for the level sensing system of the Unit 1 boron tank. The operators mentioned that the current surge through the 120 volt circuit that caused the fuse burnout might have been a secondary effect of the ground fault and fire in the Unit 1Train A switchgear.

7.5.6 Toppled Equipment (CRTs)

In the Unit 2 main control one unanchored CRT monitor toppled from the main control board. Soon after an operator re-stand it, using this monitor operators witnessed tsunami scenery at the port area. An unanchored CRT monitor toppled from a rack in the refueling-crane-mounted control room of Unit 1, see Figure 7-24. An unanchored programmable logic controller module toppled from a desk in the refueling control room of the Unit 3 reactor building.

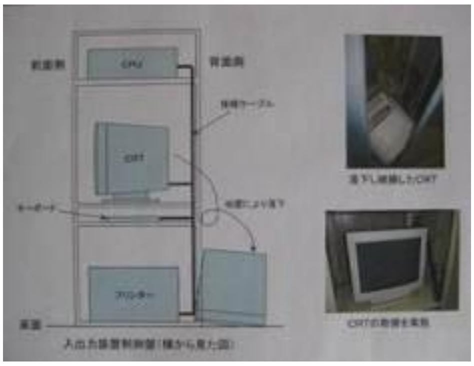

Figure 7-24 Unanchored desk or rack-mounted equipment

7.5.7 Indication Failure (Refueling Floor Radiation Monitoring System)

In the main control room panel of Unit 3 a strip chart recorder, seismic safety class C, for the refueling floor radiation monitoring system required replacement. The recorder was found to be inoperable after the earthquake for reasons not determined (the recorder was simply replaced without researching the specific component damaged or the apparent cause because this recorder was non-safety related).

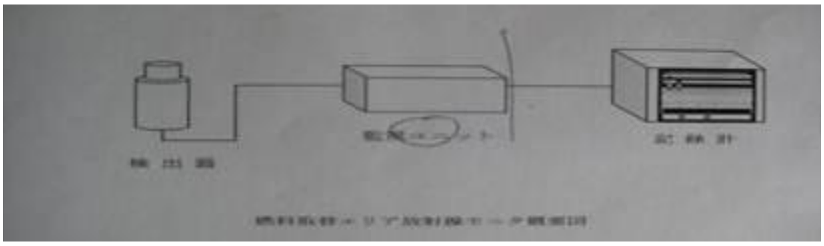

Figure 7-25 The simplified diagram illustrates the refueling floor radiation monitor, signal conditioner and the recorder

The simplified diagram illustrates the refueling floor radiation monitor, signal conditioner and the recorder that required replacement in the main control room of Unit 3 see Figure 7-25.

7.5.8 Bend of Latches (Reactor Shield Wall Hatches) and Dislodgement of Plugs (Concrete Shield)

In Unit 3 the sliding gates that close off water from the spent fuel cask pit and the spent fuel storage pool have a set of tightening bolts at the top for avoiding the lift of the gate by buoyancy when the cask pit was filled with water. Apparently uplift of the gate, perhaps due to water sloshing in the pool, loosened the bolt during the earthquake.
At seven doors in the three reactor buildings, yielding was observed in the steel latches for hatches. Locations where hatch latch yielding was observed were inspection hatches, which include for a penetration for a feedwater line, through the reactor thermal shield walls of Units 2 & 3 see Figure 7-26.

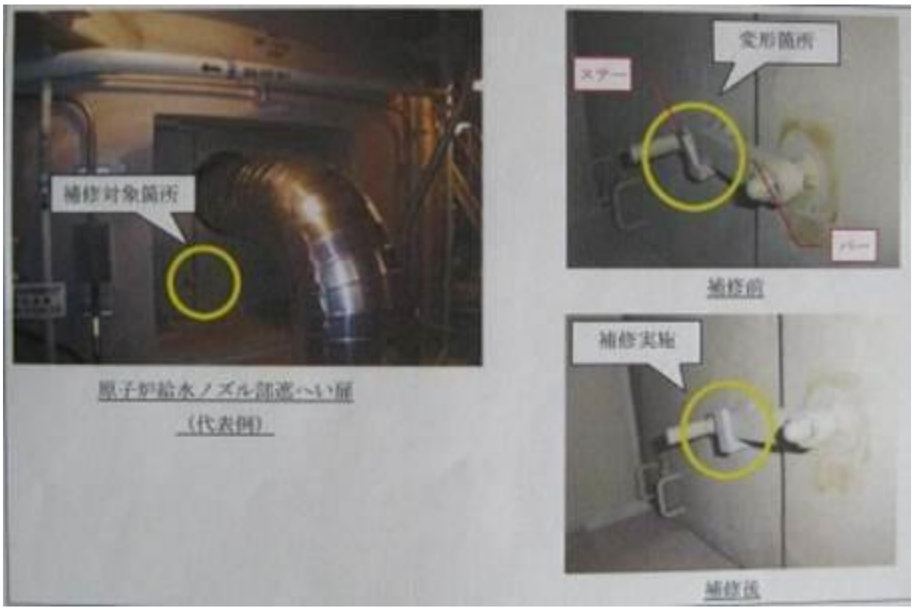

Figure 7-26 Yielding in the steel latches for hatches

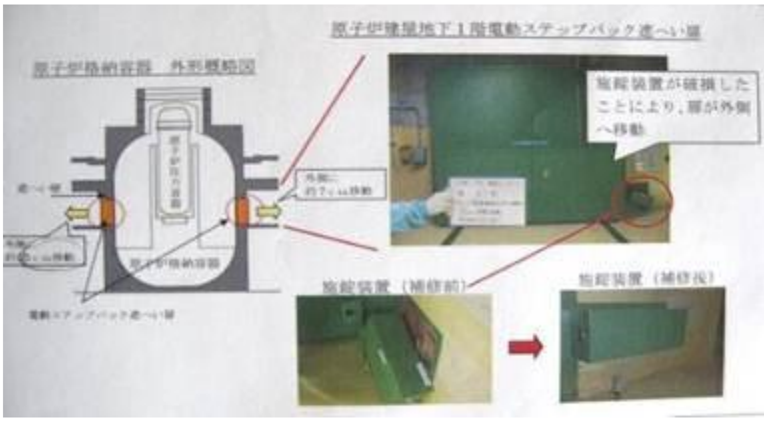

Figure 7-27 Concrete shield plugs

The concrete shield plugs for the equipment hatches of the Unit 2 primary containment vessel dislodged due to the breakage of locking device caused by sliding motion of the hatch on its rails see Figure 7-27.

7.5.9 Buried Pipe Damage (Fire Protection Pipe)

The only instance of a reported pipe failure was in a section of buried Unit 1 fire protection pipe shown below see Figure 7-28. The failure is believed to be due to soil settlement which was significant around the site. All the safety related pipes are in concrete channels preventing failure.

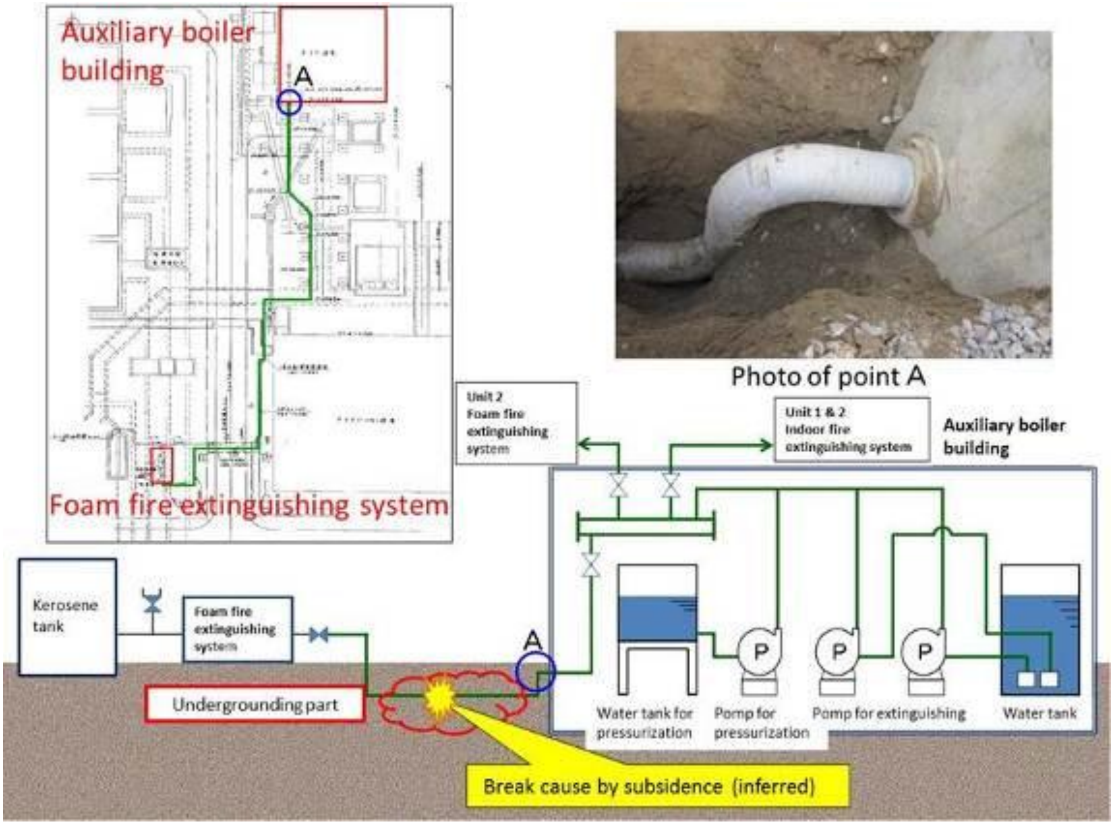

Figure 7-28 Pipe failure in a section of fire protection

7.5.10 Miscellaneous

Apparent sway of a vertically-rack 6.9-kV circuit breaker in the Unit 1 turbine building dislocated the interlock roller that push the switch for connecting circuit breaker through a mechanical linkage, see Figure 7-29**.** The switchgear was otherwise reported as undamaged.

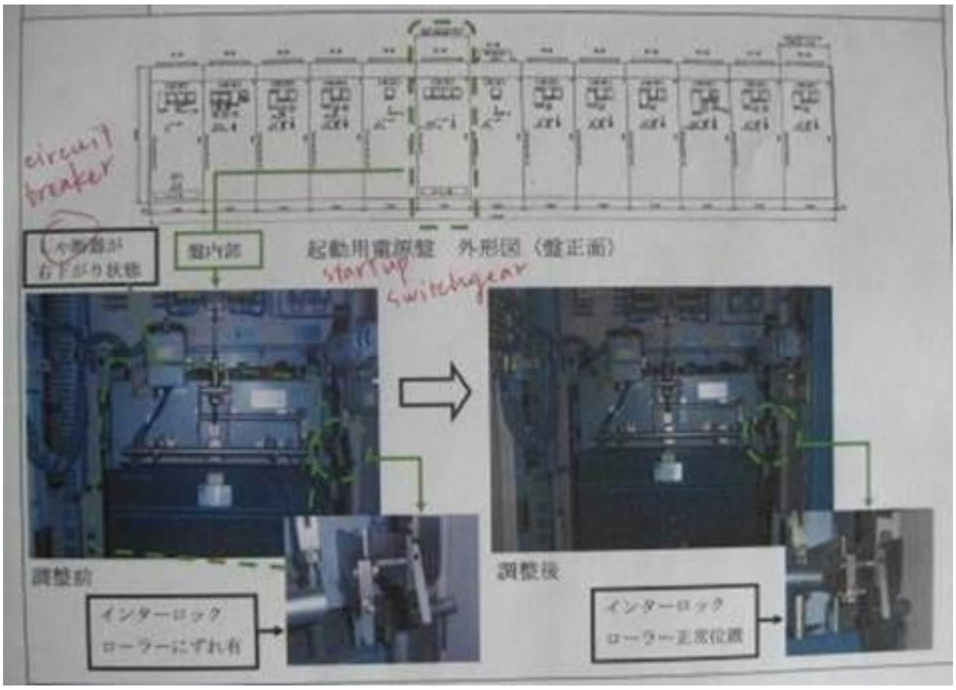

Figure 7-29 Dislocated interlock roller that push the switch for connecting circuit breaker(left), aligned interlock roller(right)

Radiation monitoring post No.6 (one of six posts located in the site along the site boundary) was found to lost its signal for MCR recorder due to the looseness of the connection at the measuring device with the cable from transmission device, both of which devices set in the rack at the monitoring post house. Although this incident, No.6 radiation monitoring by the computer system kept functioning properly because of using different cable line (there was no disconnection for this system).

The earthquake and tsunami damaged electricity and signal transmitting lines for all 4 offsite radiation monitoring stations located at diversified points within 8 kilo-meters from the site. In house monitoring facilities for 4 stations were found to be operable, then after the completion of restoration works for electricity and signals the radiation monitoring and data published on homepage were restarted.

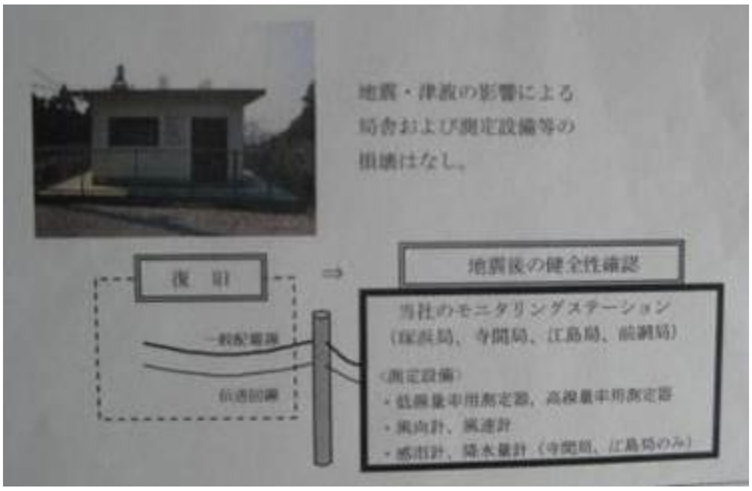

Figure 7-30 Radiation monitoring station

Radiation monitors located on the sea water discharge canals near the seashore of the site were washed away by the tsunami.

7.6 Other Findings

7.6.1 Fuel channel box damage

Tohoku EPCo has reported one incident of fuel channel box damage to NISA. The root cause investigation is not completed and no cause has been reported to NISA. The damage was purely to the fuel channel box and not the fuel pins themselves. The damage was to a plate welded on top of the fuel channel box. The fuel channel box makes coolant flow channel for fuel, but the damage did not effect on the function at all. The fuel pins were not damage during the earthquake. During the sipping of the fuel after the quake there were no new damage detected.

7.6.2 Fuel leakage prior to the earthquake

Prior to the earthquake there was fuel leakage at unit 3. At the post earthquake inspection, one fuel pin was found to be leaked, but no damage caused by earthquake was investigated.

7.6.3 Likely cause of fuel channel box damage

The internal Tohoku EPCo investigation has not been finished and there are no preliminary estimates of the source of the damage. It is important to not draw any conclusions before the root cause is investigated. The root cause of fuel channel box damage is usually case unique and no general conclusions shall be drawn.

7.7 Summary of Equipment Damage and Malfunctions

Remarkably only six equipment items appear to have been damaged to the point of rendering their system inoperable. These items are the one 6.9 kV switchgear assembly, two steam turbines, one fuse in the boron tank level monitoring system, one strip chart record in a radiation monitoring system, and a disabled overhead bridge crane due to wheel bearing damage. Given that the earthquake exposed thousands of items of equipment to severe shaking within the three units, this appears to be a remarkable rate of survival. However it should be noted that while equipment is generally the same as standard industrial fixtures, the installation in the Onagawa plant in terms of bracing and anchorage undoubtedly improved the chances of earthquake survival.

The table that follows presents an abbreviated summary of the instances of damage and malfunction included in the list provided by Tohoku EPCo Management.

Table 7-1 Summary of Damage or Malfunctions (Earthquake Shaking Only)

Cause of Damage or Malfunction	Number of Instances	Seismic Design Class	Comment
MS-SRV Position Switch Relocation	1	S	A false indication was displayed in the Unit 1 control room due to position switch relocation possibly caused by earthquake vibration.
Tilt of Swivel Attachment	2	S	Tilt of swivel attachments were found at spent fuel pool gates in Unit 3 reactor building.
Ground Faults (DC125V Circuits)	8	S	Current surges in the 125-volt DC system appear to have been primarily induced by sea water contact, as an indirect tsunami effect, or by burnout of cable insulation, as

				a secondary effect of the arc and fire.
Blade Wearing & Intermediate Bearing Damage (Steam Turbine)		5	B	Abrasion of spinning turbine blades with static nozzle diaphragm and plastic deformation of turbine intermediate bearing (thrust bearing), sole plate & its mounting bolts appears to illustrate the intensity of shaking..
Damage of Shaft Bearings & Operation Cab Flame (Overhead Bridge Cranes)		3	B	Cracking were found at the part of the steel frame supporting the operator's cab on the Unit 1 and on the Unit 2 reactor building overhead bridge cranes. Driving shaft bearings in the gear drives for the crane wheels was found to be broken in Unit 1 overhead bridge crane.
Cable Holding Caterpillar Dislodgement (Refuelling machine)		1	B	Dislodging of the cable holding caterpillar for Unit 3 refuelling machine was likely an effect of anchor point differential displacements.
Pressure Relief Valve Actuation (Transformers)	**Main**	3 (3.11 earthquake)	C	The part of transformers for all three units experienced oil pressure relief valve actuations due to sloshing of insulating oil in the transformer tanks.
		3 (4.7 aftershock)		
	Startup	2 (3.11 earthquake)		
		1 (4.7 aftershock)		
	House	1 (3.11 earthquake)		
		3 (4.7 aftershock)		
	Auxiliary boiler	1 (3.11 earthquake)		
	Exciter	1 (4.7 aftershock)		
Transformer Radiator Leak (Startup Transformers)		1	C	Leaks in transformer radiators are common in earthquakes, but usually at the flange connections that supported the

			cantilevered radiator mass.
Partial Burnout (Lightning Arrestors)	2	C	Partially burnout occurred in two over-current surge (lightening) arrestors in the sulfur-hexafluoride (SF-6) switchgear on the 275-kilovolt lines.
Over-Current Burnout	1	C	The damages high voltage breakers were known as seismic bad actors and planned to be replaced.
Fuse Burnout (120V AC Circuit)	1	C	A fuse burned out in a main control panel of Unit 1 in the 120 volt AC circuit supplying a signal converter for the level sensing system of the Unit 1 boron tank.
Toppled Equipment (CRT Programmable Logic Controller Module)	2	C	Only two instances of toppling of unanchored components are mentioned in the damage report, although toppling fixtures surely occurred elsewhere.
Indication Failure (Refuelling Floor Radiation Monitoring system)	1	C	Damage to the strip chart recorder in the Unit 3 main control panel appears to be the only instance of direct shaking damage to a control system.
Bend of Latches (Reactor Shield Wall Hatches) and Dislodgement of Plugs (Concrete Shield)	5	C	Bent locking and latching mechanisms appear to illustrate the intensity of shaking again.
Buried Pipe Damage (Fire Protection Pipe)	1	C	Pipe failure was found in a section of buried fire protection pipe in Unit 1.
Dislocation in supporting device against an accident	3	C	The earthquake induced dislocation of the arranged supporting devices beneath the control rod drives, but still it maintained its original function.
Sloshing Trips	3	B	In all cases sloshing caused the tripped of the fuel pool cooling & demineralizing pumps. The operators could restart the pumps within the sufficient time margin because they grasped that the trend of the spent fuel pool temperatures did not immediately boost up by monitoring its

			temperatures at the main control rooms.
Miscellaneous	7	C	Several radiation monitors lost signal.

7.8 Review of Tsunami Impact

The Onagawa NPS was subject to a 13.6 m tsunami wave. The tsunami protection due to the plants chosen elevation of 14.8 m was a key to the performance of the plant during the March-11 event. The first tsunami arrived to the NPS site at 15:21, 35 minutes after the earthquake, flooded the concrete pits containing the traveling screens for all three units see Figure 7-31.

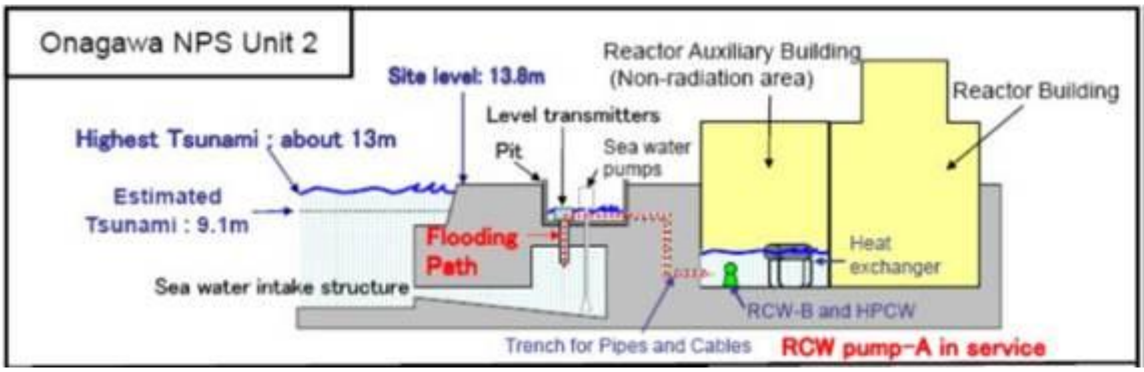

Figure 7-31 Sea water intake structure and sea water pump pit

The height of the tsunami tide created a positive pressure within the intake canal underneath the floor slab of Unit 2 seawater pump pit, forcing water into the intake canal ultrasonic water level sensor containers. Tsunami also caused inundation of the Unit 3 turbine seawater pump room through the opening of the intake canal. Water contact with the circuitry of the water level sensors automatically tripped the large circulating water pumps for the main condensers.

Time Line:
11 of March 2011
14:46 the earthquake
15:21 the tsunami arrives
15:22 the CWP trip on low level (shortage in the transmitters)
15:25 the SWSD in the RCW-B room trip
15:29 the SWSD in the HPCW room trip
15:34 the RCW-B trip
15:40 the NSD in the elevator room starts to drain the RSW-A trench
15:40 the SWSD in the RCW-A room starts to drain the RSW-A trench
15:41 the HPCW trip
15:45 the NSD trip due to flooding of the elevator room containing the pump pit

The removal of water in the RSW-A trench is now significantly smaller in 12 min (15:29 to 15:41). The water level in the HPCW room has risen more than 1 meter and at 1.5 m the cable trays start to leak from the HPCW room in to the RCW-A room.
16:50 the SWSD trip due to flooding of the RCW-A room
20:00 temporary pumps are placed in the stairwell to drain the basement
20:00 the RSW-B pump pit is inspected and empty
24:00 temporary pumps are placed in the far corner of the RCW-A
14 of March the door between the stairwell room and the HPCW room was opened
16 of March all water was removed 16 of March the door in to the RCW-B room was opened
16 of March inspection of "high water level mark uncured"

7.8.1 Flood at Unit *2*

In Unit 2 the ultrasonic wet well water level sensors had been installed in the pit of the reactor closed cooling seawater system (RSW) for Train B. The positive pressure in the intake canal blew open the steel containers for the water level sensors mounted on the pump pit floor. Water from the pressurized intake canal surged through the level sensor containers which penetrated the pump pit floor. Flooding in the Train B RSW pit eventually reached a level lower than RSW pumps' driving motors. The flooding seawater got through the train B trench, where pipes and cables were installed, connecting reactor building auxiliary area to seawater pump pit. The path of the flooding at Unit 2 could be seen onFigure 7-32.

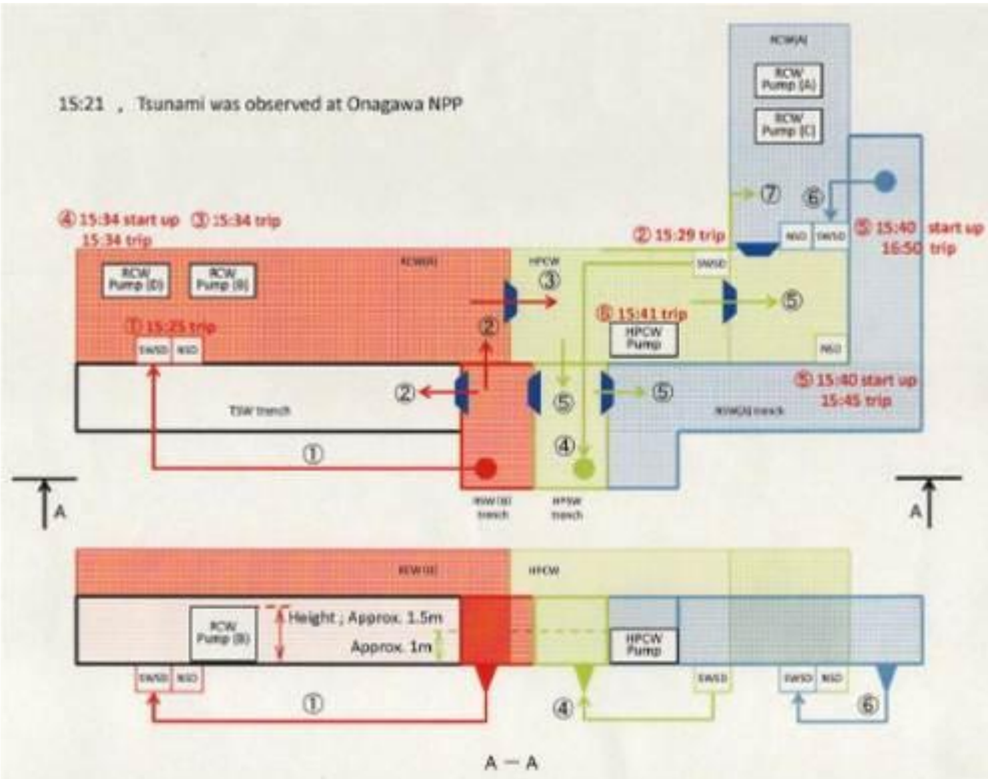

Figure 7-32 Path of the flooding at Unit 2

Water flooding the Unit 2 Train B RSW pit propagated through the pipe and cable tray trench to the reactor building auxiliary area basement. Thus the train B reactor building closed cooling water (RCW) Hx and pump room and the high pressure core spray cooling water (HPCW) Hx and pump room were inundated up to 2.5m over the floor. Train B of the RCW system cools Train B of the residual heat removal (RHR) system for the Unit 2 reactor, and also cools one of the two diesel generators supplying the 6.9 kV emergency power bus. The HPCW system cools the diesel dedicated to emergency power for the Unit 2 high pressure core spray (HPCS). Flooding of the Train B RCW pumps and the HPCW pumps therefore caused shutdown of one of the three emergency diesels, including HPCS diesel, for Unit 2. For the shutdown operation of unit 2, external electricity from one transmission line was used, and there are tied lines among emergency buses with the other units but unused. The train A diesel generator for Unit 2 was only operating on standby as the unit continued to be supplied with electricity through the off-site grid. Thus loss of the two diesels therefore did not affect operating AC power for Unit 2. It should also be noted that emergency power to Unit 2 could be supplied from the Unit 1 and 3 diesels by closing an intertie breaker between the units' 6.9 kV buses.

The water penetrated the seawater level transmitter boxes are presented in Figure 7-33.

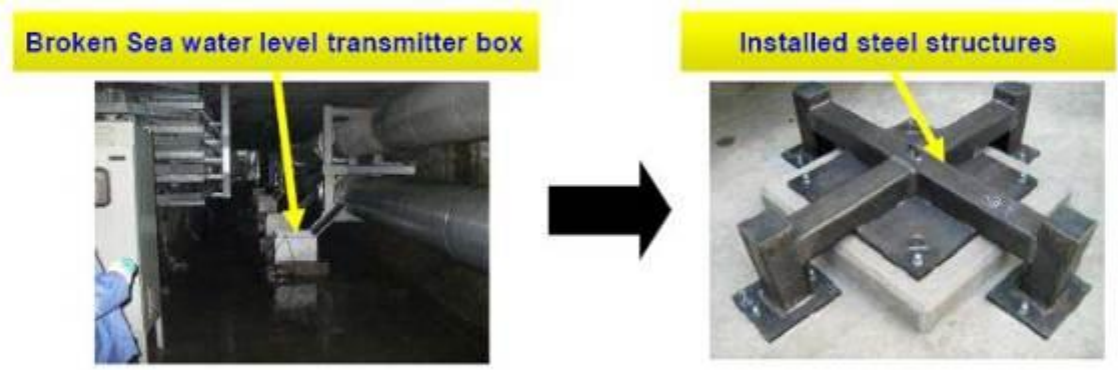

Figure 7-33 Broken sea water level transmitter box and the new type of transmitter box lid at Unit 2

During the construction of Unit 3 a new requirement on measurement on water level in the seawater intake structure were passed by the regulator. The purpose was to conserve water in the intake structure for the safety system due to shut down the CWP. To fulfill the new requirements unit 1 and 2 were forced to back fit this installation. One ultrasonic water level measurement point was installed in each intake tunnel. At the end the intake structure is divided in to 6 tunnels. At unit 1 and 3 these installations were made in the pit containing the traveling screens. Due to lack of space in the pit for the traveling screens at unit 2 the installation was made together with the S class equipment of RSW train B, shown in Figure 7-34.

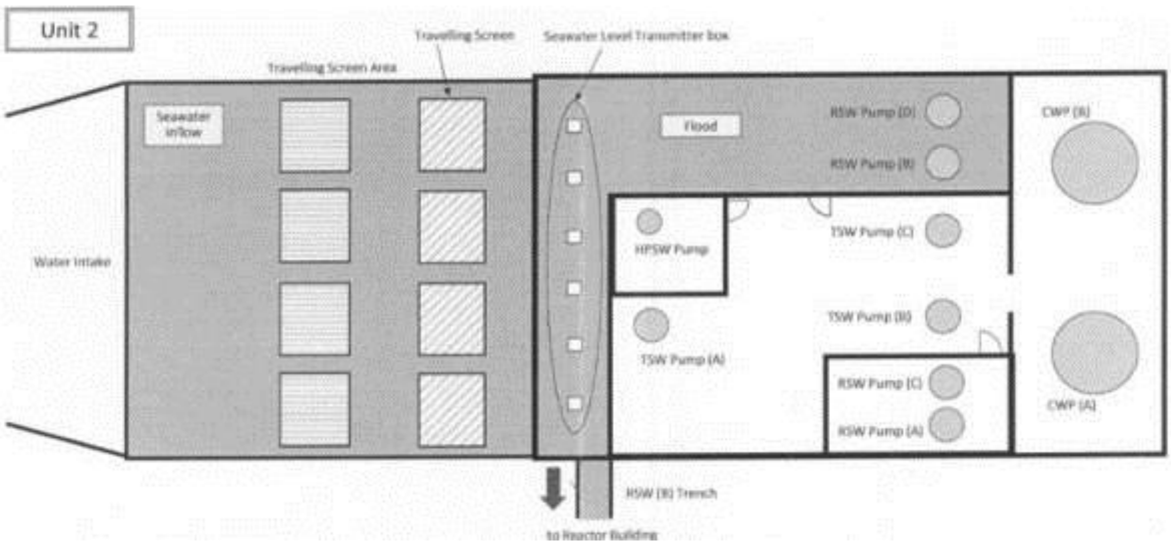

Figure 7-34 Seawater intake pits for Unit 2

There are penetrations in the wall for the RSW piping and cable trays approximately 1.5 m above the floor. The water traveled through the pipe penetration and cable penetrations in the wall into the RSW (B) trench. These penetrations had a 10 cm gap around the pipe that was a free flow path. In the RSW trench there are sump drains to remove water. This drain is connected to a sump pump located in the RSW room. The hydrostatic pressure and amount of water quickly overwhelmed the sump pump and the sump pit filled up. High level alarms are installed and pump shutoffs are set at approximately 10 cm above the bottom of the sump pits. When the water level reached the high level alarm the sump pumps shut down. Upon inspection after the flooding, the resin sealing of the RSW pipe penetration of the wall into the reactor building was damaged and bent inwards further increasing the area of the flow path see **Figure 7-35.**

Figure 7-35 Pipe penetration from the RSW pit to the RSW trench
The resin sealant (dark gray rings between wall penetrations and RSW pipes) is installed after March 11 Tsunami at Unit 2.

In 9 minutes the water level reached level of 1 m above the floor of the basement where the RCW pumps are located. Despite the water tight door, the water propagated to adjacent room, containing the HPCW. The HPCW rooms sump pumps were shut off on high water level indication. The high water level indication was reached in 4 minutes, after that the sump pumps in the RCW shut down and 5 min before the RCW located at an elevation of 1.5 m above the floor tripped. The door is a vault type with a neoprene lip that a steal rim is supposed to cut into, see Figure 7-36**.** The plant staff stated that the door was closed at the inspection they conducted 5 days later, when they removed enough water the doors where still closed. They also stated that they needed to adjust the tightness of the door after the event.

Figure 7-36 Water Tight Door in Seawater Pump Pit (left) and in RCW HX Room (middle and right) at Unit 2

This event has proven an inadequate function of a type of watertight door. Both watertight door types only works as watertight in one direction (closing direction), see Figure 7-36**.** The red door is only for people and the green is a double door with a small door in the center for people (orange coloured on the surface to open) and a big frame about 4x4 m or more for components so it has longer insulation that could leak. The sump drains system piping was also a contributor to the flooding propagated between different rooms and trenches.

From the HPCW the water continued and penetrated through another watertight door and tripped a third sump pump in the room containing the elevator and staircase. From the HPCW room there are pipe penetrations of the wall to the HPCW trench. The rubber sealing of the penetrations were pushed out into the trench making it clear the direction of the water flow.

The flooding of the elevator area occurred with the same penetration of a second watertight vault type door connecting to the RCW-A room.

The water level reduced at the same rate in all 3 rooms, RCW-B, HPCW and the staircase when the water was pumped up through the staircase.

The RCW-A room, there are 3 ways for water in to the RCW-A room from the flooded areas. The first is through "green" watertight door that was working as intended to keep the water from an external flooding out. The sump drain in the RSW-A trench is connected to the sump pit in the RSW-A room. The final way is a cable path from the HPSW room located at an elevation of about 1.5 m. If the water level would have reached over 1 m the trip in the RCW-A pump will occur. The operators detected the flood in RCW-A rooms and they bring portable pumps to keep the water level low. Fortunately AC offsite power was available and that one of the two RCW/RHR trains continued to function.

7.8.2 Flood at Unit 1

At Unit 1 the pit containing traveling screens (the dust screen pit) is submerged. The water flowed through 4 large openings in the pit floor. In Figure 7-37 areas displayed as grey were submerged. The CWP tripped due to the shutdown of startup transformer for unit 1. The CWP could later not be utilized due to loss of offsite power and the shortages in the ultrasonic water level measurement system.

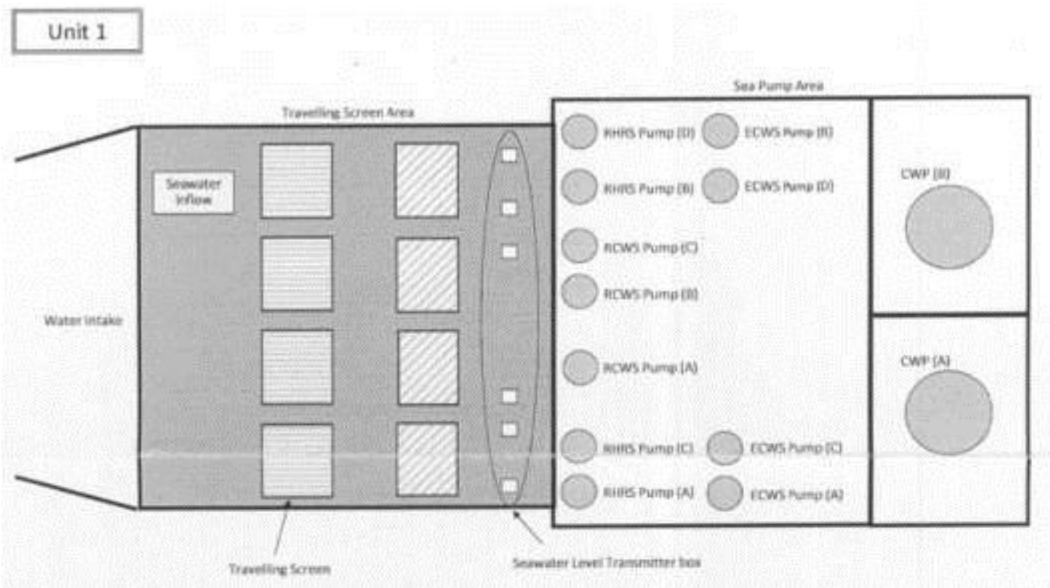

Figure 7-37 Seawater intake pits for Unit 1

7.8.3 Flood at Unit 3

At Unit 3 the pit containing traveling screens is submerged. The water flowed through 4 large openings in the pit floor, see Figure 7-38. A pit containing the TSW Pump A, B, C was submerged due to an opening. The TSW is a seawater side of turbine cooling components vital for balance of the plant. None of the flooded areas was critical for nuclear safety. In Figure 7-38 areas displayed as grey are submerged. The CWP tripped due to the flooding of the water level measuring in the travelling screen area. The short circuit created a permanent low level alarm preventing the CWP pumps from starting. The CWP could not be restarted due to a second reason since the TSW pumps that supply the cooling for the CWP were submerged and shorted.

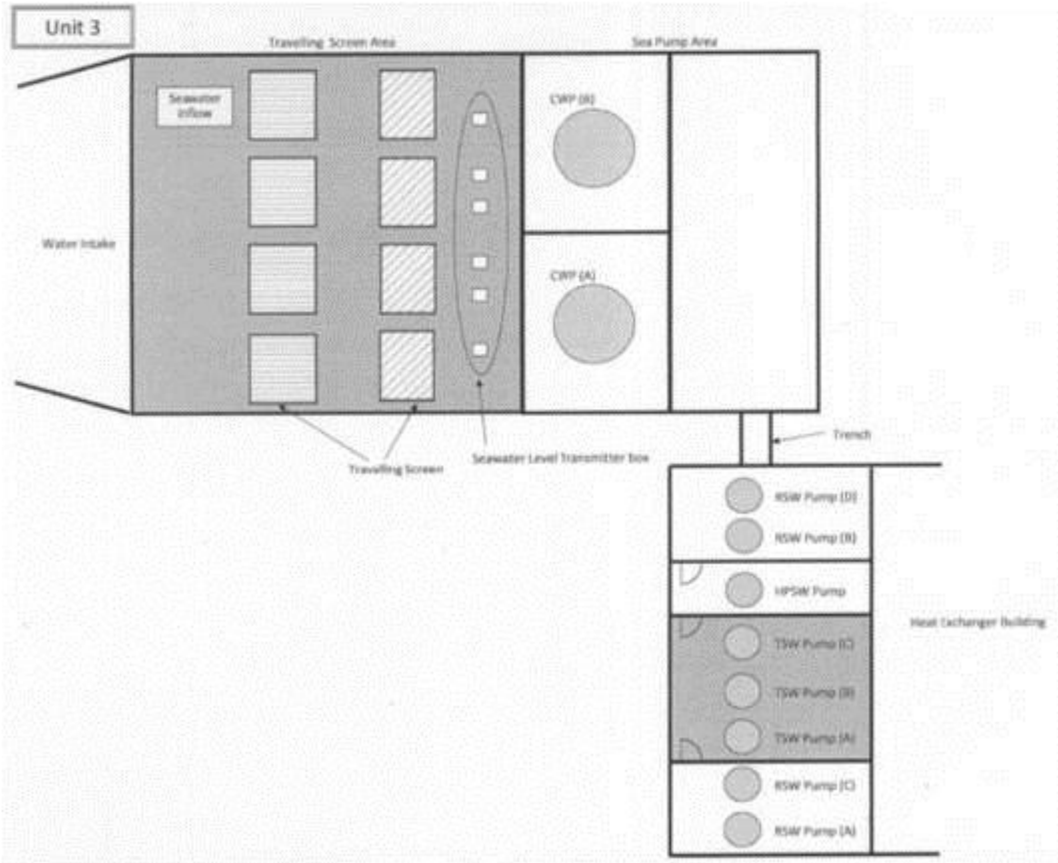

Figure 7-38 Seawater intake pits for unit 3

This meant that neither Unit 1 nor 3 could use the normal system for core cooling to reach a cooled shut down. Both units utilized manual start of the RCIC system followed by reactor vessel depressurization and operation of the RHR.

7.8.4 Tsunami Induced Flood Summary

The tsunami induced flooding created a common cause incident affecting redundant systems and degrading the RHR (safety related) demanded at that time to remove the decay heat. The potential temporary loss of the ultimate heat sink was possible with only one RHR train operable on Unit 2. This unit was undergoing startup and the reactor was not yet critical, which meant the post-shutdown cooling requirements for the decay heat removal were modest.

7.9 Summary of Findings of damage

The following sections present a summary of the primary observations of effects to the Onagawa NPS from the March 11, 2011 earthquake. Findings are presented more-or-less in their order of importance. The discussion does not include all effects observed at the plant, but only those of greater significance to safety or loss to the plant from earthquake damage (repair cost and down time).

7.9.1 Earthquake Damage to Systems

Based on the Systems Team inspections of the three units, there were no identified system failures affecting safety functions due to the earthquake. The plants were safely shutdown despite the loss of receiving offsite power directly to one unit. Only minor damage was identified on non-safety systems. The seismic design robustness seems to be significant as indicated by limited evidence of damage to Class B and Class C systems given their lower seismic design requirements.

The most significant damage to equipment due to earthquake shaking (as opposed to flood) was the failure in the 6.9 kV switchgear. It appears that a vertically-racked circuit breaker in the non-safety-related turbine building switchgear caused a short circuit and a subsequent arc due to rocking of the breaker and fracture of the insulation around the bus clamps at top (refer to illustration in the section discussing the 61 documented effects on plant systems and equipment). The short circuit arc burnt the switchgear, consuming three or four adjacent cabinets. The burnt damage in the switchgear eliminated one of two 6.9 kV buses (common conductor) in the Unit 1 turbine building. The power surge induced by the shortcut triggered the protection of the start-up transformer ending to loss of directly receiving offsite power. This shut down a portion of the non-safety-related balance-of-plant equipment. However most of the turbine building equipment that subsequently lost power would likely not be required to operate once the unit is shut down.

Had the same damage occurred in the 6.9 kV switchgear serving safety-related systems in the reactor building, one train of safety systems might have been lost. Damage in the breaker appears to have been exacerbated by the fact that it is essentially a cantilevered mass primarily restrained from rocking by its bus connections at the top. Switchgear supplying safety trains in the plant are the more seismic proven horizontally-racked breakers, where bus connections are at the rear of the breaker and the breaker mass is supported on the horizontal rails of the cabinet bolted on channel base welded on metal plates anchored steel bar reinforced concrete floor.

The primary effect of the breaker damage was to trip of the Unit 1 startup transformer. Thus the effect of the breaker damage was to require Unit 1 emergency diesel generators to supply station power.

The most expensive damage to repair was probably the worn blades, the bolt bend and sole plate deformation of thrust bearings between the high pressure and low pressure steam turbine A of Unit 2 and 3. Unit 3 was operating at the time of the earthquake with its turbines at 1500 rpm. Because the broadened gaps between the low pressure turbine blades and the surrounding static nozzles were estimated to reduce turbine efficiency, the counterpart said to decide its replacement of the Stage 9-15 blades in the low pressure turbines. The thrust bearings between the high pressure turbine and the low pressure turbine A were shipped to the factory to renovate on Unit 2 & 3. The force of the spinning turbine shifting against its bearings during the earthquake was indicated by stretched bolts, bent base-plate and spalled concrete around the bearing housing between the high pressure turbine and low pressure turbine A. Similar damage to a lesser extent was noted in the Unit 2 steam turbine, which was spinning on startup 10 rpm at the time of the earthquake. The steam turbine for Unit 1 may or may not have suffered similar damage, as detailed inspection of the unit has been postponed.

Damage to the steam turbines, apparently due to shifting of the spinning rotor, contact with the static periphery and overload of the bearing bolts, has also been observed in other NPS However Onagawa NPS appears to have experienced shaking intensity well above the level observed in any power plant in the past. The shaking intensity may have been a factor in damage to spinning steam turbines, pushing them over their threshold of damage.

In addition to the burn-out of the 6.9 kV switchgear outlined above**,** there were less significant instances of burn-out apparently due to over-currents as outlined below:

- The 275 kV surge arrestors partially burned out in the gas-insulated switchgear controlling the connections of the Oshika Lines 1 and 2. Surge arrestor burn-out apparently occurred due to insulation gap reduction caused by sway of lightning arrestors connected to the two Oshika lines. Ground faults tripped circuit breakers or burned protective fuses in 125-volt DC distribution panels in all three units. Reportedly the ground faults were due to contact with sea water of exposed conductor in the DC circuits in the intake structure or in the nearby flooded pump rooms. Apparently loss of DC power through the tripped beakers or opened fuses did not affect any safety-related system.

- A fuse was reported as burned out in the 120-volt AC power supply to the level sensing system in the Unit 1 boron tank. The cause of the fuse burn-out was not determined.

7.9.2 Systems Interactions

There were several examples of systems interaction in earthquake effects to the three units. There was no effect on shutdown of the reactors, so the interactions are noted simply as occurrences rather than actual problems. Observed system interactions are outlined as follows:

- Sloshing of water in the surge section of the spent fuel pools of all three units tripped a low water level switch, shutting off the spent fuel pool cooling system pumps. The pump shutoff was noticed several hours after the earthquake and the pumps were restarted. Spent fuel pool temperature reportedly did not significantly increase during the time the pumps were shut down.

- Due to the ground fault of ultrasonic sensors caused by flooding in train B RSW pump pit for unit 2 and seawater dust screen pit for unit 3 respectively, the main condenser circulating water pumps (CWPs) were automatically shut down. Shutdown of the circulating water pumps shortly after arrival of the first tsunami was reported in Unit 2 and Unit 3.

- Sloshing of water in the suppression pool of Unit 3 apparently activated a pressure switch that in turn activated a motor-operated valve on the suction line of the high pressure core spray (HPCS) pump. The HPCS pump itself was not started. The motor operator reportedly stopped with the valve about 80% open. Apparently power supply to the motor operator can be opened and closed by the suppression pool pressure switch, thus the momentary pressure surge due to pool sloshing was sufficient to activate the valve.

- The part of oil insulated transformers for all three units(main & house transformers for all three units, startup transformers for Unit 1 & 2 except Unit 3, auxiliary boiler and exciter transformers for Unit 2 except Unit 3) reportedly opened their pressure relief valves due to sloshing of insulating oil. Transformer pressure relief actuation did not affect operation of the startup transformers for Unit 1 & 2 and auxiliary boiler transformer for Unit 2, as these transformers had enough insulating oil in the tanks to perform their function for connecting the lines following the earthquake. Activation of pressure relief valves or over-pressure relays in oil-filled transformers is a common effect in past earthquakes.

- A false indication in the Unit 1 control room was received due to apparent slight movement of the close-side detecting switch on the actuator piston of the main steam safety relief valve. The valve position indicator in the control room read both open and closed for the valve. Apparently vertical motion of the piston moved the attached valve position switch in lower direction. It is clear that the movement of the actuator piston occurred due to upward inertia of the actuator. Because pressure fluctuations in the actuator, as the alternate considerable cause, would move the actuator piston upward only, it might not push the switch downward. The valve in fact remained closed after the activations due to high pressure right after the reactor trip caused by the earthquake so the effect was simply a miss-indication in the control room rather than an inadvertent actuation of the pressure relief valve.

7.9.3 Seismic Interactions

Seismic interaction normally implies impact on safety-related equipment by falling fixtures or by unanchored adjacent fixtures. There were no instances of damage to safety-related equipment in any of the three units of the Onagawa plant due to seismic interaction. Notable instances of seismic interaction were in fact remarkably few. This would be partly due to the general practice of anchoring most fixtures within the plant and eliminating superfluous fixtures not necessary for plant operation (attention to housekeeping). Instances of seismic interaction are outlined as follows:

- Approximately one-third of suspended ceiling fixtures fell in the three main control rooms. Fallen fixtures included the covers over fluorescent lights supported on the ceiling steel framing and the fluorescent tubes themselves. There was no damage to the control panels or operator injury and no effect on plant operation.

- Unanchored CRT monitors toppled from the Unit 2 main control panel and fell down from a rack in the control panel at mezzanine 5th floor in Unit 1 reactor building for refueling machine. Additional unanchored fixtures such as books and binders were reported to have fallen from shelves and tables, although again these effects were too trivial for individual notation.

- The earthquake induced dislocation of the arranged supporting devices beneath the control rod drives, but still it maintained its original function. The devices called control rod drive housing support made of steel bars and plates is to be used on the occasion of CRD drop-down accident. It limits the dropping height of a control rod connected with its drive in order to assure the induced reactivity at the accident. The supporting device contains grid steel structure which will contact with flange of a dropped down CRD drive on the occasion. The grids are suspended on spring-mounted rods from the structural steel above. After the earthquake these devices maintained its structure so the counterpart confirmed the device function.

7.9.4 Retention of Pressure Boundary & Interconnections

Despite the very large exposure of pressurized pipe, tanks and vessels at the plant, only one instance of pipe failure was noted. A buried fire water line for unit 1 failed between the foam fire extinguishing system's tank and the nearest outlet from a building, likely due to the extensive soil settlement observed around the site. The majority of piping routed around the site is carried in sub-grade trench, only fire water lines are buried in the ground. Trench-routed pipe would have the same generally good earthquake performance record of above-ground piping. No failures of exposed (above-ground) piping were reported anywhere in the plant. However it should be noted that pressure testing of all piping within the plant has not been performed because it was confirmed that all systems except Unit 1 foam fire extinguishing system shown above kept each operating pressure without apparent loss of system's medium, such as water, oil, or acid.

Similarly no breaches were reported in tanks or vessels either pressurized or un-pressurized. The one exception was the heavy oil storage tank located on the bay side of the flood wall that was carried away by the tsunami. Here again not all pressure vessels have been tested since the earthquake, because plant operators, maintenance and maker engineers had performed post-earthquake walk-down and confirmed that there was no indication of leakage, and operators' daily parameter confirmation endorsed no leakage from any tanks at all according to level trends.

Except for a few minor instances conductivity was retained in cable and wiring for power supply and instrumentation. There were no instances noted of damage to cable tray or conduit in the plant. Loss of conductivity appeared limited to a few instances of over-current burn-outs due to ground faults as discussed in the previous sections.

7.10 Seismic Experience Data Collection

Based on information describing the Onagawa NPS design basis, interviews with operators and plant technical staff, together with information obtaining from initial processing of seismic instrumental records complemented with walkdowns observations, all together provides the basis for evaluation of seismic performance of selected SSCs addressed during this mission. It should be noted that the 40 seismic data sheets presented in Appendix IX represent a small percentage of the equipment installations contained within the three Onagawa units.

For illustrating typical mechanical, electrical and electronic equipment in the three unit Onagawa power plant and their seismic performance, 40 data sets are presented in Appendix IX. Each data set illustrates a single equipment item or a group of more-or-less identical equipment items that survived the March 11 earthquake and the major April 7 aftershock. The intent is to present representative details on the “exposure” of typical BWR equipment installations subjected to extreme shaking.

In effect the March 11 and April 7 earthquakes were very much like shake table tests. Strong motion records on base mats and upper floors of the three reactor buildings range from 0.38g to 1.9g peak floor acceleration as an average of horizontal directions for the March 11 event. This range of shaking intensity is typical of shake table testing of large equipment for seismic qualification. Although motion was not recorded directly on the equipment base, records were usually within a reasonable distance of the equipment location. The general consistency of the measured motion for some 40 separate recordings within buildings and in the site free field, indicate that the nearest record is a reasonable estimate of the actual motion experienced by the equipment.

The earthquake exposure for equipment in Onagawa presents a certain advantage over conventional shake table testing. All three units were in some stage of operation at the time of the March 11 event, with Units 1 and 3 on line and Unit 2 in start-up. This means that most of the equipment exposed to the earthquake was operating under its normal functional loads. Depending on the type of equipment this would mean operating fluid pressure and temperature for mechanical systems, operating current and voltage for electrical and electronic equipment, and spinning loads for rotating machinery. Furthermore equipment forms the components of systems, thus incurring exposure to earthquake-induced system interaction. As described in the separate section on earthquake effects, most damage or malfunctions observed in the March 11 earthquake were system interaction effects. Examples include electrical burn-out or circuit breaker trip, and sloshing-induced switch actuations. In general shake table tests include only a small portion (if any) exposure to system interaction, such as current surge, pressure surge, shaking-induced malfunctions or seismic interaction (falling fixtures). Full representation of the potential for system interaction effects requires an entire operating plant to be subjected to an earthquake.

Each data set in the appendix presents:

- Photos of the equipment or examples from a group of more-or-less identical items
- The equipment location and the nearest strong motion record with measured peak acceleration and cumulative absolute velocity (CAV)

- A general description of the item indicating the size, mass and operating capacity, plus the attachment to the building structure (anchorage)
- The known or apparent operating condition of the equipment at the time of the earthquake
- The basis for assuming the equipment remained operable following the earthquake
- The IAEA investigation team members who collected the details on the equipment to allow for follow-up questions at a later date.

The basis for assuming that the equipment was undamaged and operable after the earthquake is of course particularly important. Instances of significant damage or malfunction in equipment were provided by Tohoku EPCo management, including some 61 notations of significant earthquake effects. Actually only six equipment items were damaged to the point of rendering their system inoperable, specifically one 6.9 kV switchgear assembly, two steam turbines, one fuse in the boron tank level monitoring system, one strip chart record in a radiation monitoring system, and a disabled overhead bridge crane due to wheel bearing damage. Given that the earthquake exposed thousands of items of equipment to severe shaking within the three units, this appears to be a remarkable rate of survival. However it should be noted that while equipment is generally the same as standard industrial fixtures, the installation in the Onagawa plant in terms of bracing and anchorage undoubtedly improved the chances of earthquake survival.

The equipment items selected for illustrative data sets focused on systems that operated through the earthquake, or were otherwise verified as operable after. A few data sets include equipment that appears undamaged, but for which there is no documented record that post-earthquake-operability has been confirmed. Because the three units have not resumed operation since the March 11 earthquake, a large portion of equipment in the plant, while apparently undamaged, has not been proven to be operable. For example most pipe and pressure vessels have not been tested at full operating pressure and temperature.

While it is very likely that equipment showing no obvious signs of damage is in fact operable, post-earthquake operability can only be assumed for equipment that operated through the event and preferably for some time thereafter.

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