Working together to enhance nuclear reactor safety

Information from examinations at the affected reactors at Fukushima Daiichi is being used to enhance reactor safety in U.S. operating plants, plants under construction, and future nuclear power plants.

By Damian Peko, Sudhamay Basu, Steven Kraft, Shinya Mizokami, and Joy Rempe

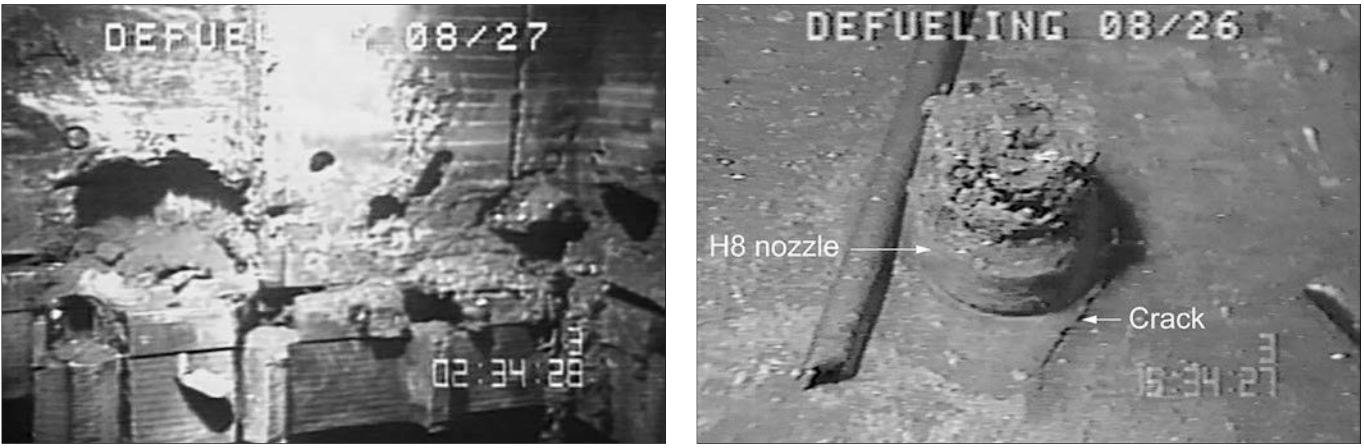
International nuclear safety and operations experts are cooperating to improve nuclear safety by using the information gathered from the March 11, 2011, accident at the Fukushima Daiichi nuclear power station. The objective is to reduce uncertainties in accident modeling and to improve and confirm the adequacy of accident mitigation strategies. During the seven years since the accident, investigations have been conducted by Tokyo Electric Power Company Holdings Incorporated (Tepco) to facilitate decommissioning efforts. Unique robots and specialized systems capture visual images, conduct radiological surveys, and obtain samples. New images suggest that relocation of fuel may have induced failure of the reactor pressure vessels (RPV) and allowed core material to relocate into the containments. This new evidence, along with previously obtained information, provides unique insights that are difficult, if not impossible, to obtain in a laboratory setting.

Background

Information acquired from investigations at Three Mile Island-2 after the March 28, 1979, accident [1] benefited the global nuclear community by enhancing nuclear safety worldwide. The information, which was obtained from plant instrumentation data, separate effects testing, and analytical evaluations, provided a basis for incorporating changes in plant equipment and systems and for improving operator training and emergency response procedures. Post-accident examinations were also key to successful fuel removal at TMI-2. Radiation surveys, water and gas sampling, and ultrasonic techniques were initially used to infer the state of the reactor.

Expert opinion differed about the extent of core damage until 1982, when a camera inserted into the reactor vessel revealed that nearly half of the fuel had been damaged and relocated from its initial core location. Subsequent examinations, including evaluations of relocated fuel and structural materials, and more detailed photographic images, such as those shown in Fig. 1, were used to determine the extent to which core material had relocated and the damage to structures within the vessel. This allowed defueling efforts to focus on developing and deploying the needed technologies to ensure that activities could be successfully completed in a timely fashion. Ultimately, TMI-2 examination data benefited the global nuclear community.

Using state-of-the-art technologies that were not available at the time of the TMI-2 defueling efforts, examinations are under way at Fukushima Daiichi. These boiling water reactors contain three main barriers to prevent radioactivity release: the fuel cladding, the RPV, and the primary containment vessel (PCV). Specialized systems and components have been developed and deployed to obtain information about the end state of debris within Units 1, 2, and 3, and current data suggest that high-temperature fuel may have relocated from the core area to regions near the bottom of, and possibly beneath, the reactor



Photos: FirstEnergy

Fig. 1. TMI-2 video examinations revealed locations where damage to the core barrel (left) and nozzles (right) was more severe.

Damian Peko is a Technical Advisor for the U.S. Department of Energy's Office of Nuclear Energy. Sudhamay Basu is retired from the U.S. Nuclear Regulatory Commission's Office of Nuclear Regulatory Research. Steven Kraft is Senior Technical Advisor for the Nuclear Energy Institute. Shinya Mizokami is a Manager at Tokyo Electric Power Company Holdings Incorporated. Joy Rempe (<jlrempe@cableone.net>) is the Principal of Rempe and Associates LLC.

vessel. Additional information, however, is required to estimate the mass of fuel material that exited the reactor vessel and to identify and develop the appropriate techniques for successful and safe debris retrieval from the plant. This forensic information is also being used by the nuclear industry, governments, and academia to enhance reactor safety.

The approach

Recognizing the unique opportunity offered by the Fukushima Daiichi investigations, the U.S. Department of Energy in 2014 formed a team of reactor safety and plant operations experts from the United States and Japan to complete the following objectives [2,3]:

1. Develop a consensus on U.S. input for high-priority time-sequenced examination tasks and supporting research activities that can be completed with minimal disruption of ongoing decontamination and decommissioning (D&D) plans for Fukushima Daiichi. An important aspect of this U.S. effort is to not adversely affect D&D road map activities on the schedule developed by the government of Japan [4].
2. Evaluate the information obtained to gain a better understanding of the events that occurred in each unit at Fukushima Daiichi; gain insights for reducing uncertainties related to predicting accident progression; gain insights related to extended equipment performance under accident conditions; provide insights beneficial to D&D activities; confirm and improve guidance for accident prevention and mitigation and emergency planning; and update and/or refine Objective 1 information requests.

Approximately 40 experts from industry, universities, and national laboratories are participating in this process, along with representatives from the U.S. Nuclear Regulatory Commission, the DOE, and Tepco. Evaluations focus on the available information from sources such as the Tepco website [5] and presentations and reports from Tepco documenting unconfirmed and unsolved issues [6–10]. Experts regularly review available evidence from several sources, including radiation surveys and sampling, data from plant instrumentation, visual images, and results of analytical evaluations.

Example results

Two examples demonstrate how insights from examinations are used to enhance nuclear power plant safety. (Additional examples can be found in references 2, 11, and 12.)

Example 1: Component and system performance

Results from examinations are of interest in assessing component and system performance during severe accidents. Of special interest in initial examinations are visual images such as pictures and videos, dose surveys, water-level measurements, water sample isotopic composition evaluations, and temperature information. Identifying leakage locations, leakage timing, and the conditions causing this leakage are of special interest because of industry efforts to update guidance provided to plant operators to prevent and mitigate severe accidents. Thus, an important aspect is to focus on identifying information that provides insights related to peak PCV temperatures and pressures that exceeded the design limits and led to radioactive material leakage from the containment.

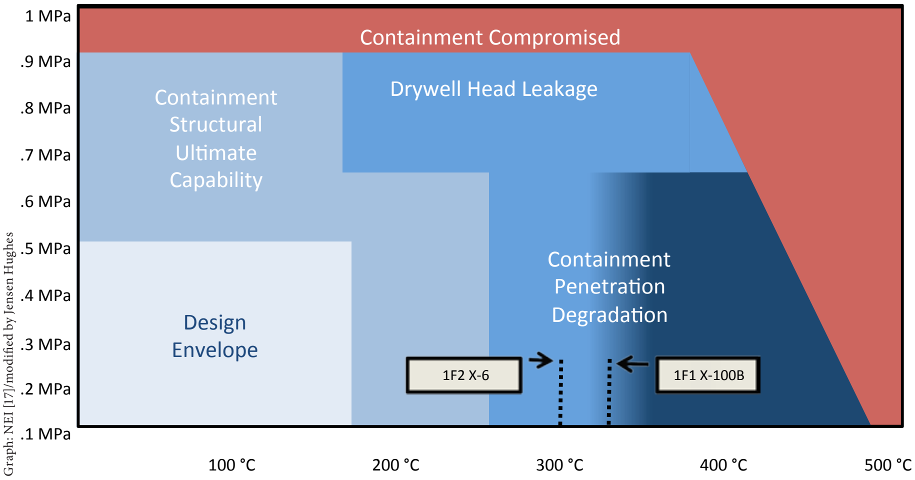
Evaluations have identified notable differences in the degradation of components within Units 1, 2, and 3. Possible causes for these differences include variations in unit designs, availability/functionality of backup cooling systems, the ability to externally inject water during the accident, the ability to vent the primary system and containment during the accident, and differences in combustible gas effects at each unit. Available information highlights different leakage points and the possibility for multiple leakage points within the PCV.

Visual observations and dose measurements suggest that the PCV drywell heads of Units 1, 2, and 3 leaked during the accident. Calculations performed with systems-level codes [13,14] predict leakage at the PCV drywell heads due to high containment temperatures and pressures [15,16]. Localized containment failures at other penetrations, however, are not typically modeled by these codes. Observations from these three units indicate that additional penetrations/piping failures occurred and need to be considered in the systems analysis codes, including the impact of the locations and sizes of such failures.

The potential for multiple penetrations to fail due to seal degradation also affects accident management strategies developed by industry. Updated Boiling Water Reactor Owners Group (BWROG) and Pressurized Water Reactor Owners Group (PWROG) accident management guidelines place a high priority on maintaining containment water levels, pressures, and temperatures at conditions that enhance radionuclide retention. For BWRs, this includes reducing containment pressures during periods leading up to fuel damage by anticipatory venting well before pressures and temperatures reach values where the containment would be compromised by severe-accident conditions. Anticipatory venting prior to fuel damage enhances containment performance when it is needed.

Continued

Figure 2 shows typical peak containment temperature and pressure information on a figure provided in NEI 13-02 [17] industry guidance for BWR venting. The seal on the drywell head is assumed to start degrading at a temperature of 285 °C (545 °F), based on engineering evaluations and testing information in the literature. The black dashed lines in Fig. 2 correspond to peak temperatures inferred from available information related to the X-100B penetration in Unit 1 and the X-6 penetration in Unit 2. These values are consistent with the values assumed to cause degradation in NEI 13-02. Thus, available Fukushima Daiichi information supports the revised industry guidance recommending that operators maintain containments at low pressure.



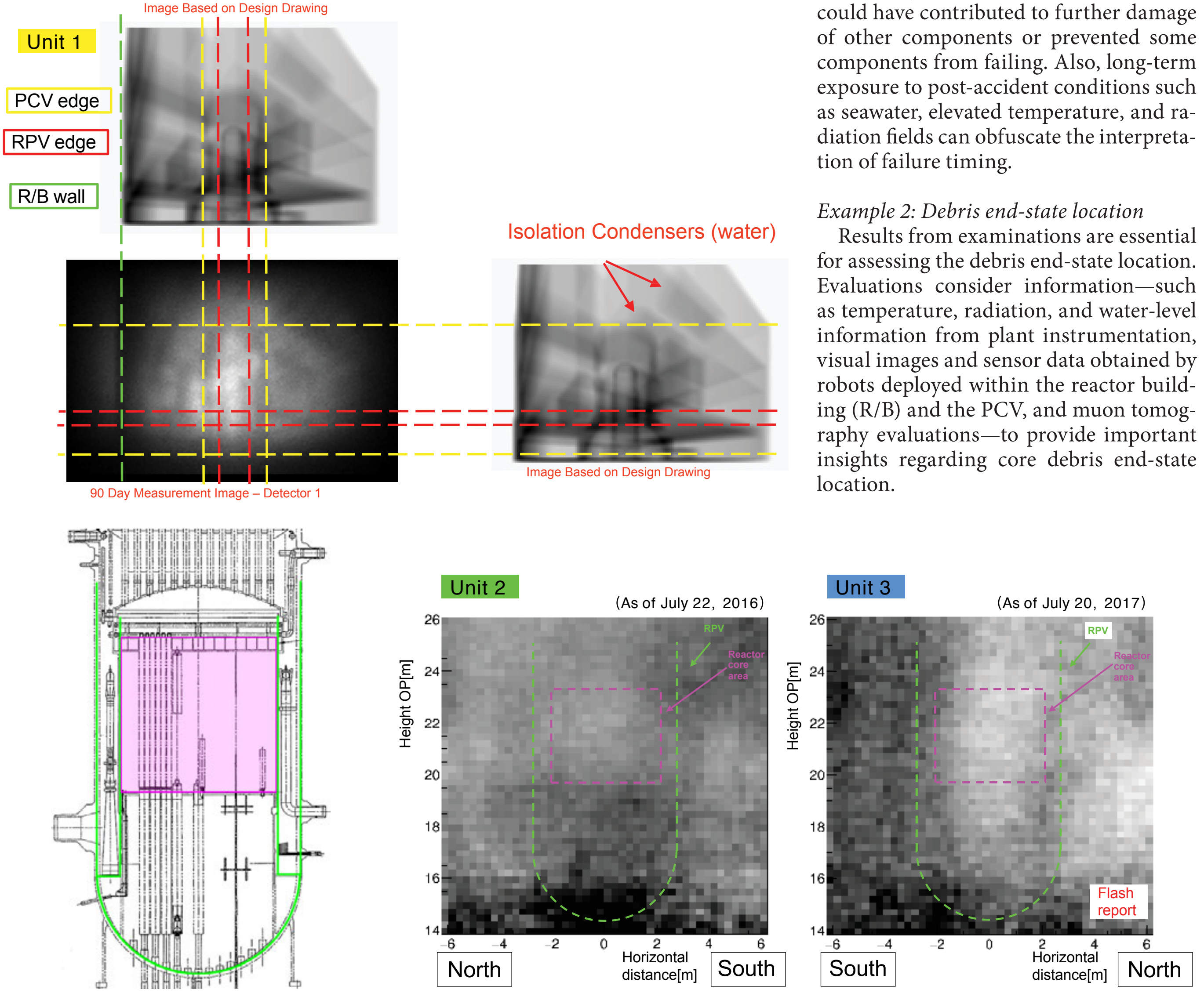
Graph: NEI [17]/modified by Jensen Hughes

Fig. 2. Containment pressure/temperature curve with available Fukushima Daiichi Unit 1 (1F1) and Unit 2 (1F2) information.

A primary limitation is that much of the initial forensics information is based on visual images—primarily photographs and videos. Distortions in visual images may be caused by lighting, image resolution, radiation effects, and surface corrosion. Another limitation is that the timing of the observed leakage and corrosion damage with respect to accident progression can be difficult to ascertain, given the complicated, multiunit nature of the accident. Early failures of some components could have contributed to further damage of other components or prevented some components from failing. Also, long-term exposure to post-accident conditions such as seawater, elevated temperature, and radiation fields can obfuscate the interpretation of failure timing.

Example 2: Debris end-state location

Results from examinations are essential for assessing the debris end-state location. Evaluations consider information—such as temperature, radiation, and water-level information from plant instrumentation, visual images and sensor data obtained by robots deployed within the reactor building (R/B) and the PCV, and muon tomography evaluations—to provide important insights regarding core debris end-state location.



Images: Tepco [20,21,22]

Fig. 3. Images of Units 1, 2, and 3 reactor vessels obtained using muon tomography methods. The darker regions correspond to denser materials, such as fuel.

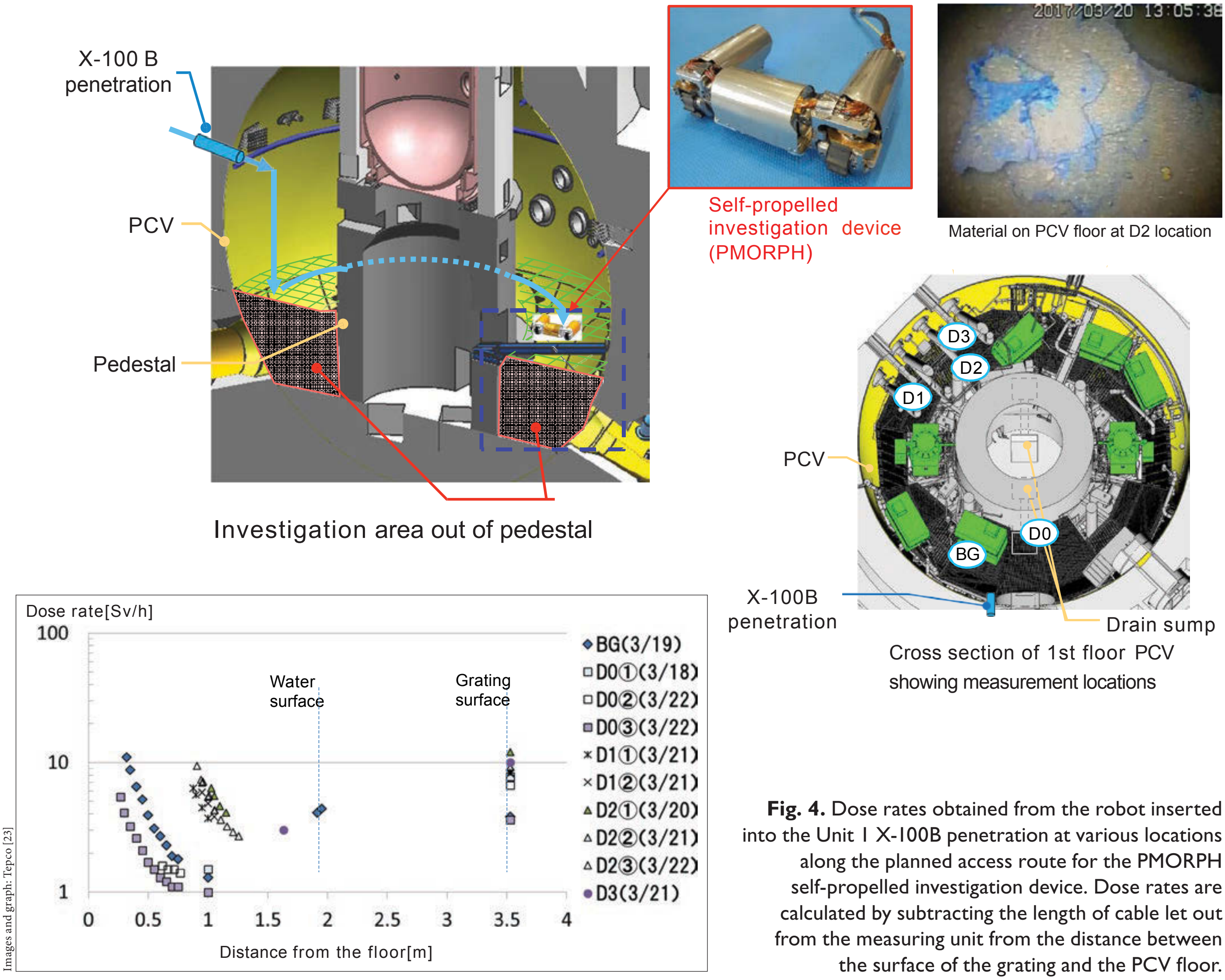


Fig. 4. Dose rates obtained from the robot inserted into the Unit I X-100B penetration at various locations along the planned access route for the PMORPH self-propelled investigation device. Dose rates are calculated by subtracting the length of cable let out from the measuring unit from the distance between the surface of the grating and the PCV floor.

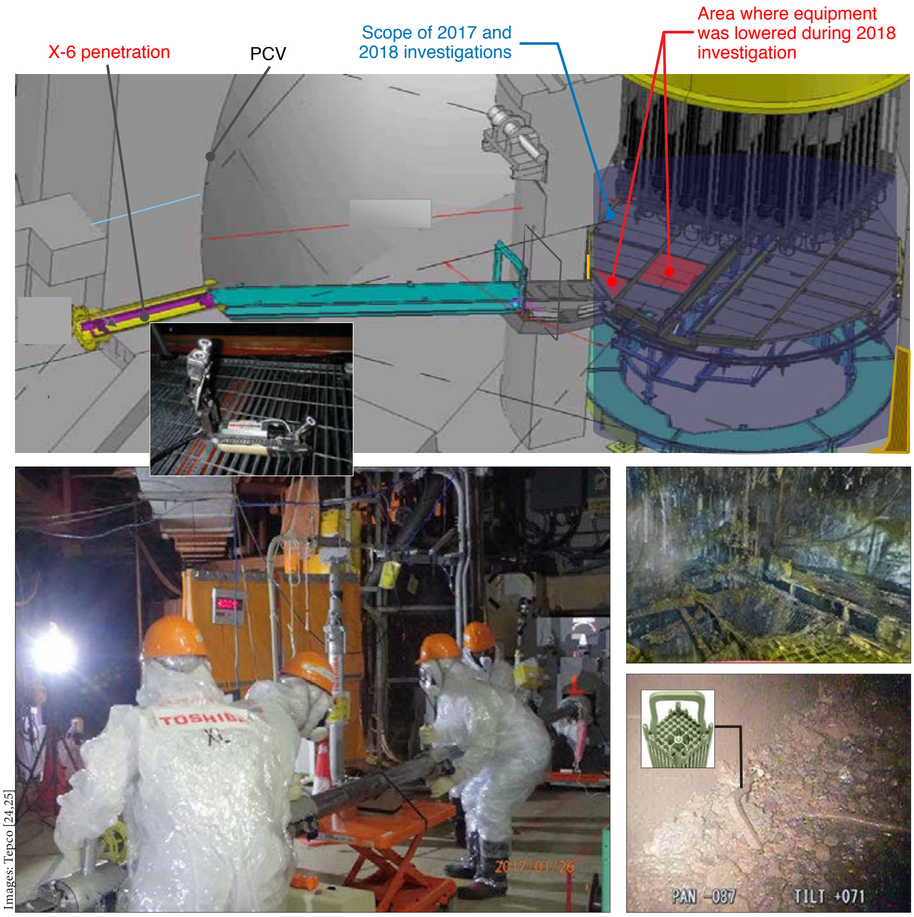
Temperature measurements using thermocouples [18] were obtained for several months following the accident. These measurements provide the first indication of where core debris likely resides and, equally important, where it does not. The temperature data suggest that some fraction of fuel remained in the RPVs for Units 2 and 3, but most of the core debris was likely outside the RPV for Unit 1.

The temperature data are consistent with U.S. [15,16] and international [19,20] predictions of debris locations. Calculations are more straightforward for Unit 1, which was essentially a station blackout with no external water injection until about 15 hours into the accident sequence, when operators were able to start reflooding the RPV with seawater. However, results from various calculations are less consistent for Units 2 and 3, where operators maintained some degree of core cooling by various means for several days. Uncertainties arise about the effectiveness of water injection (due to elevated PCV pressure) and the effectiveness and extent of backup cooling system operation under severe accident conditions. The situation is compounded by the lack of instrumentation (and the fact that surviving sensors had, in many cases, been pushed well outside their qualification envelope). Nevertheless, thermocouple data provide valuable information related to core debris end-state location and water addition strategies. For example, thermocouple data illustrate the benefit of injecting through core sprays for BWRs; the location of the spray injection optimizes the probability that core debris will be contacted and cooled by the injected water regardless of the extent of core degradation.

Muon tomography measurements using scintillation detectors are another information source for evaluating debris end-state conditions for Units 1, 2, and 3. Using this approach, high-density fuel should show up as dark regions in the images due to muon attenuation. As shown in Fig. 3, the core region appears to be essentially devoid of core material in each unit, which is consistent with previously described system-level code analyses. The potential for debris to have relocated to the bottom of the Unit 2 and Unit 3 reactor vessels is also supported by thermocouple data.

Most recently, valuable information regarding conditions inside the Unit 1, 2, and 3 PCVs was obtained by robotics examinations through containment penetrations X-100B in Unit 1, the X-6 penetration in Unit 2, and the X-53 penetration in Unit 3. Unique robots, capable of changing shape, navigating tortuous paths, diving below the water surface, obtaining temperature and radiation data, and collecting debris and water samples have been developed for these examinations. Dose measurements obtained from examinations through the X-100B Unit 1 penetration (see Fig. 4) indicate that levels increase at locations near the drywell floor. This result, along with evaluations indicating the presence of uranium in water samples obtained from within the PCV of Unit 1, also supports the hypothesis that fuel may have relocated from the RPV. Additional information is needed to determine the failure locations of the vessel and the mass of material that relocated from the vessel.

Images obtained using devices inserted through the Unit 2 X-6 penetration have also provided valuable information. As



Images: Tepco [24,25]

Fig. 5. At top, the drawing shows the Unit 2 PCV, the location of the X-6 penetration into which the robot (inset photo) was inserted, and the areas where investigations were conducted in 2017 and 2018. In the photo at lower left, workers insert a guide pipe into the X-6 penetration. At lower right: The top image shows instrumentation cables and control rod drive structures from the RPV above sagging grating. The bottom image shows a fuel assembly component and other debris that relocated to the PCV floor.

shown in Fig. 5, images of "sagging" grating suggest that it was exposed to high temperatures, and images of relocated fuel assembly components confirm that the Unit 2 vessel failed. Additional images are needed to identify the modes and locations of vessel failure and to estimate the mass of relocated fuel materials.

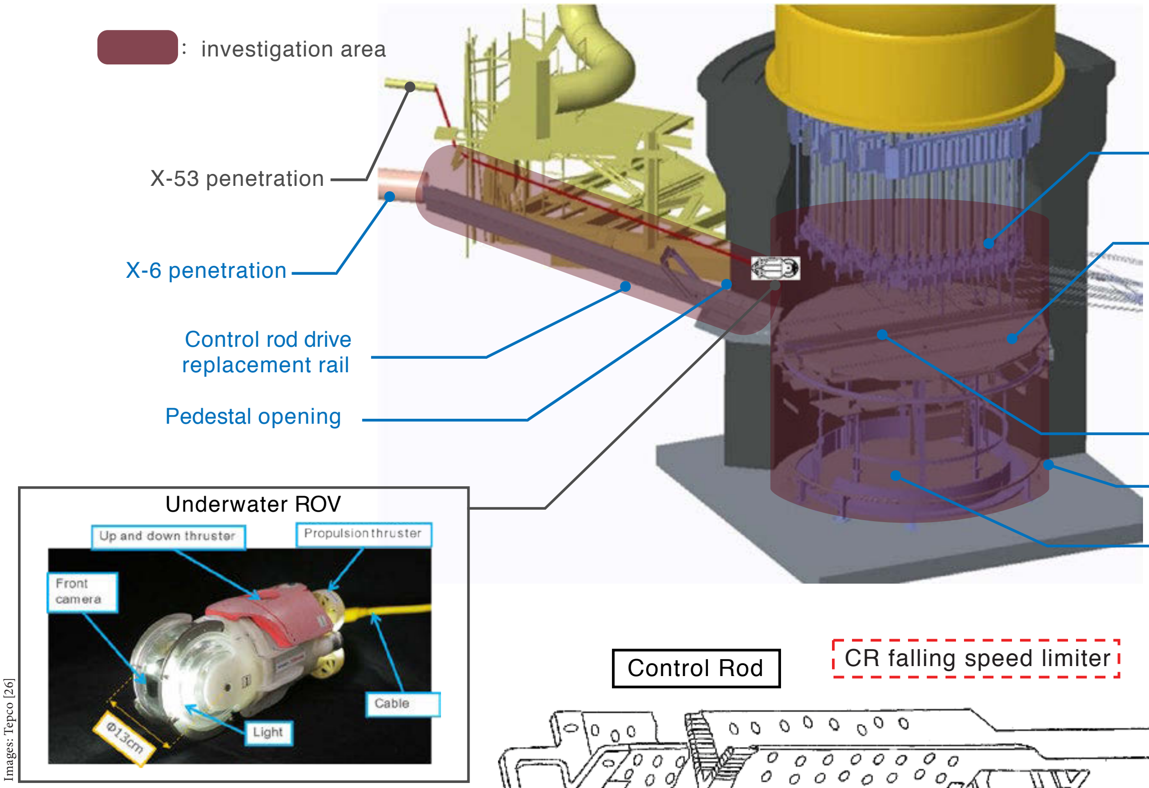
Important information was also gleaned from investigations into the Unit 3 containment performed in July 2017. Numerous images of relocated material were obtained from cameras that were installed on the submersible robot, "Little Sunfish," that was inserted into the X-53 penetration (Fig. 6). These images suggest that there is a high probability that components from the core have relocated beneath the reactor vessel, but additional information is needed to confirm vessel failure and estimate the mass of relocated fuel.

Insights gained

Forensics evaluations of examination information have led to several important safety insights being gained in the areas of component system performance, radionuclide surveys and sampling, core debris end-state, and combustible gas effects. These insights are being used by industry to update and improve PWR and BWR guidance for accident prevention and mitigation and emergency planning, in addition to reducing uncertainties in the modeling of how accidents progress.

■ ***Severe accident guidance***—Specific to the examples presented in this article, the DOE forensics effort has provided several benefits to industry severe accident guidance, as follows:

- *Containment venting*—The three Fukushima Daiichi units exhibited different patterns of PCV leakage. This variability points to uncertainties in actual leakage locations and confirms that an appropriate strategy is to maintain the containment at temperatures and pressures well below values at which degradation and excessive leakage of fission products are predicted. Revised BWROG and PWROG severe accident management guidance, based on examination information, places a high priority on maintaining the primary containment in a pressure and temperature



Images: Tepco [26]

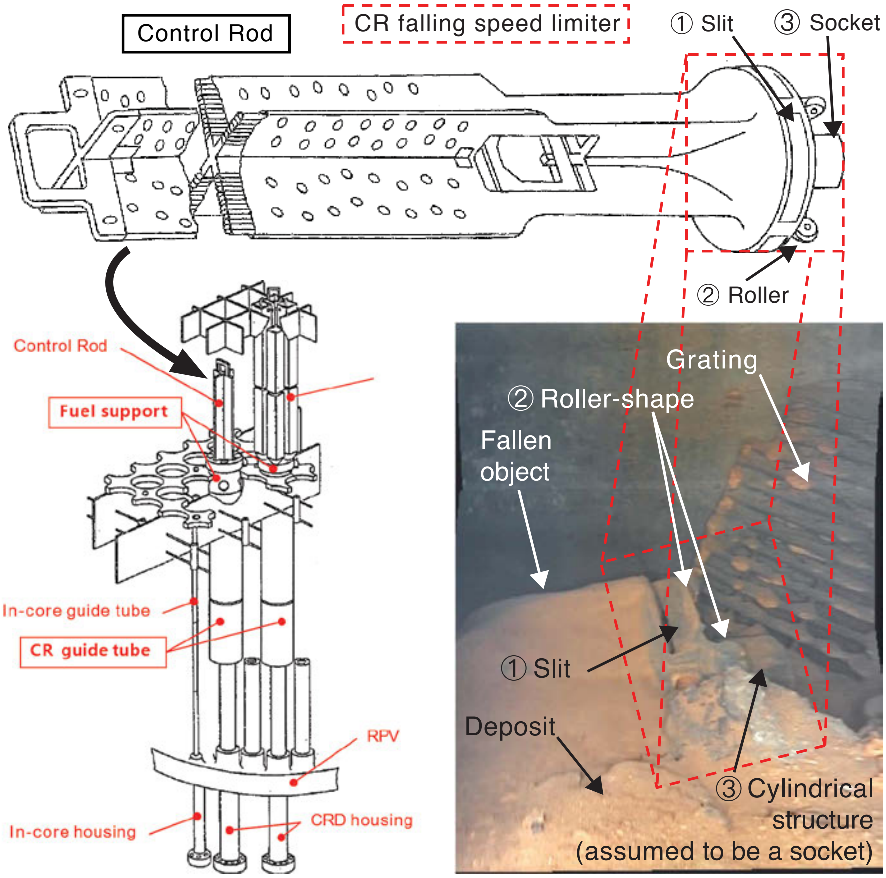


Fig. 6. The drawing at top shows the entry point of the Little Sunfish submersible remote-operated vehicle (ROV) (photo above) at the X-53 penetration of the Unit 3 PCV. The photo at far right is one of the images obtained from the ROV, looking toward the floor of the PCV. The accompanying drawings illustrate possible components that may exist in the debris shown in this photo.

range where the containment is most effective. BWR containment performance is improved by anticipatory venting prior to fuel damage using the hardened vent systems incorporated after the accident at Fukushima Daiichi.

- *Water addition*—Currently available information indicates differences in the core debris end-state location in Units 1, 2, and 3. It is believed that these differences are due to differences in accident progression at each unit (for example, cooling system operation). Revised BWROG guidance includes severe accident water addition and water management strategies to enhance the effectiveness of fission product scrubbing in the suppression pool during venting through the hardened vent system. The PWROG guidance also includes water addition (possibly via containment spray operation for fission product mitigation) during venting. The guidance considers the impact of water addition on containment integrity and contains guidelines for venting during water addition to prevent containment overpressurization.

■ ***Severe accident modeling***—Specific to the examples presented in this article, examinations have already identified several areas where efforts are needed to reduce uncertainties in severe accident modeling, as follows:

- *Primary containment integrity challenges*—The three operating units exhibited different patterns of PCV leakage of fission products and hydrogen. Many of these leakage points are not routinely modeled by system-level severe accident codes. Simulation codes predict leakage at the drywell head for the three units, and it is evident that other penetrations and piping failures should be considered.
- *Vessel failure and ex-vessel debris analysis*—Examination information indicates that there is the potential for vessel failure to have occurred at Units 1, 2, and 3. Current vessel failure models are simplistic in systems analysis codes, and evaluations of ex-vessel debris phenomena have been limited to Unit 1. An evaluation of debris interactions in Unit 2 may be useful for rationalizing differences in future observations obtained from Units 1 and 2.

Continued

- *Instrumentation modeling*—Improved modeling of instrumentation response during severe accidents may also lead to improved severe accident guidance. Current severe accident modeling codes predict conditions consistent with plant data, but predicted values may not be representative of the values being reported/displayed by the plant's instruments.

Additional insights can be found in references 2, 11, and 12.

ACKNOWLEDGMENTS

The U.S. forensics effort could not be performed without input and support from multiple individuals and organizations. The Department of Energy's Office of Nuclear Energy funded the participation of present and former national laboratory participants in expert panel meetings. In addition, various industry organizations provide substantial in-kind contributions by funding technical experts to participate in this process, including Areva, the Boiling Water Reactor Owners Group, the Electric Power Research Institute, Exelon Corporation, Fauske and Associates LLC, GE Hitachi Nuclear Energy, the Institute of Nuclear Power Operations, Jensen Hughes, the Nuclear Energy Institute, the Pressurized Water Reactor Owners Group, Southern Nuclear, and the Tennessee Valley Authority. The U.S. Nuclear Regulatory Commission, Tepco, and the Japan Atomic Energy Agency provide technical experts to participate in panel meetings. In particular, Takasi Hara, Kenji Tateiwa, Daichi Yamada, and Yasunori Yamanaka, all from Tepco, have made significant contributions, as have Richard Lee and Donald Marksberry, of the NRC's Office of Nuclear Regulatory Research, and Richard Wachowiak, of EPRI.

Finally, the authors wish to acknowledge individuals who lead and contribute to U.S. Fukushima forensics evaluation efforts: Phil Amway, Exelon; Nathan Andrews and Randall Gauntt, Sandia National Laboratories; Randy Bunt, Southern Nuclear; Phil Ellison and Teri Farthing, GE Hitachi; Mike Corradini, University of Wisconsin–Madison; Mitch Farmer, Argonne National Laboratory; Jeff Gabor and David Luxat, Jensen Hughes; Paul Humrickhouse, Idaho National Laboratory; Roy Linthicum, PWROG; Wison Luangdilok, Chan Paik, and Martin Plys, Fauske and Associates; Bob Lutz, Lutz Nuclear Consulting; Kevin Robb, Oak Ridge National Laboratory; Bill Williamson, Tennessee Valley Authority; and Robert Sanders, Areva.

References

1. Rempe, J., M. Farmer, M. Corradini, L. Ott, R. Gauntt, and D. Powers, "Revisiting Insights from Three Mile Island Unit 2 Post-Accident Examinations and Evaluations in View of the Fukushima Daiichi Accident," *Nuclear Science and Engineering,* 172, pp. 223–248 (2012). <http://dx.doi.org/10.13182/NSE12-3>
2. Rempe, J., et al., *U.S. Efforts in Support of Examinations at Fukushima Daiichi* (Argonne National Laboratory, Argonne, Ill.), Tech Rep ANL/LWRS-15/02 (2015).
3. Rempe, J., et al., "Safety Insights from Forensics Evaluations at Daiichi" (invited paper), Fukushima Daiichi Special Edition, *Journal of Nuclear Materials and Energy* (2016). <http://dx.doi.org/10.1016/j.nme.2016.08.010>
4. Nuclear Damage Compensation and Decommissioning Facilitation Corporation, "Technical Strategic Plan 2017 for Decommissioning of the Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Company Holdings, Inc.," includes a summary, overview, and full report (2017).
5. Tepco, <www.tepco.co.jp/nu/fukushima-np>, last accessed July 2017.
6. Tepco, *Evaluation of the Situation of Cores and Containment Vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and Examination into Unsolved Issues in the Accident Progression—Progress Report No. 1,* Dec. 13, 2013. <www.tepco.co.jp/en/press/corp-com/release/betu13_e/images/131213e0102.pdf>, last accessed July 2017.
7. Tepco, *Report on the Investigation and Study of Unconfirmed/Unclear Matters in the Fukushima Nuclear Accident—Progress Report No. 2,* Aug. 6, 2014, <www.tepco.co.jp/en/press/corp-com/release/betu14_e/images/140806e0101.pdf>, last accessed July 2017.
8. Tepco, *Report on the Investigation and Study of Unconfirmed/Unclear Matters in the Fukushima Nuclear Accident—Progress Report No. 3,* May 20, 2015, <www.tepco.co.jp/en/press/corp-com/release/betu15_e/images/150520e0101.pdf>, last accessed July 2017.
9. Tepco, *Evaluation of the Situation of Cores and Containment Vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and Examination into Unsolved Issues in the Accident Progression–Progress Report No. 4,* Dec. 17, 2016 (with attachments), <www.tepco.co.jp/en/press/corp-com/release/2015/1264602_6844.html>, last accessed July 2017.
10. Tepco, *The 4th Progress Report on the Investigation and Examination of Unconfirmed and Unresolved Issues on the Development Mechanism of the Fukushima Daiichi Nuclear Accident,* Dec. 17, 2015, <www.tepco.co.jp/en/press/corp-com/release/2015/1264602_6844.html>, last accessed July 2017.
11. Rempe, J., et al., *U.S. Efforts in Support of Examinations at Fukushima Daiichi—2017 Evaluations* (Argonne National Laboratory, Argonne, Ill.), Tech Rep ANL/LWRS-17/02 (2017).
12. Rempe, J., et al., *U.S. Efforts in Support of Examinations at Fukushima Daiichi—2016 Evaluations* (Argonne National Laboratory, Argonne, Ill.), Tech Rep ANL/LWRS-16/02 (2016).
13. Fauske and Associates LLC, *Transmittal Document for MAAP5 Code Revision MAAP 5.02,* FAI/13-0801 (2013).
14. Sandia National Laboratories, *MELCOR Computer Code Manuals, Vol. 1: Primer and User's Guide,* and *Vol. 2: Reference Manual,* Version 2.1.6840 (Sandia National Laboratories, Albuquerque, N.M.), Tech Rep SAND 2015-6692 R (2015).
15. Luxat, D., and J. Gabor, *Fukushima Technical Evaluation: Phase 1—MAAP5 Analysis,* EPRI Report No. 1025750 (2013).
16. Gauntt, R., et al., *Fukushima Daiichi Accident Study,* SAND2012-6173 (2012).
17. Nuclear Energy Institute, *Industry Guidance for Compliance with Order EA-13-109* (Nuclear Energy Institute, Washington, D.C.), Tech Rep NEI 13-02, Rev. 1 (2015).
18. Tepco, "Behavior of Plants after the Accident," <www.tepco.co.jp/en/nu/fukushima-np/images/handouts_111130_05-e.pdf>, Nov. 30, 2011, last accessed Mar. 2018.
19. Bonneville, H., and A. Luciani, "Simulation of the Core Degradation Phase of the Fukushima Accidents Using the ASTEC Code," *Nuclear Engineering and Design,* 272, pp. 261–272 (June 2014).
20. Tepco, "Estimation of Current Status Inside RPV and PCV at Fukushima Daiichi NPS," presentation by S. Mizokami at the 2nd International Forum on the Decommissioning of the Fukushima Daiichi Nuclear Power Station, Iwaki, Japan, July 3, 2017, <www.ndf-forum.com/ref/d2_mizokami_en.pdf>, last accessed July 2017.
21. Tepco, *Reactor Imaging Technology for Fuel Debris Detection by Cosmic Ray Muon: Measurement Status Report in Unit-1,* <http://irid.or.jp/wp-content/uploads/2015/03/20150319_e.pdf>, Mar. 19, 2015, last accessed Mar. 2018.
22. Tepco, *Locating Fuel Debris inside the Unit 3 Reactor Using a Muon Measurement Technology at Fukushima Daiichi Nuclear Power Station* (Interim Report), <www.tepco.co.jp/en/nu/fukushima-np/handouts/2017/images/handouts_170727_01-e.pdf>, July 27, 2017, last accessed Aug. 2017.
23. Tepco, *Unit 1 Primary Containment Vessel Internal Investigation,* <www.tepco.co.jp/en/nu/fukushima-np/handouts/2017/images/handouts_170327_01-e.pdf>, Mar. 27, 2017, last accessed July 2017.
24. Tepco, "Pre-investigation results of the area inside the pedestal for the Unit 2 Primary Containment Vessel Investigation at Fukushima Daiichi Nuclear Power Station (examination results of digital images)," <www.tepco.co.jp/en/nu/fukushima-np/handouts/2017/images/handouts_170202_01-e.pdf>, Feb. 2, 2017, last accessed July 2017.
25. Tepco, *Fukushima Daiichi Nuclear Power Station Unit 2 Primary Containment Vessel Internal Investigation Results (Bulletin),* <www.tepco.co.jp/en/nu/fukushima-np/handouts/2018/images/handouts_180119_01-e.pdf>, Jan. 19, 2018, last accessed Mar. 11, 2018.
26. Tepco, *Progress of Unit 3 PCV Internal Investigation (Preliminary Report of July 19 Investigation),* <www.tepco.co.jp/en/nu/fukushima-np/handouts/2017/images/handouts_170719_01-e.pdf>, July 19, 2017, last accessed Aug. 1, 2017.