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The Nuclear Legacy
Today of Fukushima

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Abstract
The accident at the Fukushima Daiichi Nuclear Power Station (FDNPS) following the Great East Japan Earthquake and the subsequent tsunami in March 2011 changed people’s perceptions regarding nuclear power generation in Japan and worldwide. The failure to prevent the accident and the response to it had an enormous impact specifically on the communities close to the site but also across Japan and globally. In this review, I discuss radiation detection technologies, their use and limits in the immediate assessment and response, and improvements since then. In particular, I examine recent developments in radiation detection and imaging systems that, in combination with the enormous advances in computer vision, provide new means to detect, map, and visualize radiation using manned and unmanned deployment platforms. In addition to smarter and more adaptable technologies to prevent and minimize the impact of such events, an important outcome of this accident is the need for informed and resilient citizens who are empowered by knowledge and technologies to make rational decisions. The accident at FDNPS leaves a legacy concerning the importance of historical information, technologies, and resilience as well as challenges regarding powerful technologies that can provide substantial benefits to human society but that are also associated with risks of which we must be aware.
1. INTRODUCTION

On March 11, 2011, the unthinkable—at least for residents living in Fukushima Prefecture and beyond in Japan—happened: a station blackout (SBO) at the Fukushima Daiichi Nuclear Power Station (FDNPS). Not only were residents, operators, and authorities ill prepared for this accident but the technological means deployed to prevent and properly respond to it were hopelessly insufficient. The impact is enormous, even almost 10 years after the accident: on energy production, society, and the economy in Fukushima Prefecture, in all of Japan, and globally. As of the time of writing, the nuclear fuel debris in the three destroyed reactor units remains to be assessed and taken out as part of the decommissioning and remediation of the whole facility, which will take several decades. In contrast to the two previous major nuclear accidents—at Three Mile Island in Pennsylvania in 1979 and at Chernobyl in Ukraine\(^1\) in 1986—the accident at FDNPS was induced not by operator errors and failures but instead by two unprecedented natural events in Japan: the Great East Japan Earthquake (also called the 2011 Tōhoku Earthquake) and the subsequent tsunami. While all nuclear power plants were able to withstand the earthquake (even with ground motions beyond design limits) and had been properly scrammed,\(^2\) the tsunami overcame the seawalls at both nuclear power plants in Fukushima Prefecture operated by the Tokyo Electric Power Company (TEPCO). The resulting loss of electrical power led to an inability to remove the remaining decay heat at FDNPS, the melting of the fuel pins, and ultimately the release of radioactive fission fragments into the atmosphere though explosions and intentional discharges from the three operational units. Not only were the FDNPS reactor units, the backup generators, and the radiation detection equipment not sufficiently protected for this event but, perhaps more importantly, authorities and adjacent communities had no available means to assess, communicate, and respond to it. Such an event was unimaginable in Japan because it was believed that nuclear power was completely safe and that the actions of the operators and authorities were to be trusted. In this specific context, the sense of safety implied that there was no risk in the operation of these

\(^1\)Chernobyl is located in the north of Ukraine, which was at that time a republic of the USSR (Union of Soviet Socialist Republics). The substantial political and economic changes due to the collapse of the USSR in 1991 made the study of health effects even more difficult. Associating health effects with radiation unambiguously was already challenging before, given the state of the health system and the lack of baseline data such as cancer incidence and mortality rates.

\(^2\)Scramming is the insertion of control rods into an operating nuclear reactor core; the rods render the reactor subcritical and stop the nuclear chain reaction by absorbing neutrons. Although the fission process itself is suppressed and the reactor is subcritical, about 7% of the steady-state power remains because of the continued decay of the fission fragments—the so-called decay heat, which is down to 0.4% after 1 day.
facilities, no need for concern or knowledge regarding the reactors, and no need for extensive evacuation plans or exercises.

People in Japan have been exposed to natural disasters such as earthquakes and tsunamis since the first settlements in the country. Technologically induced disasters rarely happened and were not expected, and this context ultimately resulted in both a lack of preparation and the enormity of the impact. It is important to note that the tsunami resulted in much more substantial casualties and widespread infrastructural damage than did the FDNPS accident: More than 18,000 citizens were killed by the tsunami, hundreds of thousands were evacuated, and large areas of farmland were devastated (1). In contrast, independent and scientific international organizations predict no or only a very small measurable health effect that is directly due to radiation exposure (2, 3). Several operators received significant radiation exposure, but they have been treated and fully recovered. It is noteworthy that two FDNPS workers drowned in one of the turbine halls because of the tsunami. However, while the direct radiation-induced health effects might not be measurable, the indirect health effects are very much observable already—effects caused by the rushed evacuation of the elderly and the sick as well as psychologically induced effects such as post-traumatic symptoms and depression (4–8). Obesity has also become a problem because of the recommendations to stay indoors, a particular concern for children (9). These observations are similar to those from the much more severe Chernobyl accident—enormous health effects driven by uncertainty, distrust, and misinformation, reflected in unnecessary abortions and suicides (10).

As with the FDNPS operators, residents, and authorities, the means to assess the impact on- and off-site were also overwhelmed by the triple disaster. All but one of the radiation monitors deployed in Fukushima Prefecture were made nonoperational (11). No reliable means to inform the response and predictive modeling were available during the critical first days.\textsuperscript{3} It took the Aerial Measuring System (AMS) operated by a US National Nuclear Security Administration team (flown in from the United States in collaboration with US Armed Forces in Japan) and the Japan Atomic Energy Agency (JAEA) to perform the first aerial measurements and provide contamination maps spanning larger areas. In Japan, this capability was not available at the time. Within a few days after the arrival of the AMS team, it was found that the main contamination stretched to the northwestern part of the site, crossing established evacuation pathways (12). The wind initially pushed the radioactive plume (from units 1 and 3) east over the ocean, but later releases (predominantly from units 2 and 4) were driven on-land, which, in combination with precipitation, led to significant depositions and contamination on the ground over a northwestern strip approximately 5 miles wide and 25 miles long. Figure 1 shows the extent of this contamination in terms of the deposition of \textsuperscript{134}Cs and \textsuperscript{137}Cs as observed by an aerial survey performed 6 weeks after the accident. The population density is shown as well, illustrating the number of people in Fukushima Prefecture eventually affected by the accident. Figure 1 also displays the locations of all nuclear power plants in or close to Japan. Of particular importance is the location of the epicenter of the earthquake relative to the three nearest nuclear power plant sites: Onagawa, FDNPS, and Daini.

To further convey the impact of the triple disaster and in particular the damage due to the hydrogen explosions in units 1, 3, and 4, Figure 2 shows aerial photographs of FDNPS before and after the accident. It also shows a satellite image from the time right after the explosions and a more recent image to reflect the vast changes on-site, including the installation of almost 1,000 water storage tanks. As discussed in Section 3, the water is slightly contaminated with tritium and

\textsuperscript{3}As discussed below in Section 3, SPEEDI (System for Prediction of Environmental Emergency Dose Information) was actually providing predictions about the fallout and contamination; however, this information was not made available to the public, mainly out of fears of causing a panic and of being inaccurate.
Figure 1

(a) Operational nuclear power plants in Japan and in close proximity in South Korea and Russia before March 2011 and the location of the epicenter of the earthquake. (b) Expanded view of Fukushima Prefecture including the $^{134}$Cs and $^{137}$Cs deposition as obtained by aerial surveys performed by the US Department of Energy (DOE) and the Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT) 6 weeks after the accident. Panel b also shows the population distribution to indicate the number of people affected in the prefecture. Panel b adapted with permission from http://hps.org/documents/IRSN_Fukushima_Report.pdf.

therefore—out of fear of the environmental and economic impact—has not been released and instead continues to be accumulated.

Initially, radiation detection capabilities were lacking and insufficient to properly assess the release of radioactive materials, in particular on-site and in communities close to the site, but substantial progress has since been achieved in assessing the contamination and guiding the decontamination and decommissioning efforts by means of conventional and advanced technologies and their deployment on- and off-site. These efforts entail more effective and accurate ways to assess, monitor, and communicate contamination and decontamination efforts over large areas and communities, using radiation detection networks and mobile deployments on cars, buses, and aerial platforms. On-site, significant progress has been made to control the reactor units, reduce the dose-rate levels, and drive the development and deployment of advanced robotics platforms to assess the highly contaminated buildings and their surroundings, including the first assessments of the nuclear fuel debris inside the primary containment vessels (PCVs). These systems have been developed for the challenging environments of high-temperature, high-radiation fields with limited access to the PCVs. Radiation hardness has come into focus recently along with what
one could call radiation smartness as the challenges found at FDNPS and associated with the accident and its consequences have required us to study, learn, and adapt to enable more effective and safer means of assessment and, ultimately, decommissioning and remediation.

In this review, I keep the broader impact of advanced technologies in mind as they are undoubtedly part of the nuclear legacy. However, I focus on the advances in radiation detection and mapping technologies that already have had and will continue to have an important impact on the response, decommissioning, and remediation of FDNPS as well as other nuclear facilities in Japan and elsewhere. I first set the stage before the accident, briefly discuss the accident, and describe the initial response. I then discuss specific advances in radiation detection technologies and their deployments in Fukushima and around the world as well as the remaining challenges. I conclude with a discussion of the FDNPS accident’s nuclear legacy to date.

2. SETTING THE STAGE

Before March 11, 2011, Fukushima Prefecture was one of the largest nuclear power–producing areas in the world, with operators and authorities planning to add two more units to the six already in operation at FDNPS (also called Fukushima I or 1F) in addition to the four units operating at the Daini Nuclear Power Plant (also called Fukushima II or 2F) located 12 km to the south of.
FDNPS. As with most nuclear reactors in Japan, all 10 units were boiling water reactors (BWRs), which had been developed and initially manufactured by GE. All of these units were so-called second-generation reactors; the 1F units had become operational in 1971–1979, and the 2F units had been introduced in 1981–1986. Only the latest units—unit 6 at 1F and all 2F units—were equipped with the upgraded Mark II containment (1). The two planned reactors were of a substantially changed, Generation 3–type design called the advanced boiling water reactor (ABWR) with significantly enhanced and standardized features including passive means of cooling, simplified pumping systems, control, and structural improvements. Since the early 1970s, Japan's energy policy has been largely driven by considerations of energy security and, in light of Japan's sparse fossil fuel resources, independence from imported energy. This resulted in the adoption of nuclear energy as a major element of electricity production policy. This policy comprised the establishment of a closed fuel cycle including fuel reprocessing and the development of fast breeder reactors to improve uranium utilization. In addition, nuclear energy would allow Japan to achieve the aggressive goals set by the Kyoto Protocol for the reduction of greenhouse gas emissions (13). All nuclear power plants in Japan have been built close to the coast to use the Pacific Ocean as a cost-effective and convenient means of cooling and ultimately as a heat sink instead of using cooling towers. As of March 2011, Japan had 54 (48 actually operating at that time) nuclear power plants producing about 30% of the country’s electricity with a goal to expand to 50% by 2030.

Important lessons had been learned by the two previous major nuclear power–related accidents: the meltdown of unit 2 at Three Mile Island in Pennsylvania in March 1979 and the explosion of unit 4 at the Chernobyl Nuclear Power Plant in Ukraine in April 1986, both of which had been caused by human errors in the operation of the units. While the impact of the core meltdown at Three Mile Island had a minimal effect on its surroundings because of proper containment of the reactor, the explosion of the reactor core at Chernobyl had a disastrous impact due to the enormous release of radioactive materials into the local environment and the atmosphere, which contaminated large areas throughout Europe and the USSR (Union of Soviet Socialist Republics). This accident and its disastrous impact on lives and on the environment were made possible by the design of the reactor, the lack of a proper containment building, the gross neglect of safety procedures by the operators, and ultimately the limited and mistakes-laden response. Children continued to consume contaminated milk and food after the accident, which led to thousands of thyroid cancer cases (10).

4 These specific reactors were originally developed in the 1950s by GE and US national laboratories. GE's nuclear energy division joined with Hitachi in the 1990s for the development, manufacture, and sale of the advanced boiling water reactor (ABWR), the first so-called Generation 3 reactor design that was built and operated in Japan.

5 The unit 2 reactor at Three Mile Island was a pressure water reactor (PWR) with a containment building, and the accident resulted in only a small, controlled release of pressure and radioactive materials.

6 In contrast to the Western BWR and PWR designs with light water coolant, the Chernobyl plant was based on a Soviet-designed, graphite-cooled BWR reactor. The flawed minimalist design enabled fast and cheap construction, energy generation, and weapons-grade $^{239}$Pu production. It not only lacked proper containment around the reactor core but also had a so-called positive void coefficient that allowed runaway neutron generation, fission, and power generation because more of the liquid water could be converted into steam, reducing its density and its ability to absorb the neutrons. In addition, the graphite in the control heads increased the reactivity even more as they were moved in, ultimately igniting and amplifying the explosion.

7 As of 2016, about 20,000 cases of thyroid cancer had been identified, about one-fourth of which were associated with the ingestion of $^{131}$I from Chernobyl (14). Only 15 of these people died of the thyroid cancer; however, most of these cases could have been avoided if the contaminated food had not been consumed and if preventive measures had been in place, such as potassium iodide pills to block the uptake of $^{131}$I into the thyroid.
As an outcome of the Three Mile Island accident, the United States established the National Atmospheric Release Advisory Center (NARAC) to provide expertise and tools to predict and map the spread of hazardous material accidentally or intentionally released into the atmosphere (see https://narac.llnl.gov/home). Complementary to this modeling tool, the US RadNet framework and its predecessors had been established to measure environmental and food samples and to assess the impact of fallout and other intrusions of radioactive materials (see https://www.epa.gov/ radnet). As a consequence of the Chernobyl accident, European countries significantly increased the deployment of radiation dosimeter networks and required all member states of the European Commission to regularly provide environmental radioactivity monitoring data to a centralized database under the umbrella of the European Atomic Energy Community (15).

With regard to developments in radiation detection technologies, historically, fundamental physics research and biomedical applications for drug development and disease diagnostics were the main drivers until the terrorist attacks on the World Trade Center in New York on September 11, 2001. Given the potential for nuclear terrorism using nuclear weapon technologies or radiological dispersal devices combining radioactive materials with conventional chemical explosives, significant funding went into the development of enhanced radiation detection technologies to prevent the misuse of these materials. In the United States, the Department of Homeland Security (DHS) was formed, and since the nuclear threat was of particular concern, the Domestic Nuclear Detection Office was created as a separate entity. The main goals of these developments and deployments remain the detection of the production and proliferation of nuclear and radiological materials, the verification of processes in nuclear facilities to prevent the diversion of materials, and the protection of borders, ports of entry, and critical locations and infrastructure. Reflecting recent geopolitical changes and state-level efforts to create new or improved nuclear weapons, more emphasis has been put on emergency response and consequence management to enhance preparedness for the use of nuclear weapons around the world. These developments in detection and response are relevant as they are being adapted in the assessment and decommissioning of FDNPS and other nuclear facilities now and in the future.

Before September 11, 2001, the nuclear weapons programs and testing, which occurred predominantly in the 1950s and 1960s, led to the development and establishment of remote monitoring technologies. These included satellite-based or high-altitude aircraft monitoring with high-resolution imagery, ground-based radiation detection and seismic sensor networks, and fixed- and rotary-wing deployable radiation detection and mapping systems. On a global scale, the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) was established in 1996 as a result of negotiations to ban nuclear weapons testing and to monitor and verify compliance through the International Monitoring System (IMS) (see https://www.ctbto.org/, https://www.ctbto.org/map/#mode=ims, and https://backyardworld.wordpress.com/maps/ctbto/). The IMS station in the city of Takasaki, 250 km southwest of FDNPS, was one of the first CTBTO stations to detect $^{131}$I, $^{137}$Cs, and $^{133}$Xe from the March 2011 accident. In addition, its seismic and acoustic sensors provided important input to the tsunami warning (16). Other national organizations have been established or expanded and have provided a wealth of information and tools to the public. In Japan, SPEEDI (System for Prediction of Environmental Emergency Dose Information) was established in response to the Three Mile Island accident in 1979 to enable modeling and prediction of radioactive materials transport within Japan (17).

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8The first test was performed in 1945, and the last was performed in 2016 in North Korea. Before 2016, the latest tests had been performed in 1980 in China. The main activities of aboveground nuclear weapons testing were conducted in the 1950s and 1960s by the United States and the USSR; these tests ended with the Treaty on the Non-Proliferation of Nuclear Weapons of 1970.
Four nuclear power stations (with a total of 11 operating reactors) were directly affected by the earthquake and tsunami: the Onagawa, Fukushima Daiichi, Fukushima Daini, and Tōkai nuclear power stations, which were located 80, 150, 160, and 260 km, respectively, from the epicenter. All reactors were in full or start-up operations except for units 4–6 of FDNPS, which were shut down for maintenance. The fuel of unit 4 had just recently been moved to the spent fuel pool inside the reactor building and was still producing significant decay heat. Units 5 and 6 were shut down, with the fuel remaining in the core for inspection, and were being actively cooled. As it was common practice to use records of past tsunamis to estimate expected maximum tsunami wave heights, TEPCO used the tsunami from the 1960 Valdivia earthquake in Chile to estimate a maximum wave height of 3.1 m. This estimate was applied in the plant’s original permit and was the basis for the construction of a 5.7-m-high seawall. The same concept was used as the design basis for tsunami protection along the eastern coast of Japan. Only the devastating 2004 Indian Ocean earthquake and tsunami with wave heights of 30 m led to renewed efforts to investigate the Jōgan tsunami of AD 869, which had been documented in public records. Trial calculations performed by TEPCO in 2008 based on new models developed for the 869 tsunami and assuming a plausible 8.2-magnitude earthquake resulted in wave height estimates of up to 10.2 m at FDNPS and an inundation estimate of up to 15.7 m. However, rather than adjusting wall heights and elevating water inlets in response to these estimates, TEPCO instead requested further study of the appropriateness of the tsunami source models in their trial calculations (18). This action can be contrasted with those taken by the Tōhoku Electric Power Company, which increased the height of the barriers to 14 m and modified water inlets at the Onagawa Nuclear Power Plant (19).

3. FUKUSHIMA DAIICHI NUCLEAR POWER STATION ACCIDENT AND IMMEDIATE IMPACT AND RESPONSE

The 2011 Great East Japan Earthquake and tsunami created a humanitarian and material disaster in northeastern Japan. These natural events caused extensive damage to coastal communities in several prefectures and were responsible for about 15,900 deaths and 2,600 missing as well as hundreds of thousands of injured and displaced persons and physical infrastructure losses exceeding $200 billion (20). The earthquake and tsunami also led to a severe nuclear accident at FDNPS, which was rated as a Level 7 event on the International Nuclear and Radiological Event Scale of the International Atomic Energy Agency, on par with the 1986 Chernobyl accident. However, releases of radioactive material to the atmosphere (mainly noble gases, $^{131}$I, $^{134}$Cs, and $^{137}$Cs) from the FDNPS accident were less than 15% of the Chernobyl releases (21). A large body of literature about the triple disaster’s causes, impacts, and lessons learned is now available (22–25). In the following section, I discuss the events briefly as they relate to this review.

The earthquake at 2:46 PM with a magnitude of 9.0 was the largest ever recorded in Japan; it caused the Japanese coastline to sink by 0.8 m and moved Japan 2.4 m closer to California (26). The horizontal ground acceleration was estimated to be 0.56 g—significantly beyond the design basis of 0.45 g for FDNPS. All three operational reactors at FDNPS were properly scrammed as designed when high seismic acceleration was detected. Off-site AC power was lost because of the collapse of one transmission tower and severe damage to the equipment in a substation. Following the off-site AC power loss, all 12 emergency diesel generators started to power the reactor safety systems. While the seawall was able to prevent flooding from the first tsunami wave (about 4 m high) at 41 min after the earthquake, the second wave 8 min later, with a height of about 15 m, overwhelmed the 5.7-m-high wall and inundated the entire plant. Within 6 min, all diesel generators—located underground—were flooded, and the emergency AC power failed. One diesel-powered generator, the air-cooled unit located aboveground at unit 6, remained
online, providing power for units 5 and 6. Units 3 and 4 were now on DC power from the backup batteries, enabling operators to read instruments in the control room and manipulate remote-controlled valves until the batteries lost power, which happened about 36 h later. In units 1 and 2, the battery room was flooded, and these units were in an SBO within minutes. As a result, two critical resources were lost: power to operate pumps and a heat sink outside the reactor buildings. Within 48 h, all three units lost any means of heat removal. The heat from the radioactive decay of the fission daughters produced steam in the reactor pressure vessel (RPV), increasing the pressure. The necessary opening of the steam-relief valves allowed the discharge of steam out of the RPV, leading to a loss of cooling water and a descending liquid level that exposed the core, increased the cladding temperature, and ultimately resulted in the breaking of the fuel cladding and release of fission products from the fuel rod gaps. At high-enough temperatures, the oxidation of the zirconium in the cladding, associated with creation of hydrogen gas and a further increase in temperature, resulted in the melting of the cladding, the steel structures, and the fuel, whose mixture (the so-called corium) ultimately sank through the RPV onto the bottom of the PCV. Gaseous fission products, such as xenon, cesium, and iodine, were released as aerosols in the process, with the uranium and plutonium fuel remaining in the core. The accumulation of hydrogen gases on the reactor service floors on top of the PCVs and their explosions in units 1 and 3 damaged the steel frame roof and led to the release of all gases and aerosols into the environment. The incurred damage to the reactor units can be seen in Figure 2.

Figure 3 shows dose-rate measurements of the few operating radiation detection instruments along with the intentional and unintentional releases of radioactive materials. It is estimated that
the core damage in units 1–3 occurred within about 4, 75, and 36 h, respectively, after the earthquake. The venting of units 1–3 and the hydrogen explosions of units 1, 3, and 4 resulted in peak dose rates that initially were less than 1 mSv h$^{-1}$ but that by Monday, March 14, reached levels of up to 12 mSv h$^{-1}$ at the main gate on the southwest side of the plant, approximately 1 km away. The hydrogen explosion in unit 4 occurred as a result of the gases released from unit 3 being pushed into unit 4 because of the shared use of the exhaust stack. No hydrogen explosion occurred in unit 2 because there was a leak, which may have been induced by the explosion of unit 1. Eventually, sea water and fresh water were injected successfully (1–4 days after the earthquake), and AC power was restored on March 20, leading to the cooling of and control over the three reactor units.

The venting and, in particular, the hydrogen explosions resulted in dose rates that made all the operations and actions on-site enormously more difficult and time-consuming because access was limited and full-body radiation protection was required. In addition to insufficient information about the state of the reactor units, the lack of radiation measurements created significant uncertainties regarding the estimation of the releases and their transport within and outside of the plant site. As can be seen in Figure 3, it took several days to establish continuous radiation monitoring stations on-site. Most of the radiation detection instruments were down because of damage or lack of power. Within the first few days, mobile radiation detection systems were deployed to provide some information about the magnitude and direction of the releases. Motivated by the danger of a core meltdown and the potential release of radioactivity, compulsory evacuation orders were put in place. At 6 h after the earthquake, mandatory evacuation was implemented for everyone within 2 km of the plant. The evacuation area was increased over the next 24 h to 20 km. In total, about 140,000 people were evacuated because of the FDNPS accident, a large fraction of the ~400,000 who were evacuated because of the tsunami and nuclear plant accident. The Daini Nuclear Power Plant avoided an SBO because its external AC power was not completely taken out, some of its air-cooled diesel generators were located on higher ground, and its reactors were of newer design and had more robust passive cooling systems. In contrast to the two TEPCO-operated nuclear power plants, the Onagawa Nuclear Power Plant farther north, whose seawall height recently had been increased, was not overwhelmed by the tsunami waves. Not only did this plant survive without major problems but it became a shelter for fleeing residents of the nearby town of Onagawa, which was destroyed by the tsunami and had more than 800 deaths.

During the first explosions at FDNPS units 1 and 3, the wind was blowing eastward toward the ocean and, with it, most of the radioactive releases. However, as the wind changed from Monday to Tuesday, the releases of unit 2 went over land, and the fallout and deposition on land were enhanced by rainfall. Because no radiation detection equipment was available, no measurements could be made to determine the location and magnitude of the deposition and associated contamination. Predicting weather patterns and dispersion of gases and aerosols is already challenging in Japan's complex topography and rapidly changing meteorological conditions, even with high-quality, reliable input data. Without reliable data about the magnitude and timing of the releases, predicting plumes and depositions is even more uncertain. SPEEDI was supposed to perform these modeling calculations; however, no data and information from these predictions were made available out of fear that they might be wrong (28). The first systematic and large-area surveillance of radioactive contamination was carried out by AMS, which commenced measurements on Thursday, March 17. AMS was able to detect and map the extended contamination to the northwest, which intersected some of the evacuation pathways (29).

To address the concerns about immediate and long-term health effects, the Fukushima Health Management Survey was established in June 2011 with the goal of monitoring and improving the long-term health of residents (30). It consists of a basic and voluntary survey of all residents.
in Fukushima Prefecture, continued annual thyroid examinations for residents aged 18 years or younger as of the time of the accident, comprehensive health checkups, mental health and lifestyle surveys, and pregnancy and birth surveys. The primary concern is the monitoring of potential health effects that could be directly attributed to radiation (e.g., thyroid cancer in children, which occurred in Chernobyl). In addition, the survey allows the monitoring of indirect effects due to the evacuation, lifestyle changes, and mental health problems. This large-scale health monitoring is referred to not as a study—such as in the case of the Life Span Study to monitor the long-term effects of the survivors of the Hiroshima and Nagasaki bombings—but, rather, as a health management survey. This language is used to avoid the perception that the residents are being used as study subjects to serve the interest of science rather than the interest of the individuals. It was found that 98% of the 550,000 people surveyed had received doses of 5 mSv or less, which is comparable to the average annual background dose in an unaffected area. More than 320,000 children were examined in two phases: the first within 3 years after the accident and the second in the following 2 years. The examination, which was based on ultrasound screening, found an increased number of thyroid cancers compared with the baseline at that time, and initially this finding amplified people’s concerns and attracted media attention. However, the observed increase in cancer incidence was not consistent with the expected age profile, the geographical dose distribution, or the pathologic profile observed in the Chernobyl cases with regard to the changes in the two screening phases (31). The current interpretation of this observed increase is that it suggests a so-called screening effect reflecting an incorrect assumed baseline; that is, there may be a large pool of people who naturally have thyroid cancers that are not diagnosed because their cancers do not become malignant. This conclusion aligns with comparative studies in the north and south of Japan that showed statistically consistent increased cancer incidence rates. The main outcome of this study to date is a better understanding of diagnostic screening of large populations to avoid overdiagnosis and unnecessary treatment—specifically of early-phase thyroid cancer in children.

Overall, enormous progress in stabilizing and assessing the reactor units and in reducing radiation exposure on- and off-site has been achieved. On-site, all debris has been cleared, contamination has been removed, and surfaces have been covered to avoid erosion. One remaining challenge is to deal with the large amount of cooling water that was pumped into the reactors as well as the groundwater that entered the units and also became contaminated. Several barriers have been built to reduce the inflow of groundwater and the outflow of contaminated water through the damaged structures along with large-scale water decontamination and storage facilities. Noteworthy is the 1.5-km-long, 30-m-deep ice wall built around the four units that will be operated for several more years (32). The water decontamination is achieved in several steps including the removal of $^{137}$Cs and $^{90}$Sr and 62 other radioisotopes by a combination of adsorption, reverse osmosis, and ion exchange columns (33, 34). Since 2017, all the water has been decontaminated (except for tritium) and is being stored in close to 1,000 tanks, each with a capacity of 1,000 m$^3$; as illustrated in Figure 2, these tanks occupy an increasingly large area on the FDNPS site. This water has not been released because of its remaining tritium content. The tritium is produced in ternary fission and in neutron activation interactions (e.g., on $^{10}$B, which is used in the control rods). Because of the chemical similarity to light water, no effective technology is available to date to allow the removal of tritium on the necessary industrial scale.

The ongoing accumulation of tritium-contaminated water reflects a fundamental challenge in dealing with decontamination efforts more broadly: the balance between the benefits and risks of actions or inaction. For years, scientists have recommended releasing the water into the Pacific Ocean slowly over time to utilize the ocean’s large dilution factor; they argue that the probability of observing biological effects of tritium is very small even in much larger concentrations because of the isotope’s short biological half-life and low electron energy. In contrast, the fishing industry, out
Decline in dose rates over time as measured by aerial systems. The magnitude and geographical extent of high contamination declined significantly over the 7 years shown, as reflected in the disappearance of the areas with dose rates above 19 µSv h⁻¹. As of 2020, all areas are below 10 µSv h⁻¹. The yellow line in the distribution in panel d shows the remaining evacuation zone. Data from Reference 38.

Off fear of radiation, has demanded that all contamination associated with the accident be removed or avoided to ensure safe levels in the fish and to maintain trust among customers and markets (see, e.g., 35–37). To date, no water has been intentionally released into the ocean; it is expected that within 2 years, the available space of about 1,250 storage tanks at FDNPS will be reached, and no solution has been identified for the necessary expansion. Of note, within 1 year after the accident, when significant releases of contaminated water still occurred, the concentration of ¹³⁷Cs in water at a distance of a few hundred meters was less than the concentration of naturally occurring, chemically similar ⁴⁰K.

Off-site, enormous efforts to remove debris and up to 5 cm of topsoil over large areas have been completed, creating new challenges in dealing with the radioactive waste. Thousands of cubic meters of low-level radioactive waste have been collected in tens of thousands of black plastic bags and kept in intermediate storage areas. The recent Typhoon Hagibis, which was one of the worst typhoons in the last 50 years to make landfall in Japan and was associated with about 100 confirmed deaths, caused extensive flooding in the larger Tokyo area and Fukushima Prefecture, washing away hundreds of the plastic bags containing the removed soil. This event renewed safety concerns about the contamination around FDNPS, reflecting the continued sensitivity and anxiety associated with the site. At the time of writing, thousands of fixed and mobile radiation detectors are being deployed by Japanese authorities, independent organizations, and citizens, and the data are all available online. Figure 4 illustrates measured dose rates in Fukushima Prefecture and their changes over 7 years, from November 2011 to November 2018, observed by aerial systems. Both TEPCO nuclear power stations (FDNPS and Daini Nuclear Power Plant) and about half of the formerly operating power plants will be decommissioned. The Government of Japan and the Fukushima prefectural government are investing substantial funds for the cleanup and revitalization of the prefecture. These efforts include the establishment of research institutions and facilities related to FDNPS as well as initiatives to make the prefecture a major national and global hub for the development and deployment of renewable energy.

Beyond Japan, while the earthquake and tsunami received some attention, and despite the enormous suffering and deaths due to the tsunami, the accident at FDNPS has had the most substantial impact: initially in the responses to the threat of radioactive fallout and contamination across the northern hemisphere and, subsequently, in reconsiderations of the use of nuclear power or at least reevaluations of the use and oversight of nuclear power and associated emergency response measures.
4. ADVANCES IN RADIATION DETECTION TECHNOLOGIES

The need to assess the contamination and to monitor the decontamination and decommissioning efforts in Fukushima Prefecture over the last 9 years have driven considerable advances in radiation detection technologies and deployment platforms. These technologies will also be relevant in the decommissioning of other nuclear power plants and in the prevention of and responses to nuclear incidents in the future. Significant progress has occurred in parallel, driven by nuclear security concerns as the misuse of nuclear materials remains one of the most serious threats to society. Complementing the developments in radiation detection technologies and deployment platforms are improvements in contextual sensing and data processing capabilities that enable new and advanced concepts in the detection, mapping, and visualization of nuclear radiation. Here, I focus on technologies that are relevant in the larger context of the FDNPS accident and that are related to nuclear safety, nuclear security, and emergency response. In the following subsections, I break down the discussion of technological advancements in radiation detection and associated deployment platforms into stationary and mobile systems. Given the scope of this review, the discussion must be limited to some exemplary—albeit important and characteristic—concepts and technologies.

4.1. Stationary Systems

Stationary radiation detection systems are being used in two ways: (a) as networks of many remotely operating instruments deployed across all environments and (b) as individual instruments, mostly human-controlled, to assess the contamination of specific samples (e.g., foodstuffs and people) or the nuclear reactors themselves. The radiation discussed here, which is used as a messenger or probe, is from γ-rays and muons. Electrons and α-particles from β and α decay as well as neutrons that are associated with fission will only be discussed briefly.

4.1.1. Radiation detection networks. While the technologies that are now deployed in radiation detection networks across Fukushima Prefecture and the rest of Japan (and globally) are not necessarily new or even advanced, they are now ubiquitous, being operated by government and citizens’ organizations, and the data are available online to anyone with access to the Internet. Most of the broadly distributed instruments are simple dosimeters that are realized as Geiger–Müller gas- or Si-based counters. The observed counts per time can be translated to a dose rate. More advanced and more expensive radiation detection instruments are typically based on small NaI(Tl) or CsI(Tl) scintillation-based spectrometers, which provide not only counts and dose rates but also γ-ray energies that allow the identification and assessment of specific radionuclides as the source of radiation, such as 131I, 134Cs, and 137Cs. By March 16, 2011, the Government of Japan had started to install a large number of radiation dosimeters to measure dose rates in the air within and outside of the evacuation areas around FDNPS. Within 1 year, about 4,000 instruments were operational in the Fukushima and surrounding prefectures, and the data were available to the public through several websites and public displays (39). Although these initiatives were very successful in providing up-to-date information for the public, the Japanese government recently decided to shut down most of the instruments because of the costs of maintaining proper operation and also because radiation levels have decreased. In most areas, dose rates are now similar to global natural background levels, and radiation levels remain elevated only in the areas northwest of the site (e.g., the town of Namie), which therefore remain evacuated, as shown in Figure 4.

As a consequence of the FDNPS accident, radiation networks have been further extended globally. RadNet, operated by the US Environmental Protection Agency, has been enhanced...
substantially and now consists of 140 measurement stations across the United States that provide hourly exposure rates (see https://www.epa.gov/radnet). The Joint Research Centre of the European Commission now provides extensive information and radiation levels across all member states in near real time via the European Radiological Data Exchange Platform network. Monitoring information is collected from about 5,000 automatic surveillance stations in 39 countries (40). In contrast to these government-driven radiation detection networks, Safecast is a global volunteer-centered citizen science project working to empower people with data about their environments (see https://safecast.org). It was started after the FDNPS accident to provide data collected by citizens for citizens and has become the largest radiation detection network in the world. Safecast provides dosimeters and organizes public discussion to engage citizens in measurements and data analytics.

At the University of California, Berkeley, we established the Berkeley RadWatch project to provide transparent and relevant measurements of radioactivity in our environment on a prompt basis for public use and education (41; see also https://radwatch.berkeley.edu). We were among the first to observe the appearance of radioactive materials outside of Japan during the night of March 17, 2011, in good agreement with predictions. The first observations in rain water implied that the contamination would end up anywhere in our environment and in the food produced locally. Since we assumed that the use of physical quantities and units would be confusing to the public, we decided to compare our measurements to the radiation dose a passenger receives from cosmic radiation during a round-trip flight across the United States, which is similar to the dose received in a flight from San Francisco to Tokyo.9 Berkeley RadWatch also publishes high-energy-resolution energy spectra from a mechanically cooled high-purity Ge detector that continuously monitors radioactive particles in the air. It not only publishes the energy spectra every 15 min but also measures and publishes the concentrations of numerous radioisotopes found in the air. As part of the Berkeley RadWatch project, the DoseNet project was initiated. DoseNet supports the design and fabrication of simple radiation dosimeters by students and their distribution and use across the world, with a focus on high schools, to provide opportunities to learn basic concepts in science and engineering and to learn what is normal in our environment (see https://radwatch.berkeley.edu/dosenet/). The radiation detectors have been complemented by meteorological as well as CO2 and air pollution sensors to allow the study of other environmental quantities and their relationships. Figure 5 shows a multisensor instrument that was developed and built at the University of California, Berkeley. The availability of affordable and compact sensors as well as computers such as the Raspberry Pi makes the global distribution of such instruments to individuals and to communities via DoseNet or Safecast possible. The D-Shuttle project represents yet another example that illustrates the power of deploying multiple compact, affordable dosimeters. This project included 206 high school students from within and outside of Fukushima Prefecture in Japan as well as France, Poland, and Belarus (44). Each participant wore a D-shuttle dosimeter for 2 weeks while keeping a journal about their location. All observed dose rates were similar, and there were no statistical differences among the different regions.

In addition to the large-scale networks of dozens or thousands of stationary radiation measurement devices deployed predominantly for the mapping of temporal changes of radiological

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9One such flight is associated with an effective dose of approximately 4 mrem (40 µSv). Typical natural background dose rates are about 0.1 µSv h−1. In some areas, background rates of up to 20 µSv h−1 are measured without any detrimental health effects being observed. In general, levels below 10 mSv have not been unambiguously associated with health effects. The Life Span Study has shown a linear relationship between health effects and dose at levels above 100 mSv (42, 43).
Figure 5

Details related to the DoseNet project, including a map indicating the locations of the deployed sensors. The figure shows information that is available on the corresponding website, including the history of dose rates and energy spectra obtained using the CsI spectrometer, which was integrated into some of the systems. The dose rates observed at Futaba High School (about 20 km south of FDNPS) and in Kōriyama City (about 50 km west of FDNPS) are comparable to those at many other locations in the network and lower than those observed at some others (e.g., Stockholm, Sweden) (43). Campolindo refers to a location in the San Francisco Bay Area. Abbreviation: FDNPS, Fukushima Daiichi Nuclear Power Station.

materials associated with accidents in radiological or nuclear facilities, networks of mobile, human-portable or vehicle-borne instruments have been developed and deployed, driven by nuclear security. As an example, the SIGMA project launched in 2014 by DARPA (the US Defense Advanced Research Projects Agency) has pioneered the development of large-scale radiation detector networks to prevent terrorist attacks that involve nuclear materials (45). At its core are smartphone-sized devices that are complemented by larger detectors on vehicles, along major roadways, or on structures. The large-scale procurement and deployment of more than 10,000 compact devices allowed significant reductions in the cost per device, the development and demonstration of advanced deployment of adaptive architectures, and the acquisition of data

In 2017, the observation of $^{106}$Ru across the European radiation detection network pointed to the releases from the Russian Mayak nuclear facility, which might have been related to the production of $^{144}$Ce for use in the SOX neutrino oscillation experiment at Gran Sasso in Italy.
that could be used to enhance algorithms. These algorithms include advanced machine learning methodologies to improve the sensitivity of the detection and identification of relevant radioisotopes while minimizing the nuisance or false-alarm rate. This development has been complemented by advances in computer vision to use contextual and non-nuclear signatures to inform and improve detection and localization via the use of object-tracking algorithms.

4.1.2. Individual radiation detection systems. Single and non-networked radiation detection systems are used when the subject or object to be measured can be brought to the system or when the object assessed is stationary and the detector can be brought to it. The former circumstances apply in the monitoring of food or people; the latter approach is possible in the mapping of the reactors by muon radiography or the mapping of contamination and leaks by means of γ-ray imaging.

4.1.2.1. Dosimetry and monitoring of radiation exposure. The monitoring of all produce for sale from Fukushima has been required since immediately after the accident. This has ensured the safety of the produce for consumption and—as a secondary effect—provided data to inform the study of changes in the radioactivity levels in a wide range of food items after a nuclear accident (46). Several monitoring systems were developed and used, some of which had been adapted from clinical positron emission tomography; a particular concern was to scan the large quantities of rice produced in Fukushima and the surrounding prefectures (47, 48). A typical system consists of a conveyor belt and detector arrays made of either BGO or NaI(Tl) scintillators surrounded by lead or iron shields to minimize the interference from the potentially contaminated surroundings. These systems have been designed to scan objects such as 30-kg rice bags within seconds to a sensitivity below 50 Bq kg\(^{-1}\), which is sufficient to confirm that the produce is below the regulatory limit (100 Bq kg\(^{-1}\) for this type of foodstuff\(^{11}\)). In addition, individual NaI- and high-purity-Ge-based counters have been acquired and distributed across communities in Fukushima Prefecture to enable local residents and farmers to test the food produced in their backyards and farms. Each year since 2011, millions of food items have been monitored, and many of the measurement results have been made available according to time, location, and food type (49). Of the more than 10 million bags of rice scanned per year, 72, 28, 2, and 0 bags were found to exceed the limit in the years 2012, 2013, 2014, and 2015, respectively.

As part of the Health Management Survey by the Fukushima prefectural government, residents’ exposure was assessed in three ways: (a) estimation based on their location during the phase of high dose rates and measured or modeled air-dose rates, (b) measurement with personal dosimeters, and (c) measurement with whole-body counters (WBCs). WBCs are used to reliably assess internal radiation exposure after ingestion or inhalation of radioactive materials. A typical WBC consists of several NaI(Tl) scintillator detectors to measure γ-rays emitted from the subject in either a sitting or standing position; the whole-body count is performed within a few minutes. The conversion of counts to internal dose is based on phantoms and benchmarked Monte Carlo simulations. Although the first limited WBC measurements were performed only at the end of June 2011 in Fukushima Prefecture, by the end of the year, more than 15,000 had been performed, and an additional 90,000+ scans were performed in 2012. All residents who showed additional

\(^{11}\)This limit and the limits of 50 Bq kg\(^{-1}\) for milk products and 10 Bq kg\(^{-1}\) for drinking water, which were defined in April 2012 by the Japanese government, are about a factor of 5 lower than the previous limits in Japan and about a factor of 10 below the limits established in the United States and Europe. These differences are due to varying assumptions about the fraction of contaminated food that is consumed over the year and the total allowable internal dose per year. An important context for these numbers is the concentration of 50 Bq kg\(^{-1}\) in naturally occurring \(^{40}\)K typically found in milk.
exposure burdens were found to have consumed food that had not been monitored, such as local wild mushrooms and berries (50, 51). As with many other aspects of the response to the accident, these observations are relevant in guiding future actions that require a careful trade-off between costs and benefits. Out of the hundreds of thousands of people scanned, only 25 were identified as having an additional dose exposure of 1 mSv, and only 2 people had more than 3 mSv. In most cases in which contaminated foods had been consumed, the exposure was significantly less than 1 mSv. The Babyscan system was developed and introduced in 2013 to account for the smaller anatomy of children, reflecting a primary concern about the internal uptake of contamination in children (53). Three units were installed, and in 2014, more than 2,700 children were scanned with them; no measurements exceeded the detection limit. This finding provided immense reassurance to the parents, a large fraction of whom had completely avoided local food and even tap water despite the monitoring efforts, reflecting people’s distrust of the authorities and misperceptions of the radiation risks. Thus, the introduction of the Babyscan was very successful, specifically in enabling evidence- and fact-based communication.

To address concerns about an early uptake of $^{131}$I among residents—an issue that led to a significant increase in thyroid cancers after the Chernobyl accident—thyroid monitors were used to monitor evacuees and residents as early as March 2011. Because iodine accumulates in the thyroid, a thyroid monitor typically consists of an NaI(Tl) detector with a collimator mounted on an arm that allows the instrument to be brought close to the thyroid gland. This concept was first introduced in the 1940s and, because of its widespread use, was readily available for screening in Japan. Such measurements and estimates, considering evacuation pathways and dose-rate measurements and models, pointed to fairly small iodine exposures of a few millisieverts—substantially lower than the mean value of 490 mSv estimated in the evacuees from the area around Chernobyl in 1986. On the basis of the external air-dose-rate measurements and the estimated locations of about 412,000 evacuees and residents between March 11 and July 11, 2011, and a shielding factor of 0.4 for staying indoors for 16 h and outdoors for 8 h, the mean dose in the Fukushima evacuee population was estimated to be 0.8 mSv, with 99.5% of all measurements below 3 mSv—the average annual dose in Japan and the United States. These numbers can be seen as reflecting an upper limit because personal dosimeters worn by residents and evacuees showed a considerably lower external dose rate by about 40%. This difference has been attributed predominantly to the underestimation of shielding factors in and around buildings.

4.1.2.2. Muon imaging. Muon imaging makes use of muons, which are produced by cosmic ray interactions in the atmosphere, to create images of objects (54). Muon imaging has become famous in the search for hidden chambers in the Egyptian pyramids, the mapping of volcanoes, and more recently in the attempt to image the internal structures of the Florence Cathedral (55–58). The technique was originally implemented as transition radiography (similar to X-ray radiography), whereby the attenuation of muons was measured as a function of position within or behind the object of interest, resulting in a two-dimensional radiograph. As an extension of radiography, muon tomography—the three-dimensional reconstruction of objects—was introduced in 2003 and uses the Coulomb scattering properties of muons in matter, which depend on the density, atomic number, and shape and extension of objects (59). It requires measurement of the incident and outgoing muon flux on an event-by-event basis, with the object of interest positioned between the two muon-tracking detectors. The fundamental properties of muons and their high energies allow them to penetrate hundreds of meters of rock, providing a unique advantage compared with

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12 It is worth mentioning that the body burden in adult males in Japan in 1964 was 535 Bq per body—much higher than the observed body burden in Fukushima in 2011 and afterward (52).
conventional imaging modalities and making them suitable for imaging objects behind or inside of shielding materials that are too thick or deep for other approaches. Therefore, muons are of particular interest in the detection and imaging of nuclear materials, which are characterized by high density and high atomic number and are typically shielded. Prime examples include the imaging of nuclear fuel in reactors (or of fuel debris, as in the three units at FDNPS), imaging of spent nuclear fuel stored in dry casks, and detection of the illicit transport of nuclear materials. Besides their ability to penetrate extended shielding materials and their scattering properties, which allow the identification of materials with high density and high atomic number, muons are naturally occurring and ubiquitous. This means they are cost-free, unlimited, and entirely passive and are therefore neutral with regard to health and safety regulations. The great disadvantage in the use of muons is their low flux of about 1 muon per square centimeter and per minute, which limits their use to applications that are not time-critical.

The advantage of muon imaging in the assessment and localization of the fuel and the fuel debris in the three reactor units at FDNPS was realized very soon after the accident. It provided a unique opportunity to image the interior of the reactor vessels despite their large structures and shielding and the very large radiation dose rates found in the reactors, which made access impossible, at least for the first few years. Two separate efforts were initiated: one to build a muon tomography system and one to build a far simpler, smaller radiographic system (60, 61). The advantage of the smaller system is its ease of deployment. However, it is significantly inferior in terms of field of view (FOV), angular resolution, and contrast compared with the tomographic system. Between February 2015 and September 2017, four different measurements, each 1–3 months long, were performed with the simpler radiographic system located outside reactor buildings 1–3. While the image quality was found to be quite limited in terms of spatial resolution, contrast, noise, and FOV, it was possible to infer some information about the location of the fuel debris.13 Although the muon tomography system had been built and would have been available for measurements, it was not used. It likely would have provided better images because it is inherently three-dimensional, has higher sensitivity (since it makes use of the scattering and attenuation of muons), and provides higher specificity to distinguish high-density, high-atomic-number materials (e.g., uranium) from lower-density, lower-atomic-number materials (e.g., concrete, water). By now, robots have been developed that can operate in the high-radiation fields of the RPV and provide the necessary information about the location of the fuel debris. However, it is unfortunate that the more advanced muon imaging technology was not used in place of the simpler and less capable one.

4.1.2.3. γ-Ray imaging. The use of γ-ray imaging has been well established in medicine since the 1950s and in astrophysics since the 1970s. Over the last 20 years, it also has found applications in nuclear security and safety and in radiation protection. The goal of γ-ray imaging is to measure the spatial distribution of γ-ray-emitting radionuclides or that of chemical compounds that are labeled with such radionuclides. It represents a radiotracer technique that has found applications not only in medicine but more broadly in biology, chemistry, and the mapping of environmental processes.14 The ability to measure the energies as well as the angle of the incident γ-rays allows the generation of radioisotope-specific images. In contrast to transmission imaging, γ-ray imaging is an emission-based imaging modality, but it is also able to provide two-dimensional projection

13 The image quality was limited by statistical and structural noise due to the large structures such as the PCV and the RPV and shielding walls, with spent fuel pools serving as the reference for calibrations. The limited FOV in the radiographic measurements allowed for imaging of only the RPV and not the PCV, which also restricted the effectiveness of the muon imaging.

14 George de Hevesy is known for the development of the radiotracer concept, which led to his winning the Nobel Prize in Chemistry in 1943.
and three-dimensional tomography. Different γ-ray imaging modalities have been developed to address the specific needs and constraints of its use. The first γ-ray maps were created in the 1940s using the newly available artificial (i.e., human-made) radionuclides by simply moving a single collimated radiation detector over the region of interest—for instance, to measure the uptake of $^{131}$I in the thyroid (62). A major advance was the introduction of the so-called Anger camera, named after the invention by Hal Anger in 1957. The Anger camera consists of a two-dimensional position-sensitive NaI(Tl) detector and a collimator that is used to create a projection of the radionuclide distribution onto the detector (63). The two-dimensional positions of individual γ-rays are encoded by a two-dimensional array of photomultiplier tubes, which are attached to the scintillation crystal. The collimator is typically built of a high-density, high-atomic-number tungsten alloy, and its geometry and dimensions are the driving factors in the achievable sensitivity and resolution of the system. Most collimators are built as parallel-hole or single- or multiple-pinhole collimators or as coded-aperture systems. In contrast to parallel- and single-pinhole collimators, multiple-pinhole and coded-aperture systems create overlapping source projections that require dedicated image reconstruction algorithms. Similar to the spatial modulation of the incident γ-ray flux in a coded aperture, rotation modulation collimators modulate the incident γ-ray flux in time by using rotating one- or two-dimensional collimators in front of a non-position-sensitive detector. Reflecting the finite sizes of collimator and detector, collimator-based systems typically have an FOV less than $\pm 30^\circ$. Because of the increased penetration and scattering of γ-rays in the collimator, the achievable performance degrades substantially for higher energies. Compton imaging, a collimator-less γ-ray imaging modality that uses the kinematics of the Compton scattering interaction process to allow the reconstruction of the directions of incident γ-rays, was first described in the 1970s and first realized in COMPTEL in the 1990s (64–66). It has become more readily available over the last 20 years with the advancement of three-dimensional position-sensitive semiconductor detectors (67–73). It provides imaging capabilities with relatively high sensitivity over a wide range of energies—typically $\sim 150$ keV to several MeV, where Compton scattering is the main interaction mechanism—and conceptually with an omnidirectional or unlimited FOV. Because no collimator or lens is required, Compton imaging systems can be made to be relatively lightweight and compact. The trade-off with these benefits is the limited image contrast and angular resolution that can be achieved; the angular resolution is greater than $1^\circ$ and is typically about $5–10^\circ$. In many cases, the complexity of the instrument and its readout and the necessary event and image reconstruction methods may be considered additional disadvantages compared with collimator-based systems.

The use of γ-ray imaging became of interest in Fukushima to assess contamination and to monitor decontamination efforts on-site and in the reactor and turbine buildings as well as off-site in the evacuated areas. The goal was to deploy γ-ray imaging instruments to map contamination more accurately and more safely compared with hand-portable, human-carried radiation detectors. Contamination maps can be created without the need to move the radiation detector close to the contamination—a feature that results in quicker assessment and a reduced dose to the operator. A wide range of collimator-based and Compton scattering–based imaging systems have been developed or refined over the course of the last 10 years (74–80) by research groups or companies with now commercially available instruments (e.g., 81; see also https://www.mirion.com/products/ipix-ultra-portable-gamma-ray-imaging-system, https://h3dgamma.com/h100.php, http://phdsco.com/, and https://www.gammareality.com/). These developments have been partially driven by the availability of position-sensitive semiconductors [e.g., CdTe, CdZnTe

$^{15}$The invention of the cyclotron and the discovery of fission led to the production of a wider range of radionuclides of interest for radiotracer and γ-ray imaging studies.
(CZT), high-purity Si and Ge] and scintillators [e.g., cerium-doped multicomponent gadolinium aluminum gallium garnet (GAGG)] along with advances in compact and integrated readouts (82).

To overcome the limitations in the use of a passive collimator or aperture to image $\gamma$-rays at low energies, a new concept introduced in 2009 allows simultaneous coded-aperture and Compton imaging with active detector elements only. The High-Efficiency Multimode Imager (HEMI) consists of coplanar grid (CPG) CZT detectors, each 1 cm$^3$ in size and arranged in two planes with one plane sparsely populated with 32 detector elements and the second plane fully populated with 64 detector elements arranged in an 8 $\times$ 8 array (83, 84). The placement of the elements in the front plane was chosen pseudorandomly to minimize the imaging artifacts in the near and far fields for coded-aperture imaging. The CPG configuration was chosen for the CZT detectors to improve the energy resolution by compensating for the limited charge-carrier properties observed in CZT and all room-temperature operational semiconductors (85). This approach of using active mask elements provides a compact and comparatively lightweight instrument (< 3 kg with battery) with imaging capabilities of about 50 keV to several MeV. It also provides the maximum possible overall detection efficiency because all interactions in the mask will be registered. As with the other collimator-based systems, the limited FOV defined by the finite extension of the mask remains. To overcome this limitation, a spherical design was developed in which each CPG CZT detector element serves simultaneously as detector and mask. The feasibility of the Portable Radiation Imaging, Spectroscopy and Mapping (PRISM) system has been shown, and a fully operational instrument consisting of 130 detector elements has been realized (86, 87). The spherical arrangement of detector elements not only provides the first realization of an omnidirectional coded-aperture imager (and with only active elements) but also enhances the system’s performance as a Compton imager because, on average, the detector elements are further separated compared with those of the planar devices described above, resulting in a larger separation between the first two interactions and an improved angular resolution for more events. This system is also hand-portable and can image and map sources and contamination very effectively. It represents a “smarter” way to use radiation detectors as imagers. A more compact, lighter version called mini-PRISM consists of a cubic arrangement of about 64 of the same detector elements, which can provide similar coded-aperture and Compton scatter imaging capabilities on small unmanned aerial systems (sUASs) as well.\footnote{An sUAS includes the unmanned aerial vehicle as well as the control of and communications with it. sUASs are sometimes also called drones, although the definition of drones is ambiguous because the term can refer to other unmanned systems or vehicles, including those with fully autonomous deployment.}

All $\gamma$-ray imaging systems described above and relevant to the efforts in Fukushima are equipped at least with a visual camera to allow the overlay of the visual with the $\gamma$-ray image and thus provide important contextual information about the location of the contamination. Some systems are also equipped with a laser to measure the distance from the instrument to a specific location in the FOV, which allows better estimation of the dose rate at that location. After the first couple of months following the FDNPS accident, only the radioisotopes $^{134}$Cs and $^{137}$Cs remained of relevance, and by now, only $\gamma$-rays from $^{137}$Cs remain of interest, at least for $\gamma$-ray imaging. The dominating $\gamma$-rays with 604 and 798 keV for $^{134}$Cs and 662 keV for $^{137}$Cs are almost ideal for the Compton imaging modality. Therefore, most of the $\gamma$-ray imagers deployed in Fukushima were Compton cameras. To keep the random- and false-coincidence rates acceptable, the Compton cameras deployed in the reactor and turbine buildings to date have been heavily shielded by lead, in particular in locations with dose rates at levels of millisieverts per hour.
4.2. Mobile Systems

Static radiation detection systems and networks as discussed above provide continuous monitoring in time but are noncontinuous in space because they typically are sparsely distributed. They can observe temporal changes quickly at the location of the radiation detector, and this capability is important in monitoring critical pathways and locations, in observing changes over larger areas, and in communicating about radiation more broadly or about concerns of contamination more specifically. In contrast, mobile radiation detection systems provide continuous monitoring in space but are noncontinuous in time because, in general, they are not used continuously. As a requisite to track the location of the system over time during the deployment, a global positioning system (GPS) is typically integrated and is synchronized to the radiation detection system. In so-called GPS-denied environments, other means for localization are required, such as inertial measurement units (IMUs). Mobile ground vehicles are limited to the mapping and monitoring of roadways; hand-carried instruments can map areas in urban and more difficult-to-access areas but are limited in speed. Aerial vehicles can assess otherwise-inaccessible areas and provide continuous spatial radiation maps over large areas quickly. AMS (see Section 1) is composed of manned fixed-wing and rotary-wing aircrafts and radiation detection systems that can respond quickly to radiological emergency events (29). While these large, manned aerial platforms can cover an extensive area quickly, which is particularly important when mapping large-scale radioactive plume depositions, they are limited in resolution, are expensive to operate and maintain, and require time to reach the location of the incident. In Fukushima, it took several days after the large releases of radioactive materials for the AMS to be deployed. sUASs can be operated closer to surfaces and objects, providing much higher-resolution and higher-fidelity mapping capabilities even in complex indoor and outdoor environments. They can be deployed in hazardous environments to reduce the risks to human operators from structural damage or radiation exposure. To cover larger areas, multiple vehicles can be deployed in swarms. Advances in sensor technologies and data processing capabilities will enable the proliferation of autonomous systems including the ability to deploy individual systems as well as swarms to map radioactive materials in three dimensions efficiently, accurately, cost-effectively, and in real time. While the ability to operate completely autonomously and in swarms for radiological mapping is currently under development, semiautonomous systems have been developed and are already available. Semiautonomous operation implies the independent operation of an sUAS to follow a path prescribed by GPS waypoints. Because sUASs are substantially cheaper to procure, operate, and maintain than large, manned aerial vehicles, they can be stationed in many locations. In addition, the radiation detection and mapping equipment can easily be replaced by other sensor systems and deployed for a multitude of missions.

4.2.1. Three-dimensional scene data fusion. As described previously, the development of compact, hand-portable \( \gamma \)-ray imaging systems over the last 10 years has enabled the static deployment of such systems in a wide range of applications. Parallel advancements in computer vision now make it possible to combine these complementary technologies, enabling unprecedented and smarter ways to detect, map, and visualize nuclear radiation fields. Scene data fusion (SDF) represents the realization of this combination through the integration of contextual sensors, such as visual cameras or lidar, and nuclear radiation detection and imaging instruments (88–90). SDF enables the three-dimensional mapping and visualization of \( \gamma \)-rays in the context of local scenes while the instrument moves freely through the physical environment.

Fusing complementary imaging modalities is not a new concept. For example, in biomedical imaging, X-ray imaging, which reveals anatomical features, is routinely combined with radionuclide imaging, which reveals functional or physiological features. The combination provides
unparalleled means to inform diagnosis of disease, to monitor therapy, and to develop pharmaceuticals to cure a wide range of diseases (91, 92). A static gantry is sufficient because the subject of study can be brought to the instrument. In contrast, for the assessment of contamination after a nuclear incident, the monitoring of a nuclear facility, or the search for radioactive materials, the instrument needs to be brought to the radiation field and freely operated. SDF uses contextual sensors, such as lidar or visual cameras, to map a scene in three dimensions, providing the “anatomy” (i.e., structural information) of the local environment. A simultaneous localization and mapping (SLAM) algorithm acts on the data from the contextual sensors to construct a three-dimensional model of the environment while simultaneously solving for the position and orientation of the system within the scene with centimeter-level precision (93, 94). The measured radiation counts or reconstructed radiation image can then be projected into the three-dimensional scene map. Measuring the three-dimensional scene allows the voxelization of objects whose surfaces have been mapped and the reconstruction within these objects in three dimensions, as is done in tomography. The Localization and Mapping Platform (LAMP) represents a realization of SDF in a compact and modular package that can integrate the radiation detection or imaging instruments and can be hand-carried or mounted on unmanned ground vehicles (UGVs) or aerial vehicles (95). All the reconstructions, mapping, and data fusion can be performed in or close to real time while LAMP is being moved through or over the scene. SDF has been demonstrated in environments ranging from small rooms to large stadiums and villages. First steps in the development and realization of SDF were taken in 2004 using a position-sensitive high-purity Ge detector as a $\gamma$-ray imager on a cart combined with a 4$\pi$ photo camera (96). This provided omnidirectional or 4$\pi$ static $\gamma$-ray images overlaid with a visual image to guide the localization of radioactive sources. The integration of a single-beam lidar scanner resulted in the first volumetric image (97). To improve the image quality (specifically, the image contrast) efficiently, a list-mode maximum-likelihood expectation maximization reconstruction was integrated (98). The introduction of more compact $\gamma$-ray imagers (e.g., HEMI, lidar sensors) as well as algorithms (e.g., SLAM) allowed the realization of SDF from moving platforms (99–103). Contextual sensors typically are rotating lidar, complemented by GPS/IMUs to enhance the accuracy in the localization, and visual cameras. Lidar systems are able to create point clouds and three-dimensional maps in real time; visual imagery–based photogrammetry requires substantial computer processing and is not yet able to provide accurate and complete three-dimensional maps in real time. SDF inherently tracks the position and orientation of the instrument and provides the basis for accurate intensity and quantitative reconstructions, such as emission rates, source activities and mass, and dose rates, anywhere in the scene. Figure 6 shows results obtained with LAMP in combination with mini-PRISM, which was hand-carried through a $^{238}$Pu production facility. The measurement took about 2 min and resulted in the detailed mapping of the cluttered facility and the three-dimensional reconstruction of $^{217}$Np in the pipes via the reconstruction of $\gamma$-rays at 312 keV. Figure 6 also indicates the augmented reality view provided in real time. The full data set that was collected allows virtual replay of the measurement and optimization of specific data reconstruction parameters to enhance or suppress specific features and signatures.

Similar developments have been pursued in the United Kingdom using simpler radiation detection and mapping concepts (e.g., 104; see also https://www.createc.co.uk/innovation/products-technologies/n-visagegamma-imager/). One such lightweight system that is being deployed in buildings on the FDNPS site is equipped with single-beam lidar and a small, collimated CZT detector. JAEA and other institutions in Japan have adopted these concepts for demonstrations on-site at FDNPS and off-site, including deployments using sUASs and robots. While these developments in Japan have shown progress, they are not yet able to take data from moving platforms and instead require measurements to be made statically. Complete
Three-dimensional reconstruction in a $^{238}$Pu production facility. A hand-carried mini-PRISM $\gamma$-ray imager, which consisted of 64 CPG CZT detectors arranged in a cube (inset, upper left), was used. The measurement took about 2 min. The $^{237}$Np contamination in two pipes was detected, mapped, and visualized in near real time. Also shown is the real-time AR view (inset, right) that the operator could see while carrying the instrument or remotely on a computer. Abbreviations: AR, augmented reality; CPG, coplanar grid; CZT, CdZnTe; PRISM, Portable Radiation Imaging, Spectroscopy and Mapping.

three-dimensional maps from larger areas or complete buildings of FDNPS could have been created already, which would have provided enormous benefits in the planning and monitoring on-site and in the buildings in addition to ensuring the safety of the operators. Unfortunately, these technologies—although available—have not been deployed yet in Japan.

### 4.2.2. Manned platforms.

Within hours of the first major releases of radioactive materials from FDNPS, radiation detectors were mounted onto cars and driven to and around the site to complement the stationary measurements. Over the following months, radiation detectors also were mounted onto buses to monitor urban and suburban areas regularly, at least in the nonrestricted areas. NaI(Tl) spectrometers and simple Geiger–Müller counters were typically used to measure air-dose rates. One limitation of these measurements—as shown in Figure 7—is the limited range. The sparsity in the mapping locations can be seen in the stationary and car-borne deployments. In contrast, the airborne instruments are able to map contaminations or depositions contiguously over larger areas (but sparsely in time, as reflected by the fact that these airborne measurements were performed only a few times per year or less).

Parallel efforts supported by DHS have been developing more advanced technologies to detect and map radiological sources at standoff distances of a few meters to up to 50 m. The RadMAP (Radiological Multi-sensor Analysis Platform) was built as a development platform for emerging concepts in mobile radiation detection and imaging (105). It also allows the systematic study of
natural radiological background variations and their correlations with contextual data, such as visual and hyperspectral imagery. It has been used to acquire extensive background measurements and correlated contextual data that can be used to test algorithms as well as detection and imaging modalities (106). As a result of these developments, more compact systems are now being built for car-borne instruments; these systems consist of similar contextual sensors and several large NaI(Tl) detectors, which are mounted in a vertical barrel-like arrangement to enable enhanced radiation detection and localization up to 20 m (depending on the background, source strength, and speed), reflecting their focus on urban environments (107).

Conventional means of aerial assessment include manned helicopters and fixed-wing airplanes that can map large areas quickly. Many countries own such assets not only for mapping after nuclear incidents but also for other emergencies and monitoring missions. The AMS fixed-wing aircrafts typically fly at an altitude of 300 m, a speed of 72 m s\(^{-1}\), and a line spacing of 700 m; helicopters typically fly at 150 m, 36 m s\(^{-1}\), and 300 m (29). In the event of an accidental or intentional release, the fixed-wing system is expected to provide initial coarse ground deposition maps and 1-m-above-ground exposure rate equivalents or air-dose rates. Its purpose is to validate or modify a deposition model and provide local decision makers guidance on evacuation and shelter decisions. Helicopters are used to map radioactive material deposition with greater resolution and sensitivity compared with the fixed-wing aircraft. They are deployed over longer durations as the incident timeline progresses from the emergency phase to the recovery phase. The achievable spatial resolution in these deployments can be approximated to be on the order of the altitude of the flight, defined by the air attenuation and inverse squared distance scaling of the radiation flux. To distinguish between radioactivity in the air while flying through a plume and ground depositions, manned aerial systems are often equipped with so-called upward-looking detectors that are shielded underneath.

Figure 7
Comparison of dose-rate measurements in Fukushima Prefecture performed by (a) stationary instruments, (b) car-borne systems, and (c) airborne systems. Data from Reference 38.
Japanese researchers supported by the Government of Japan collaborated in the initial AMS measurement campaigns and have continued to perform aerial radiation monitoring since then using similar NaI(Tl) detectors. Within the first year of the accident, starting in April 2011, the areas within a 40- to 100-km radius of FDNPS were measured four times, and the range was extended across the whole of Japan (108). As illustrated in Figure 4, the air-dose maps that were created show important information about the extent of and changes in the contamination over several years. As with car-borne systems, more advanced radiation detection and imaging systems have been developed for manned helicopters compared with the systems deployed in Japan. The Airborne Radiological Enhanced-sensor System (ARES) consists of 92 time-synchronized CsI(Na) detectors with dual photomultiplier readouts arranged in an active coded mask configuration to improve angular resolution in the roll dimension of the helicopter (109). Being able to provide some imaging capability increases the accuracy of the reconstruction, in particular for single overflights and for point or compact sources. Similar to the HEMI and PRISM instruments, the implementation of an active mask is necessary for aerial platforms, which have stringent weight constraints. In contrast to the systems mentioned above, which operate at 1 Hz, ARES operates at 10 Hz, including the inertial navigation system and the visual camera, which provide localization and orientation (pose) estimates at that rate. Detector energy data, measured in event-by-event or list mode, are binned accordingly in time, providing more accurate localization capabilities, specifically for higher-speed flights. In addition, SDF concepts have been deployed using the visual cameras and photogrammetry (90).

4.2.3. Unmanned platforms. Critical dose-rate measurements were performed within a few days after the FDNPS accident with manned and stationary systems. Manned aerial systems provided essential information about the deposition of fallout across Fukushima Prefecture. However, for on-site assessment and monitoring, the use of manned systems was limited because of concerns about radiation exposure to the human operators, and stationary systems could only be used to measure dose rates in the human-accessible and fixed locations. These limitations motivated substantial investments, in particular in robotics, in Japan. On the FDNPS site, the goal of unmanned platforms continues to be the automatic, remote-controlled, or autonomous assessment of structural damage and the access and mapping of the highly contaminated areas within the buildings. Detailed assessment of the PCVs and RPVs and of the fuel and fuel debris has been of particular interest.

Initially, only general-purpose and off-the-shelf UGVs and robots were available; these were used to assess structural damage, water levels, temperature, and radiation levels. Of particular importance was the deployment of visual cameras to assess the structural damage and access pathways into the units and into the PCVs. Given the complex nature of the nuclear facility and the damage and contamination, systems were quickly found to be insufficient (see the reports available at http://irid.or.jp/en/research/). They were too big, not agile enough, and not able to operate in the wide range of environmental conditions (including in water) or in areas with high dose rates. Most of the systems were lost because of operator mistakes, loss in communication, or the breakdown of the robot. Subsequently, remote-controlled robots were developed for specific purposes and specific requirements, such as operation on and under water, access through pipes, and operation in very-high-radiation fields (see the reports at http://irid.or.jp/en/research/). Some were designed to adapt and change shape during operation. In addition, large mock-up facilities were built to enable the development and optimization of technologies and to provide training in the operation of the robots. The first radiation and dose-rate measurements in the PCVs of all three units were done by analyzing the image noise in the cameras mounted on the robots, before the cameras (and, sometimes, the robots) broke down. Initial measurements indicated dose rates
up to hundreds of sieverts per hour—a radiation level that is deadly within minutes for humans. The first noisy images and dose rates from within a PCV were obtained in April 2015, and by end of 2017, more detailed images and maps from above and under water were obtained from all three units. In parallel, researchers at JAEA acquired a compact Compton imager built of GAGG scintillators. GAGG is characterized by a high light yield and good proportionality, resulting in good energy resolution and a fast decay time to provide fast timing properties, which are important for Compton imaging in high-radiation fields (110). GAGG has been deployed in one of the turbine buildings and recently in a hallway in the reactor building of unit 1, using a commercially available PackBot robot. For this system to operate at dose rates of a few millisieverts per hour, it had to be shielded by 1–2.5 cm of lead. Photogrammetry was used to reconstruct the scene in three dimensions and project the radiation imaging onto it, but this method still required static measurements and careful tracking and pose estimation. The SLAM concept, which was developed more than 10 years ago and demonstrated with the US-developed HEMI system on a JAEA-operated RMAX helicopter in Fukushima 5 years ago, has not been adopted to date.

As an extension of the manned aerial systems—specifically, to achieve better spatial resolution in the mapping of air-dose rates and cesium depositions, which is relevant to providing more accurate guidance for decontamination and its verification—smaller aerial systems were adopted by JAEA, in particular the semiautomatically operating RMAX helicopter built by Yamaha, which was originally developed for spraying pesticides in farming (111, 112). RMAX helicopters are flown at altitudes between 50 and 100 m—lower than manned helicopters and with smaller line spacings, thus yielding better spatial resolution on the order of tens of meters. In contrast to the large NaI(Tl) detectors used for the manned aerial platforms, smaller LaBr₃(Ce) detectors, which provide faster counting capabilities and better energy resolution, were used. Faster counting is important for operations in contaminated areas at lower altitudes. With this system, measurements in proximity to the FDNPS site were performed between August 2012 and September 2016. The unmanned system was able to observe four distinct areas close to the site that showed increased air-dose rates, which were likely associated with four distinct releases of radioactive materials from the plant and different wind patterns. This association is also supported by the slightly different ratios of ¹³⁷Cs to ¹³⁴Cs observed, which reflect the releases from different units with different fuel burn-up. Measurements were performed in the evacuated areas on top of riverbeds to observe and study quickly changing patterns associated with the transport of radioactive materials in rivers and their deposition in riverbeds and vegetation alongside rivers. Other sensitive areas such as schools and kindergartens were surveyed before and after decontamination. Because the measurements were performed over the same areas several times over several years, long-term changes in air-dose rates could also be observed, and the data collected can be used in the study and prediction of long-term effects of decontamination efforts and other human-induced (or non-human-induced) changes. Faster decreases in air-dose rates were observed in agricultural and urban areas compared with the mountainous and forested regions, reflecting the decontamination efforts and other human activities, specifically farming. The impact of human activities has also been observed in the determination of effective and ecological half-lives in the air-dose rate. Effective half-life describes the total decline, and ecological half-life corrects the total decline with the physical half-life of specific radioisotopes, such as cesium in Fukushima. The unmanned aerial system observed an ecological half-life of about 17 years within about 10 km of FDNPS; in the area 3–80 km from FDNPS, the manned aerial systems observed an ecological half-life of about 57 years. Compared with an ecological half-life of 90 years observed in previous studies not related to nuclear incidents, a clear trend in the decline of air-dose rate can be observed that reflects the impact of human activities, such as the extensive decontamination and cleaning efforts (113).
An sUAS-based $\gamma$-ray- and neutron-mapping LAMP system (a), which can detect and localize a heavily shielded source in a car (b) within seconds. The source used here was one significant quantity of a plutonium surrogate, shielded with 12–15 cm of lead and tungsten. (c) The $\gamma$-ray reconstruction (blue) is consistent with background radiation; the neutron reconstruction (red) highlights the three-dimensional location of the source. Abbreviations: LAMP, Localization and Mapping Platform; sUAS, small unmanned aerial system.

The availability of small and affordable unmanned aerial systems has increased over the last 10 years; they are now commercially available with radiation detection systems attached. A typical detection system consists of a small, lightweight survey meter or spectrometer and GPS that provides two-dimensional maps of radiological ground depositions. Three-dimensional SDF goes beyond these two-dimensional projections and enables the full three-dimensional reconstruction of scenes and integrated radiation maps with measurements from sUASs. Figure 8a,b illustrates one such advanced sUAS-based instrument, which consists of an array of CLLBC $[\text{Cs}_2\text{LiLa}(\text{Br}_{1-x}\text{Cl}_x)]$ scintillators$^{17}$ that are integrated into a LAMP system and mounted on an sUAS. CLLBC provides excellent energy resolution and sensitivity for $\gamma$-rays and high sensitivity for thermal neutrons, and therefore it enables the three-dimensional mapping not only of $\gamma$-rays but also of neutron sources (103). Figure 8c shows the results of the measurement of a plutonium-surrogate source with an activity that corresponds to about one significant quantity of $^{239}\text{Pu}$. The source was heavily shielded with lead and tungsten to suppress the $\gamma$-ray signature. The CLLBC-based LAMP system was able to detect and localize the source in the van within seconds of the flyby using the neutron measurements, whereas the $\gamma$-ray measurement reflected only background radiation. JAEA has pursued the deployment of its GAGG-based $\gamma$ camera on an sUAS and was able to successfully localize hot spots on the ground by hovering over them for several minutes. As for the robot-based system, the tracking of the system has not been implemented to date, limiting the measurements to static ones (115).

Of note, researchers at the Institute of Environmental Radioactivity, one of many new institutes and facilities established in Fukushima Prefecture after the FDNPS accident, have attached dosimeters with GPS on wild boars that live in the difficult-to-access mountainous and forested regions near FDNPS. In this way, the boars have been used as a mobile, remotely operating platform to map radiation levels in difficult-to-access areas.

$^{17}$CLLBC represents a new class of so-called elpasolite scintillators characterized by high light yield and good proportionality resulting in a relative energy resolution of <3% at 662 keV, which is excellent for a scintillator. CLLBC has very high efficiency for thermal neutron detection and some sensitivity for fast neutron detection. It can be grown to fairly large dimensions commercially (5 cm in diameter, 5 cm long) (114).
Three-dimensional fused radiation maps obtained with a combined dual-modality coded-aperture imager (a,b), with a Compton imager (c), or in proximity mapping mode (d) integrated with LAMP in a hand-portable configuration. The maps show UF₆ containers that are empty or partially filled with ²³⁵U at different enrichment levels or that are contaminated by ¹³⁷Cs. All measurements were done within a few minutes. Abbreviations: DU, depleted uranium; LAMP, Localization and Mapping Platform.

### 4.3. Future Trends in Radiation Detection and Imaging

Several trends toward smarter, more robust, and more agile technologies to enhance the detection, mapping, and visualization of radioactive materials are already being pursued or can be envisioned. They range from development of specific radiation detection hardware and data analytics to swarms of autonomously operating multisensor systems that would provide detailed, embedded radiation maps over large and complex areas and structures and real-time visualization using augmented and virtual reality. Three-dimensional SDF, one outstanding example of the opportunities provided by advances in complementary fields, has the potential to revolutionize the way we detect, map, and visualize nuclear radiation. The implementation of LAMP provides a compact and modular hardware and software framework that is agnostic to specific radiation detection and imaging methodologies as well as deployment platforms. PRISM and PRISM-like implementations of radiation detectors represent an elegant and smart way to enhance detection and imaging capabilities. **Figure 9** illustrates the use of an SDF-enabled handheld multimodality γ-ray imaging system in the assessment of cylinders being used to store UF₆, which is used in the uranium enrichment process. The figure shows the implementation with a Compton imager for ¹³⁷Cs and ²³⁸U, with a coded-aperture imager for ²³⁵U and down-scattered radiation, and in so-called proximity mode implying the back-projection of counts.

One enhancement currently under development is the use of the new generation of organic scintillators as structural components. A possibility for the future that would reflect yet another...
area of tremendous progress would be to print such materials. Advanced or additive manufac-
turing has become an indispensable tool—facilitating the cost-effective creation of objects—that
was inconceivable before. This tool might allow us to cheaply print not only radiation detectors
but also most components of radiation detection systems and platforms, enabling the large-scale
deployment of such systems. Radiation detection materials will continue to improve, including
their implementation and readouts. For example, many new scintillation materials have been de-
veloped over the last decade, such as the aforementioned CLLBC elpasolite or GAGG ceramic
materials, that promise high efficiency, high energy resolution, fast timing, and mechanical and
environmental robustness. The new generation of oxide scintillators with light decay times of a
few nanoseconds offers the possibility of pulse-mode operation and spectroscopy at $10^9$ cps—two
orders of magnitude higher than is currently possible. As an example, this capability would allow
pulse-mode operation in areas with dose rates of hundreds of millisieverts per hour or higher,
depending on the implementation. Nanocomposites will help to enhance existing scintillation de-
tectors, and new hybrid or organic semiconductor films will make possible the deployment of
conformal photosensors that can also be produced by means of advanced manufacturing. New
integrated detector readouts will enable the compact, low-power operation of many-channel sys-
tems, potentially right on or as part of the detector. In parallel to the detector and signal processing
hardware, algorithms are being developed that allow the processing of data from a broad range
of sensors and sources to extract features and signatures of relevance. Machine learning and ar-
tificial intelligence methodologies are being developed and implemented to utilize the extensive
data being collected and becoming available thanks to the new generation of multisensor systems
as well as other contextual data that are being collected on many scales and in many dimensions.

New approaches to the mobile detection of weak radiological signatures hidden in spatially
and temporarily changing backgrounds are being developed that integrate visual imagery and
three-dimensional scene information to estimate these backgrounds (116, 117). Visual images are
segmented semantically, and each segment or class—for example, trees, roads, or sky—is associ-
ated with a specific background signature. Such computer vision concepts allow the identification
and tracking of objects, which can provide important information about changing radiation rad-
bounds, and the localization, tracking, and labeling of an object of interest. Furthermore, detec-
tion algorithms are trained to identify shielding and scattering objects that affect the energy and
flux of the incident $\gamma$-rays, specifically by correlating these objects with scene and visual image
information. Such multisensor systems provide not only improved means for the detection and
localization of radiological materials but also situational awareness that is critical to guiding the
operation and response. New wireless communication technologies will provide unprecedented
means of collecting and distributing large quantities of data with minimum latency to enable agile
operations, real-time responses, and optimization across entire networks. Edge computing will
allow the processing of large data sets locally on each network node to potentially minimize the
transfer of data for specific missions and associated constraints, and the faster and larger data band-
width of the new generation of wireless networks will enable the effective use of cloud computing.
The Nuclear Street View (86)—allowing people to see naturally occurring background radiation
and its variation on a scale of buildings—will be widely available without causing panic or affecting
the real estate values of houses with slightly increased radioactivity levels. The basic understanding
of radioactivity in our world will reduce misperceptions about radiation and prevent the misuse
of such information, particularly in social media.

The developments described in this section will help to prevent the accidental or intentional
releases of radioactive materials and will be critical in the response and recovery after a radiological
or nuclear incident. In addition, they will enable effective decontamination, decommissioning, and
remediation at FDNPS and the many other nuclear power plants and nuclear facilities around the
world. These advancements ought to be integrated into operating nuclear power plants as well as the new generation of plants that will be built in the future. Although newer nuclear power plants are designed to be inherently safer and more robust to loss of power or external events compared with the previous generations, a finite risk of accidental or intentional releases will always remain. Therefore, smart and adaptable concepts in radiation detection should be integrated to monitor the operations of nuclear power plants, to effectively assess the releases of radioactive materials if needed, and to provide effective response capabilities and communications between operators, responders, authorities, and the public.

5. THE LEGACY OF FUKUSHIMA TODAY

Each of the three major accidents to date at operating nuclear plants has left or will leave a legacy of surprise, beyond-design, human mistakes and of suffering, resilience, and lessons learned. Three Mile Island was the first major accident associated with the meltdown of one reactor core, which—thanks to the containment—did not result in health-threatening releases of radioactive materials. However, as it was the first major accident, it came as a surprise to operators, regulators, and the public and raised new doubts about the safety of nuclear power plants. It led to changes in design and risk assessment, in how nuclear power plants are regulated and operated, and in the establishment or enhancement of incident-response capabilities, such as aerial monitoring systems like AMS and advanced modeling tools like those developed at NARAC. Chernobyl remains the most destructive nuclear disaster to date with its legacy of human error, inherently unsafe design, lack of protection and containment, prioritization of political ambition over human life, and misinformation—but also of human resilience and bravery. The accident at FDNPS stands out for having occurred in Japan—a technologically advanced nation with the benefit of lessons learned from previous incidents and an economy that enabled the development and implementation of advanced and robust technologies to help prevent and better respond to such accidents. However, in contrast to the prior two accidents, this one was induced by two major natural events—the Great East Japan Earthquake and the subsequent tsunami—that caused three reactors to lose power almost simultaneously (the earthquake took out the off-site power supply, and the tsunami took out the on-site power supply). The fact that the available data from the Jògan tsunami in AD 869 and more recent predictions about seismic events did not result in new requirements reflects the inherent problems in regulating such facilities in Japan—problems that were compounded by the close relationship in the past between regulators and operators. This neglect was amplified by the design flaw of positioning air-cooled generators and critical electric switchboards under the reactors, which allowed these generators and switchboards to be easily taken out by the tsunami. Instead of promoting attitudes and practices to emphasize safety and the concept of safety culture, competing goals such as production and costs were prioritized in the design and operation of the plant. The top-down command structure, with the central government in command to direct actions and resources, prevented a more effective response on-site. This issue was also reflected in the complete lack of preparedness for such an accident among the public and in adjacent communities. The operation of nuclear power plants was supposed to be without risk, and the actions of operators and authorities were to be trusted without question. Preparing for such an event would have implied that these plants might not be safe. As Koichi Kitazawa, chairman of the Rebuild Japan Initiative Foundation’s Investigation Commission, said during an NPR interview in March 2012, “You can’t adequately prepare for a disaster that you don’t admit can ever happen” (118) (quotation paraphrased by A. Kuhn).

The FDNPS accident also stands out as the first major nuclear accident in the new era of social media, in which information, beliefs, and opinions can be exchanged instantaneously across
the world without any vetting of the information. It provides enormous benefits but risks as well, particularly with regard to responding to accidents. Social networks can be useful, but they also can serve as platforms for misinformation, creating or reinforcing misperceptions—especially in sensitive and often-misunderstood topics such as nuclear radiation. In Fukushima, social media did provide some means of communication across the local communities, yet it mainly amplified the uncertainties and fears about the situation as well as the risk of radiation and potential health effects. As in Chernobyl, the operators and response personnel showed great resilience and bravery in their actions. Also, despite the lack of reliable information, rational decisions were made in the adjacent communities to evacuate, which was the best response given the uncertainty of the situation. In retrospect, the evacuation—in particular that of the sick and elderly—led to casualties that could have been prevented by keeping people indoors in homes and clinics. Such preventive measures might have been possible if the right data had been available. However, even if that had been the case, the residents and the communities did not expect an accident to happen, and therefore they would not have been able to effectively use the information. Thus, it is important not only to use advanced and robust technologies to provide the critical data and associated information but also to ensure that the information can be used to inform an effective and rational response. The fact that the Onagawa Nuclear Power Plant was not flooded and served as a shelter for the residents of the village of Onagawa, which was completely destroyed, emphasizes the need to explore and utilize historical data as well as the inherent safety and robustness of such plants.

In contrast to FDNPS and the Daini Nuclear Power Plant, which are operated by TEPCO, the Onagawa plant, operated by the Tōhoku Electric Power Company, was built at sufficient height with a sufficiently high seawall. Since the accident, the seawall at Onagawa has been raised from 14.8 to 30 m, and Tōhoku Electric Power is seeking approval to operate two of its three reactors again in the near future.

While the FDNPS accident in itself caused extensive suffering, organizations such as the WHO agree that there will very likely be no measurable public health effect that is directly attributable to the radiation. What did result in measurable health effects can be attributed to the prompt evacuation—in particular, that of the elderly and fragile population—and the uncertainty about the future. The difficulties in evacuees’ daily lives, separation from family members, and loss of property and business/employment were further complicated by the fear of developing cancer from accident-related radiation exposure and the societal stigma that resulted from those exposures. The unpreparedness and lack of knowledge about radiation as well as the sometimes-confusing communications (or lack of communication) compounded this effect (119–121).

Technologies have advanced tremendously over the last 9 years and will continue to do so, which will help us to prevent and respond to nuclear accidents. These advances range from inherently safer nuclear power plants to radiation detection and imaging instruments and networks. Of particular importance are technologies to make systems more robust to prevent accidents and to enable more effective responses after an event. More effective, agile, and smarter means in the detection, mapping, and visualization of nuclear radiation have been developed, such as the SDF concept, which enables fast, accurate, and remote assessment and visualization of complex environments and radiation fields by integrating advances in radiation detection and imaging with innovations in computer vision, machine learning, and robotics. Being able to visualize complex radiation environments in three dimensions not only helps operators, first responders, and decision makers but also facilitates the communication of radiation-related information to the public. However, in addition to developing superior technologies, it is necessary to ensure that these technologies are utilized effectively and swiftly without prioritizing local or national interests. This is particularly important for events such as the FDNPS accident, which have a global impact.
The Fukushima accident occurred because of a combination of a natural disaster and human mistakes, such as the neglect of historical information. It reflects the critical need for the development and adoption of more robust and smarter technologies as well as resilient communities and societies. It is necessary but not sufficient to deploy technologies that can provide data and information even in catastrophic events; citizens also must be able to make use of such information to guide effective responses and rational, evidence-based dialogue afterward. Social media can play an instrumental role in providing the platform for rational and not fear-driven communications, specifically when trusted sources—from government and nongovernment organizations—are established before the event. The resources of the Internet and social networks, the availability of affordable sensors, and the existence of nonprofit organizations and programs such as Safecast and DoseNet are collectively empowering citizens and the next generation to observe, compare, learn, and communicate about the world around us. These trends will result in more technologically and scientifically literate citizens and societies, which will be critical in the development and adoption of advanced technologies to address some of the major challenges regarding human well-being now and in the future. The last 9 years have shown profound misperceptions not just about nuclear radiation but about almost any advanced technology, such as genome editing and modifications, nanotechnologies, and even vaccination, reflecting more broadly the existing misperceptions of the concept of risk. One has to be aware of the risks related to the development and adoption of advanced technologies; one also has to be aware of the potentially substantial negative impact of not adopting them.

In Fukushima and Japan, enormous progress has been made in containing the nuclear disaster, developing new technologies, introducing important changes in the oversight and operation of nuclear power plants, and improving communication with and thereby empowering the public. Hopefully, the legacy of Fukushima will enable continued rational discussions about advanced technologies in general and energy production in particular, in Japan and globally.

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Errata

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