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The Three Mile Island, Chernobyl, and Fukushima Daiichi Accidents and their Radiological Impacts

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Abstract
Abstract: Fukushima Daiichi is the most recent in a series of major power reactor accidents. With Three Mile Island and Chernobyl, Fukushima Daiichi offers another event in which severe fuel damage occurred, fission products were released to the environment, and public evacuations were implemented. Improvements in plant and regulatory performance are required to eliminate major reactor accidents. These events are minimized by protecting the three fission product barriers and focusing attention on preserving these structures. Protection of fission product barriers is a necessary and sufficient requirement to limit the radiological aspects of a power reactor accident.

Keywords
Fukushima Daiichi, Chernobyl, Three Mile Island, major power reactor accidents
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1.0 Introduction

Within the last 40 years, there have been three significant accidents involving nuclear power facilities that required public evacuations following the release of fission products to the environment. In 1979, a pressurized water reactor (Three Mile Island Unit 2 (TMI-2)) had a small-break loss of coolant accident (LOCA) with associated fuel damage [1-25]. TMI-2 was caused by a combination of operator errors and design weaknesses. Operator errors, an inadequately evaluated test procedure, and an unforgiving reactor design led to the 1986 accident at Chernobyl Unit 4 (Chernobyl-4), an RBMK design, located in the Ukraine [16,17,22-32]. These factors contributed to a power excursion that resulted in violent reactor disassembly and severe fuel damage. In 2011, the Fukushima Daiichi Nuclear Power Station (FDNPS) in Japan, consisting of six boiling water reactors, was struck by a massive seismic event and subsequent tsunami that led to significant core damage and an offsite release of radioactive material [23-25, 33-56]. Additional aspects of power reactor accidents and their associated elements are provided in Refs. 57-98.

Each of these power reactor events had unique operational aspects and presented significant radiological challenges. They were also of significant public interest. Media reports and information provided by the operating utility were not always representative of the actual hazards or operational events. The quantification of the released radioactive material, environmental effects, and doses delivered to the public were not always clearly stated or presented in terms that were easily understood by the public. A need for improvements in operator performance, dose management, accident mitigation, and risk communication were demonstrated during all three major power reactor accidents.

An effective radiological response is dependent on maintaining safety system operability and preserving the three fission product barriers. The operability and preservation of safety systems are determined by the design characteristics and the licensing rigor applied to their qualification. This requires a credible assessment of the design basis and beyond design basis accidents. These aspects are examined in this paper with a focus on their radiological impacts.

The radioactive material releases and their mitigation are affected by the specific reactor design and its requisite safety systems. These design considerations are addressed in subsequent discussion, and provide a basis for discussion of the TMI-2, Chernobyl-4, and Fukushima Daiichi accidents.

Although this paper describes the three major reactor accidents and addresses their essential elements, its focus is on selected aspects that have important radiological consequences and the impact of these issues on the future advancement of fission power technology. Accordingly, this paper focuses on reactor design considerations (Section 2), common accident characteristics and causes (Section 3), emergency preparedness programs (Section 4), risk communication (Section 5), public impacts (Section 6), environmental impacts (Section 7), emergency response actions (Section 8), and emerging issues including appropriate worker and public dose limits (Section 9). Although all three accidents have important ramifications, the Fukushima Daiichi accident is emphasized.

2.0 Reactor Design Considerations

Since most operating reactors are pressurized water reactors (PWRs) and boiling water reactors (BWRs) [21,22], this paper focuses on these reactor types. Specific details of the Chernobyl RBMK reactor are provided in the discussion of its specific accident sequence.

From a radiological perspective, nuclear reactor designs limit the release of radioactive materials following a severe accident. In its most basic form, reactor design is structured to protect three fission product barriers. Since each barrier inhibits the release of fission products, protection of these barriers is a design priority.

2.1 Fission Product Barriers

The radiological consequences of a reactor accident are minimized if the fission product barriers are preserved. These barriers and their status during an event are a key consideration in the International Atomic Energy Agency’s (IAEA) International Nuclear and Radiological Event Scale (INES) that is used to classify nuclear accidents [57]. The INES classification of the Fukushima Daiichi event was a significant item of media interest during the first few weeks of the event, because media, industry, and government reports did not consistently convey the severity of this accident [43,45,66].

Most reactor types incorporate three fission product barriers that inhibit the movement of radioactive materials into plant areas and the environment. As such, preserving the integrity of the fission product barriers is crucial to maintaining control of radioactive material and implementing an effective health physics program [21,22]. Since PWRs comprise about two-thirds of commercial water reactors with the remainder dominated by BWRs, discussions of fission product barriers focus on their designs, characteristics, and terminology.

In a PWR, these barriers are the fuel/cladding, reactor vessel and associated reactor coolant system (RCS) piping, and the containment structure or reactor building [21-23]. BWR fission product barriers are the fuel/clad, reactor pressure vessel (RPV) and included piping, and the containment vessel. The spent fuel pool in a PWR (BWR) is located in the auxiliary building (reactor building) which do not have the same capability to retain radioactive material as the three primary fission product barriers.

The first fission product barrier includes the fuel pellet or fuel material. The fuel material and its associated cladding retain solid and gaseous fission products. For pellet/cladding configuration fuel, fission product activity is often classified as either gap activity or total fuel pin activity [21,22]. Gap activity is that fission product activity residing in the gaps between the fuel pellets and the gap between the fuel pellets and the cladding. The total fuel pin activity is the gap activity and the activity contained within the fuel pellet.

The second fission product barrier is the primary coolant system boundary including the reactor vessel and its included piping and components. Any break in primary piping permits radioactive material to be released into the containment structure.

The third fission product barrier is the containment structure that encloses the primary coolant system. Any breach of the containment structure creates a pathway for radioactive material to reach the environment. Penetration of any of the three fission product barriers facilitates the release of radioactive material in an uncontrolled manner. The breach of multiple fission product barriers is an indication of a major reactor accident.

The fuel of a commercial power reactor consists of uranium dioxide (UO_2) pellets enclosed a zirconium alloy tube. Fission products are retained within the fuel pellet, and the zirconium alloy cladding supplements this fuel pellet barrier. Damaging the fuel/cladding fission product barrier releases fission products to the reactor coolant system / reactor pressure vessel (RPV). The fuel/cladding barrier was breached at TMI-2, Chernobyl-4, and Fukushima Daiichi. TMI-2 and Fukushima Daiichi events involved a loss of core cooling with subsequent fuel melting [1-25,33-56]. At Chernobyl-4, fuel was ejected from the core following a power excursion [22-32].

The second barrier, the reactor vessel or RPV and included piping, was breached at TMI-2 and Fukushima Daiichi and destroyed at Chernobyl-4 [1-56]. With two fission product barriers damaged, only the containment structure prevents a release of fission products to the environment.

A breach of the containment eliminates the final barrier and allows fission products to escape to the environment. At TMI-2, the containment remained intact and survived a hydrogen detonation [7,23]. The release of radioactive materials at TMI-2 occurred when highly contaminated water was transferred from the containment building sump to the auxiliary building sump. This transfer facilitated a fission product release through the waste gas system in the auxiliary building [1-25].

Chernobyl-4 had no containment building. The power excursion severely damaged the core and coolant system and released fission products and core materials directly to the environment [22-32].

At Fukushima Daiichi, multiple containment vessels were damaged and suspected to be leaking [23,24,33-56]. The accident sequence involving the breaching of the three Fukushima Daiichi fission product barriers at multiple reactors and the release of fission products to the environment is addressed in subsequent discussion.

2.1.1 Fission Product Releases

The dominant fission products released in a major reactor accident are radioiodine and noble gases [21-23]. The Chernobyl-4 and Fukushima Daiichi accidents also involved the release of particulates including ^{137}Cs and ^{90}Sr/^{90}Y [23,24,84-87]. These fission product releases affect the emergency response following an accident and the implementation of protective actions including evacuation and sheltering. Protective actions associated with power reactor accidents are addressed in subsequent discussion [69,71,73].

2.1.2 Fission Product Deposition

Following a release of fission products to the environment, particulate material, including radioiodine, radiocesium, and radiostrontium, is deposited on the earth and contaminates ground and surface water. These radioactive materials are incorporated into various biota. The contaminated water, plants, and animals enter the food chain and are consumed by man. This presents a challenge to subsequent land and water use, and requires establishing acceptable contamination levels in foods and water.

2.2 Accident Assumptions

Analyses that evaluate the impact of a reactor accident on the facility and the surrounding environment require establishing assumptions regarding the status of the facility and its integral safety systems. The availability and reliability of reactor safety systems are crucial to accident analysis and are an important aspect in the licensing of facilities. Facility licensing defines a set of parameter values that determine and serve to quantify design and beyond design basis events (DBEs) [16,19,20,24,43,49,52,58-66]. Radiological consequences are calculated for a set of design basis accidents (DBAs) that categorize major event types.

For example, the magnitude of the design basis earthquake and subsequent induced events (e.g., tsunami and aftershocks) and their impact on the facility are key accident analysis parameters. The earthquake magnitude determines the height of seawalls for tsunami protection, the location and requirements of safety equipment (e.g., emergency diesel generators and direct current batteries), and the required defense-in-depth systems to ensure accident mitigation. Underestimating the hazard can have catastrophic consequences.

Issues associated with credibly selecting design and beyond design basis events are clearly illustrated by the Fukushima Daiichi accident. Underestimating the design basis earthquake and resulting tsunami led to events that disabled onsite and offsite electric power systems. Loss of these power systems disabled active safety systems that led to significant core damage and the release of radioactive material to the environment [23,24,33-56]. The consequences of the Fukushima Daiichi accident and failure to adequately define credible design basis events present a long-term challenge to the nuclear industry.

Once design basis events are defined, their impacts on design basis accidents are evaluated. These DBAs include loss of coolant accidents (LOCAs), steam generator tube ruptures, fuel handing accidents, and waste gas decay tank ruptures. Therefore, the assumed bounding parameters defining the design basis event (e.g., earthquake, flood, and tornado) and their resulting impact on plant systems (e.g., duration of power loss and extent of primary system damage) govern the required plant redundancy (e.g., defense-in-depth requirements). These assumptions when coupled with the plant response to an event (e.g., extent of core damage, core damage frequency, and offsite release magnitude) determine the capability of a design to be licensed. The licensed design must be capable of sustaining the stresses of normal, abnormal, and emergency conditions. As such, properly defining design basis assumptions has a significant impact on plant safety and protection of the public and the environment.

2.3 Design Basis Assumptions

The design basis concept and associated accident modeling assumptions rely on the premise that sufficient safety margins are present in the reactor and its safety systems. Models used in accident analysis also maintain sufficient conservatism to account for analysis uncertainties. In addition, adequate defense-in-depth is included in the reactor design to compensate for uncertainties in accident progression and analysis data. The defense-in-depth concept is validated if safety system redundancy, independence, and diversity are preserved with respect to the anticipated frequency and consequences of challenges to these systems. Safety system requirements are specified in terms of General Design Criteria specified by the regulatory agency (e.g., Appendix I to 10 CFR Part 50 [67] for US Nuclear Regulatory Commission (NRC) licensees). Ultimately, the accident design yields an associated core damage frequency that is part of the basis for its acceptance.

Associated with the core damage frequency assessment and its associated design basis assumptions are specific dose consequences of the postulated design basis accidents [67-70]. The dose consequences are evaluated in terms of a set of key parameters that are defined by licensing agencies. In the US, the NRC defines these parameters in a series of guidance documents including Regulatory Guide 1.195, *Methods and Assumptions for Evaluating Radiological Consequences of Design Basis Accidents at Light-Water Nuclear Power* Reactors [20]. These parameters include the fission product inventory available at the time of the accident, fraction of the core fission product inventory released into the containment, timing of release phases, and the radionuclide composition and its chemical form.

2.3.1 Fission Product Inventory

Fission product inventory is an important parameter in assessing the radiological consequences of a postulated accident [20,61,67-70]. The inventory of core fission products available for release to the reactor coolant system is maximized by assuming the limiting values for fuel enrichment, fuel burnup, and core power.

Fission product inventories vary with facility operating history. The inventories increase as the operating cycle length increases and the fissile material is consumed. Since only a portion of the core is replaced during a refueling outage, the actual inventory available for release varies with the time following a refueling outage. Core inventories also vary with the reactor type, fuel enrichment, and power history.

TMI-2 only operated for a few months before its accident [7], but had sufficient fission product inventory to lead to a General Emergency classification [71] and the evacuation of the public within 16 km of the facility. Fukushima Daiichi and Chernobyl-4 had a longer operating history than TMI-2.

2.3.2 Release Fractions

Upon failure of the fuel and reactor coolant system fission product barriers, a fraction of the core fission product inventory is released into the containment. USNRC Regulatory Guide 1.195 [20] provides guidance for these release fraction values.

When the fuel is melted and the cladding is breached, the core inventory release fractions for iodine and noble gases are assumed to be 1.0 and 0.5, respectively [20,58]. This assumption was a gross overestimate of the TMI-2 source term, which released minimal radioiodine. A smaller than anticipated iodine source term occurred because of the release pathway from the reactor building to the auxiliary building waste gas system facilitated iodine removal prior to its release to the environment.

Melting is assumed to release the gap activity and most of the activity within the fuel pellets. The TMI-2 accident demonstrated the conservatism of this assumption since some fission products remained in the reactor coolant system or containment and were not released to the environment [7,14,23,24]. For example, iodine interacted with other fission products to form soluble chemical forms, adhered to reactor internal or containment structures, or remained in solution following the actuation of the reactor building spray system. The spray system used a solution of sodium hydroxide and water to reduce the containment building pressure [7,22,23].

For non-LOCA events, NUREG 1.195 assumes that only the cladding is breached [20]. The release fractions of the core inventory, based on a cladding breach, only include the gap activity. These core inventory release fractions are given in Table 1.

Table 1 Non-LOCA Fraction of Fission Product Inventory Based on Available Gap Activity[a]	
Fission Product	Release Fraction
^{131}I	0.08
^{85}Kr	0.10
Other Noble Gases	0.05
Other Iodines	0.05
[a] Based on Regulatory Guide 1.195 [20].	

2.3.3 Timing of Release Phases

Once the fuel and reactor coolant system fission product barriers fail, radiological consequence models usually assume that the liberated fission products immediately enter the containment. To ensure maximum radiological consequences, the released core activity is assumed to be immediately available for release from containment for DBAs in which fuel damage is projected.

This immediate release approach is advocated in Regulatory Guide 1.195 [20]. However, the TMI-2 accident indicated that specific event sequences could lead to release delays that permit physical and chemical processes to affect the source term. When calculating offsite releases and their radiological consequence, the release sequence and its duration must be considered to obtain an accurate assessment of offsite doses.

2.3.4 Radionuclide Composition

Design basis analyses define the elements in each nuclide group that should be considered in radiological consequence models. In the US, these are defined in terms of isotopes that dominantly contribute to the protective action guide dose values [69]. Since US reactors include containment structures that act as a fission product barrier, noble gases and radioiodine are the dominant source term components. Smaller quantities of particulates (e.g., cesium and strontium) are released, but these radionuclides have important environmental implications. At Fukushima Daiichi radiocesium affected the sale and distribution of various foods (e.g., rice, spinach, fish, and meat) for months following the accident [43,50,52,53,66].

3.0 Major Power Reactor Accident Causes and Characteristics

With the basic design characteristics established, details of the specific accidents can be considered [1-56]. These accidents have common aspects as well as unique characteristics derived from the specific reactor type. Specific accident details are addressed in subsequent discussion.

3.1 Three Mile Island

The Three Mile Island Nuclear Generating Station included two pressurized water reactors located in central Pennsylvania near the state capital of Harrisburg. The reactors are located on an island in the Susquehanna River. TMI-2 operated for only a few months before the accident and TMI-1 was not affected by the event [1-25].

3.1.1 TMI-2 Accident Sequence

At approximately 4:00 a.m. on March 28, 1979, TMI-2 was operating at about 100% power when the plant automatically shut down when a pump, supplying feed water to the secondary side of a steam generator, stopped operating or tripped. The loss of feed water removed the steam generator's ability to cool the reactor, resulting in a temperature and pressure increase in the reactor coolant system. The pressure increase caused a power operated relief valve (PORV) in the pressurizer to open as designed, but the valve failed to close when the RCS pressure returned to the normal operating range. With the PORV open, water and steam flowed out of the RCS, and a loss of coolant accident was initiated [1-25].

After significant water inventory was lost, extensive core damage occurred, and large quantities of radioactive material were released into the reactor coolant system. The core achieved sufficient temperatures for the fuel cladding to oxidize and produce hydrogen that was released into the containment atmosphere. Sufficient hydrogen was generated to support an explosion [7,23,24]. The TMI-2 containment survived the hydrogen explosion with minimal damage, and no fission products were released to the environment at this stage of the accident.

3.1.2 Fission Product Releases

During the TMI-2 accident, approximately 50% of the noble gases and particulate cesium, 30% of the iodine, and other fission products were released from the damaged fuel into the reactor coolant [12,17]. These radioactive materials decreased in concentration as the material flowed from the RCS [23,24,45,46].

Reactor coolant flowed from the core through the open PORV and into the reactor coolant drain tank located in the reactor building basement. After filling, the drain tank's rupture disk failed and core coolant exited the tank and collected in the reactor building sump. The sump filled and water in the containment basement reached a depth of about 2.1 m. This water, containing fission products, was pumped to the auxiliary building sump where fission products, primarily noble gases and some iodine, were collected by the waste gas system and released to the environment [7,23,24].

No removal of noble gases occurred within this pathway, but radioiodine was removed during the water transfer through chemical reactions and other removal mechanisms. The small quantity of iodine released to the environment forced a reanalysis of accident source terms and development of improved models of iodine interactions with the various plant systems, structures, and components [1,2,7].

The high-efficiency filtration system in the auxiliary building was designed to remove greater than 99% of the particulate activity. In addition to mechanical filtration, ventilated auxiliary building air was processed by multiple charcoal filters, which chemically removed 90% to 95% of the radioiodine. However, neither the mechanical filters nor the charcoal absorbers were designed to remove noble gases, which escaped directly into the environment.

3.1.3 Issues Associated with the Event

There are numerous issues associated with the TMI-2 accident. These include operational, human factors, control room design, and health physics related items [7,23,24]. The weaknesses revealed by the TMI-2 accident resulted in improvements in control room instrumentation that facilitate the operational and health physics response to future events. This paper focuses on specific issues that affected the subsequent radiological response. Upgrades to emergency preparedness programs and their capability to provide radiological and environmental data were additional improvements that were derived from the TMI-2 event. In addition, improvements in communications systems to provide real-time information to risk counties, state governments, and regulators were a result of the lessons learned from TMI-2 [1-25]. A number of these items affected the Fukushima Daiichi accident and are addressed in subsequent discussion.

3.2 Chernobyl

The Chernobyl site includes four reactors of the same type, but only Unit 4 was involved in the severe accident. Chernobyl-4 was a pressure-tube reactor with the Soviet designation RBMK. The RBMK has a unique design, and it is graphite-moderated and boiling water cooled. Vertical pressure tubes within the graphite contain low-enriched UO_2 fuel, control rods, or instrumentation. The reactor permits on-line refueling through selective pressure tube isolation. A negative feature of the design is a positive void reactivity coefficient under a range of operating conditions. The RBMK design includes emergency core cooling systems and steam suppression pools, but did not incorporate a containment fission product barrier [23,24,28].

The Three Mile Island accident was a loss of coolant event resulting in core damage with minimal off-site effects. Chernobyl-4 was significantly more severe, and it resulted in radiation related fatalities and significant off-site doses. The Chernobyl-4 accident is characterized as a reactivity or power excursion, and the event was caused by the violation of standing safety requirements, an unforgiving reactor design, and failure to properly evaluate a planned evolution [16,17,22-32].

The proposed test was designed to verify that Chernobyl-4 could safely operate during a loss of off-site power event by using the stored energy in the turbine generator to power safety-related equipment until the emergency diesel generators supplied auxiliary power. Although the test is similar to evolutions performed in commercial reactors, its execution was severely flawed.

The original test procedure placed the Chernobyl-4 reactor into a safe configuration, which included a power reduction. This plan was disrupted when the plant was directed to increase power to meet local electrical demands. Upon direction to resume the test, power was again reduced. However, there was insufficient time to restore the plant to the configuration required by the original test procedure.

In reestablishing the prerequisite power condition for the test, operators placed Chernobyl-4 into an unstable plant configuration. Since this configuration would result in an automatic reactor shutdown, the operators purposely bypassed several safety systems including the reactor control and emergency core cooling systems.

With safety systems bypassed, the Chernobyl-4 reactor was more vulnerable to a severe event. This vulnerability was exacerbated by the reactor's positive void coefficient that leads to an increase in reactivity as the volume of steam within the core increases.

Upon initiation of the test with the reactor in an unanalyzed condition, the core's steam volume expanded with a coincident increase in reactivity, which dramatically raised the reactor's power level. With increasing reactor power, the expanding void volume and associated reactivity addition resulted in a prompt criticality.

Prompt criticality led to rapid power and temperature increases. The increased temperature rapidly expanded fission gasses within the fuel, which ruptured the fuel cladding, and released fragmented and possibly melted fuel into the coolant channels. The addition of hot material into the coolant produced additional steam. This combination of high temperatures and rapid steam production stressed the pressure tubes within the core, which subsequently ruptured. The resulting temperatures overpressurized and heated the cavity surrounding the graphite moderator. Cavity overpressurization led to ejection of a portion of the core and burning graphite moderator from the reactor vessel. Following the energetic ejection, the reactor building failed and facilitated a significant environmental release of radioactive material with subsequent radiation exposure of facility workers and the public [26-28]. The Chernobyl reactor building provided a confinement structure which is significantly less robust than the containment fission product barrier.

The Chernobyl accident resulted in 31 plant personnel and firefighter fatalities resulting from radiation, fire, and building collapse. Releases of noble gases, radioiodine, and particulates represented a substantial portion of the radioactive material inventory of the damaged reactor's core, and is significantly larger than the TMI-2 accident release source term [12,17].

3.2.1 Issues Associated with the Event

Operational issues associated with the Chernobyl-4 accident include bypassing safety systems and improperly evaluating and implementing a test procedure. Specific issues affecting the radiological response are provided in subsequent discussion. A number of these health physics issues also occurred during the Fukushima Daiichi accident

Onsite radiological response actions were not always performed in an ALARA manner. Weaknesses in the health physics response led to high worker exposures that resulted in a number of related health effects including 29 deaths. Workers receiving 6 – 16 Gy had severe skin burns over 60 – 100% of their bodies. In this dose range, 21 deaths occurred in the cohort of 22 affected workers. Seven of 23 workers receiving doses in the 4 – 6 Gy range perished. In the 2 – 4 Gy dose group, one fatality occurred [26-32]. In addition to these onsite radiological issues, offsite monitoring was less than optimal.

As with TMI-2, communication with outside organizations and information flow were major concerns. Acknowledgment of the event by the government of the former Soviet Union only occurred after fission products were detected by an operating reactor in another country. The closed nature of the Soviet Union was a contributing factor in the initial lack of information flow. Information flow also affected emergency response actions including evacuation of the public [26-32].

Both TMI-2 and Chernobyl-4 had weaknesses in the dissemination of radiation related information. Communications and emergency response weaknesses have been common issues associated with major nuclear events at power reactors.

3.3 Fukushima Daiichi

The Fukushima Daiichi facility consists of six BWRs whose basic characteristics and accident related damage associated with fission product barriers are noted in Table 2. A comparison to the TMI-2 accident is also provided. Since Chernobyl-4 did not include a containment fission product barrier, it is not included in Table 2. From a health physics perspective, the condition of the fuel in the reactor pressure vessel and fuel pool, and the integrity of the reactor pressure vessel and containment vessel (CV) are the primary concerns for power reactor accidents [21-24,45].

Table 2

Condition of the Fukushima Daiichi and Three Mile Island Fission Product Barriers

Condition	Fukushima Daiichi Unit No.						Three Mile Island Unit No.	
	1	2	3	4	5[a]	6[a]	1[b]	2
Power output (MW_e)	460	784	784	784	784	1100	819	792
Status before event	Operating	Operating	Operating	Outage	Outage	Outage	Operating	Operating
Fuel assemblies in core	400	548	548	0	548	764	177	177
Fuel condition	Damaged (core melt)	Damaged (core melt)	Damaged (core melt)	Defueled	Not damaged	Not damaged	Not damaged	Damaged (core melt)
Reactor pressure vessel structural integrity	Partially damaged and leaking[j]	Partially damaged and leaking	Partially damaged and leaking	Not damaged	Not damaged	Not damaged	Not damaged	Minimal damage[c]
Containment vessel structural integrity	Damaged and leakage suspected[j]	Damaged and leakage suspected	Damaged and leakage suspected	Not damaged	Not damaged	Not damaged	Not damaged	Minimal damage[d]
Reactor building integrity	Severely damaged	Partly opened[f]	Severely damaged[e]	Severely damaged[e]	Undamaged	Undamaged	Undamaged	Undamaged[g]

Table 2

Condition of the Fukushima Daiichi and Three Mile Island Fission Product Barriers

Condition	Fukushima Daiichi Unit No.						Three Mile Island Unit No.	
	1	2	3	4	5[a]	6[a]	1[b]	2
Fuel condition in spent fuel pool	Most spent fuel is not damaged[h]	Most spent fuel is not damaged[h]	Most spent fuel is not damaged[h]	Most spent fuel is not damaged[h]	Not damaged	Not damaged	Not damaged	[i]

[a] Units 5 and 6 were relatively unaffected by the earthquake/tsunami.
[b] TMI-1 was not affected by the TMI-2 accident.
[c] Minor surface cracks were observed in the cladding in the lower portion of the TMI-2 reactor vessel. This fission product barrier remained intact.
[d] The TMI-2 containment building incurred minimal damage from the hydrogen explosion. This fission product barrier remained intact.
[e] Hydrogen gas from Unit 3 is believed to have entered the Unit 4 reactor building and exploded.
[f] A vent hole was opened on the rooftop to avoid a hydrogen explosion
[g] In a pressurized water reactor, this structure is the auxiliary building. It contains the spent fuel pool and portions of the emergency core cooling system
[h] Based on fission products detected in the spent fuel pool water. As part of the recovery effort, the Unit 4 spent fuel pool was defueled in 2014.
[i] The TMI-2 spent fuel pool contained no spent fuel. The reactor was in service only a few months before the accident.
[j] Damage estimate supported by initial 2015 muon tomography examinations [44].

At Fukushima Daiichi, the three fission product barriers are the fuel/clad, the RPV and associated piping, and the CV. A secondary structure or reactor building, analogous to the auxiliary building in a PWR, encloses the spent fuel pool. In a PWR, the auxiliary building and containment are separate structures connected by a fuel transfer canal.

The fuel is contained within a steel reactor pressure vessel, and the containment vessel surrounds the RPV. The Fukushima Daiichi containment vessel includes a pear-shaped dry well and a wet well or suppression pool, which has the shape of a torus.

At Fukushima Daiichi, the reactor building includes a steel-framed service floor. The service floor is located above the reactor pressure vessel and contains the spent fuel pool, its support structures, and portions of emergency cooling systems. The containment vessel is below the service floor of the reactor building.

The CV surrounds the RPV and its recirculation loops. It is a steel-lined pressure vessel encased over most of its surface by reinforced concrete. The suppression pool is located below the drywell, is connected to the drywell through a piping system designed to vent RPV pressure, and condenses and cools any vented steam.

At Fukushima Daiichi, the fuel pool resides above the containment vessel. This is in contrast to the PWR arrangement that has the spent fuel pool horizontally displaced and physically separated from the RPV. The arrangement at Fukushima Daiichi facilitated the venting of hydrogen to the reactor building, which led to damage to that structure and its components following hydrogen explosions.

The Fukushima Daiichi accident is unique because three separate hydrogen explosions occurred following core damage [23,43,45,66]. These explosions affected the spent fuel pools in Units 1, 3, and 4. Unit 4 was in an outage condition, and its hydrogen explosion was probably caused by gas released from Unit 3. For this reason, both reactor specific as well as spent fuel pool related discussions are provided. The accident sequence outlined in subsequent discussion is derived from Refs. 43, 45, 49, 52, 53, and 66.

3.3.1 Reactor Accident

At 2:46 p.m. local time on March 11, 2011, the Richter magnitude 9.0 Tohoku-Chihou-Taiheiyo-Oki earthquake struck the Fukushima Daiichi Nuclear Power Station in Northeast Japan [23-25, 33-56,66]. Following the seismic event, the operating reactors (Units 1, 2, and 3) automatically shutdown and the control rods were inserted into the core. The Fukushima Daiichi reactors may have sustained some initial damage, but survived the earthquake. A specific seismic damage assessment must await a detailed physical inspection of the facility.

The Fukushima Daiichi facility responded normally following the reactor trip. Containment isolation valves automatically closed, and valve closure provided an effective barrier to the release of radioactive material from the RPV. All offsite power was lost at 3:42 p.m., and emergency diesel generators started to power the electric pumps used to provide cooling water to the reactor cores and spent fuel pools. At that time, the reactors were in a stable configuration with all fission product barriers intact. Reactor safety systems functioned as designed to this point in the accident sequence.

Following the earthquake, a tsunami struck the facility with a wave height of 14 - 15 m, which exceeded by almost a factor of three the design basis tsunami height of 5.7 m. Since the ground elevation at FDNPS Units 1 – 4 is 10 m above sea level and Units 5 and 6 are at an elevation of 13 m, Units 1 – 4 were flooded by 4 – 5 m and Units 5 and 6 by up to 1 – 2 m of sea water. This flooding contributed to the more severe damage at Units 1 – 4.

The tsunami breached the facility's protective seawall, and disabled the Unit 1, 2, 3, and 4 emergency diesel generators at 3:45 p.m. when their fuel oil supply was disrupted. One diesel generator and its support systems survived the tsunami and powered a portion of the Units 5 and 6 safety systems. The operation of this diesel generator prevented core damage and the release of fission products from Units 5 and 6.

At that time, the FDNPS Units 1 – 4 were in a station blackout condition. A limited battery supply was available to power the emergency core cooling system pumps. Although stable, this reactor configuration is only effective as long as the suppression pool remains below 100^{o} C and battery power is available to provide core cooling capability.

In a few hours, the batteries were depleted and core cooling capability was lost in Units 1, 2, and 3. Core temperatures increased, and temperatures and pressures increased in the RPVs.

Rising pressure required that the steam relief valves be opened to reduce RPV pressure and steam is discharged to the CV and suppression pool. Consequently, the water level in the RPV decreases and the fuel is eventually uncovered. With diminished fuel cooling capability, cladding failures occur which releases fission products into the CV and suppression pool.

The FDNPS sequence of events following water addition to a degraded core is similar to the fuel failures that occurred during the TMI-2 accident [15]. A specific Fukushima Daiichi fuel damage sequence will be forthcoming as the reactor pressure vessels are defueled and the damaged core materials examined. The temperature thresholds for the various stages of core degradation at TMI-2 are suspected to have occurred at the FDNPS. The use of these temperature thresholds facilitates the subsequent discussion [15].

When core temperature exceeds about 1200^{o} C, the zirconium cladding alloy protecting the UO_2 fuel is oxidized by the water/steam in the RPV, and hydrogen is produced:

$$\mathbf{2Zr + 2H_2O \rightarrow 2ZrOH + H_2 \uparrow} \qquad (1)$$

This reaction is exothermic which adds to the RPV heat load. With increasing RPV temperature and pressure, the hydrogen gas is vented to the suppression pool and then into the dry well.

With the loss of cooling capability, the fuel/clad temperatures increase and additional degradation in the fuel/clad fission product barrier occurs. At about 1800^{o} C, the fuel cladding and adjacent steel structures in the RPV melt. Upon reaching 2500^{o} C, fuel rods fracture and a debris bed is created within the RPV. At about 2700^{o} C, uranium-zirconium eutectics melt.

If the FDNPS recovery activities proceed in a manner similar to TMI-2, verification of the extent of fuel degradation will not be known for years. However, the radiation levels and isotopes released from the Fukushima Daiichi facility are suggestive of severe fuel damage/melting. The current assessment of fuel degradation is summarized in Table 2.

With severe fuel damage, fission products (e.g., Cs, I, Kr, and Xe) are liberated from the fuel and released, but the majority of the U and Pu remain in the core. The fission product aerosols are discharged from the RPV into the suppression pool, which reduces the quantity of radioactive material available for release to the environment. Similar activity reductions occurred during the TMI-2 accident. When the fission products enter the dry well, the associated aerosols are further depleted by surface deposition.

At this stage of the event, the CV is the only remaining barrier between the fission products and the environment. The CV has a design pressure of 0.4 –0.5 MPa, and the accident induced pressure rises to about 0.8 MPa. This pressure increase is driven by the normal nitrogen inerting of the CV, added hydrogen from the zirconium cladding oxidation, and boiling within the suppression pool. Since the design pressure was exceeded, operators depressurized the CVs to ensure their long-term integrity.

Venting removes energy from the CVs and reduces their pressure to about 0.4 MPa. These positive aspects are offset by the release of fission aerosols, noble gases, and hydrogen to the upper levels of the reactor building.

In Units 1, 3, and 4, the released hydrogen explodes in the reactor building, which destroys their steel frame upper building structure and roof. Unit 4’s explosion was probably caused by hydrogen from the Unit 3 reactor that accumulated in the Unit 4 reactor building.

The CV is damaged and suspected to be leaking in Units 1, 2, and 3. Destruction of portions of the reactor buildings in Units 1, 3, and 4 was dramatic and may have damaged structures needed for subsequent decontamination and decommissioning of the FDNPS.

In Unit 2, a hydrogen explosion may have occurred inside the CV, which damaged the suppression pool containing highly contaminated water. This resulted in the uncontrolled release of fission gasses and products from the CV. The resulting high dose rates led to evacuation of the site.

Initial fuel damage was mitigated upon restoring water to the RPV. This restoration involved the use of seawater.

In Unit 1, most of the core melted and formed a material mass composed of fuel, control rods, and reactor pressure vessel materials, which is often called corium [14,15]. Initially, the corium was assumed to reside at the bottom of the RPV. However, it now appears that the corium has melted through the bottom of the RPV and eroded a portion of the 2.6 m thick drywell concrete. This erosion dissipated the corium heat content and permitted the mass to solidify. Much of the fuel in Units 2 and 3 appears to have melted, but to a lesser extent than in Unit 1 [43,44,49,52,66].

Corium breaching of the Unit 1 RPV is supported by the vessel's water level. The operating utility determined that the water level was more than one meter below the bottom on the fuel, which suggests that water is leaking from the CV into the reactor building. This determination is also supported by initial muon tomography studies [44].

As in the case of TMI-2, it will take time for a complete accident sequence to be firmly established. The accident sequence and extent of core damage will evolve as the Fukushima Daiichi reactor pressure vessels are defueled.

3.3.2 Spent Fuel Pools Inventory

The spent fuel pools are a significant consideration at the Fukushima Daiichi Nuclear Power Station recovery effort because there is more fuel in the pools than in the Unit 1, 2, and 3 reactor vessels [43,49-54,66]. Their structural integrity must be maintained to ensure the fuel is covered with sufficient water inventory to cool the spent fuel. Loss of pool water inventory and associated fuel uncovery could result in fuel damage with a fission product release directly to the environment. The damaged Unit 1, 3, and 4 reactor buildings provide little reduction in the source term and minimal aerosol depletion if additional fuel damage were to occur.

Each of the Fukushima Daiichi reactors has a spent fuel pool and there is an additional common pool. The fuel inventory in each pool represents a significant source term and is addressed in subsequent discussion [43,49-54,66]. This inventory is important because the fuel in the spent fuel pools at Fukushima Daiichi is only protected by a single fission product barrier (i.e., the fuel/clad).

3.3.2.1 Unit 1

The Unit 1 spent fuel pool has a capacity of 900 fuel assemblies. At the time of the accident, it contained 292 irradiated fuel assemblies and 100 unirradiated fuel assemblies. The most recent additions of irradiated fuel assemblies occurred in March 2010. The March 12 explosion that destroyed the outer shell of the Unit 1 reactor building occurred near the spent fuel pool. Although hydrogen explosion debris landed in the Unit 1 spent fuel pool, most fuel in the pool is undamaged.

The original Unit 1 defueling plan projected defueling of the spent fuel pool to occur in 2017. In a December 2014 status report, the utility projected an additional 2 year delay with a new start date of 2019. RPV defueling is currently projected for 2025.

3.3.2.2 Unit 2

At the time of the accident, the Unit 2 spent fuel pool contained 587 irradiated and 28 unirradiated fuel assemblies. This pool has a capacity of 1240 fuel assemblies and it last received irradiated fuel in September 2010. During the early phase of the accident, the operating utility was concerned that the pools would be depleted of water inventory because the decay heat load could not be removed. Initially seawater and subsequently fresh water were added to the pool. Most of the fuel in the Unit 2 pool is believed to be undamaged. Defueling plans for the Unit 2 spent fuel pool and RPV are in development and have yet to be finalized.

3.3.2.3 Unit 3

The Unit 3 spent fuel pool has a capacity of 1220 fuel assemblies and held 514 irradiated and 52 unirradiated fuel assemblies at the time of the accident. The Unit 3 pool received its most recent addition of irradiated fuel in June 2010.

The Unit 3 hydrogen explosion may have damaged a portion of its spent fuel pool. The operating utility was concerned about water inventory loss from the pool. On March 17, 2011, helicopters dropped seawater into the pool. Subsequent water additions sprayed water from fire trucks and other vehicles. Starting on March 24, seawater was injected into the Unit 3 pool using an existing cooling and purification line.

A May 8, 2011 water sample from the Unit 3 spent fuel pool contained elevated levels of fission products. The sample contained 140 kBq/cm^3, 150 kBq/cm^3, and 11 kBq/cm^3 of ^{134}Cs, ^{137}Cs, and ^{131}I, respectively. A video examination of the pool area showed debris scattered over the interior of the reactor building.

In August 2015, the 20 metric ton fuel handling machine (FHM) was removed from the Unit 3 pool. Subsequent video examinations of the Unit 3 pool revealed bent fuel assembly handles that were damaged by the FHM and rubble on top of fuel assemblies. However, most the Unit 3 spent fuel appears to be undamaged. Defueling plans for the Unit 3 spent fuel pool and RPV are in development and have yet to be finalized.

3.3.2.4 Unit 4

Unit 4 shut down for routine maintenance in November 2010, and all fuel assemblies were transferred from the reactor to the spent fuel pool. With 1331 irradiated fuel assemblies in the pool, the thermal loading in the Unit 4 spent fuel pool was larger than in the other units. The Unit 4 pool has a capacity of 1590 assemblies and contained 204 unirradiated assemblies. It last received fuel in November 2010.

The hydrogen explosion may have caused a reduction in the cooling capability in the Unit 4 pool. Starting on March 20, 2011 water was added to the pool. On May 8, the operating utility concluded that some of the fuel in the Unit 4 spent fuel pool might have been damaged. Spent fuel pool structural integrity improvements have been made to the walls of the reactor building supporting the pool. The March 15, 2011 hydrogen explosion and the March 11 seismic event may have damaged these structural members.

In 2012, the first of the 204 new fuel assemblies were removed from the Unit 4 spent fuel pool and transferred to the common spent fuel pool for detailed inspection. No fuel assembly deformation or corrosion was observed. The Unit 4 spent fuel pool defueling operation was initiated in 2013 and completed in 2014. Unit 4's fuel was transferred to the common spent fuel pool.

The Unit 4 spent fuel pool defueling operation is a significant milestone that eliminates a source of radioactive material and permits the pool to be used for other recovery tasks. At TMI-2, the spent fuel pool contained submerged demineralizer systems that removed radioactive material from the reactor coolant and led to a significant source term reduction [8,9,12-14,18,22,23].

3.3.2.5 Unit 5 and 6

Although temperatures initially rose in the Unit 5 and Unit 6 pools, the restart of an emergency diesel generator provided power to cool these plant areas. The Unit 5(6) spent fuel pools have a capacity of 1590(1770) fuel assemblies. At the time of the accident, there were 946(876) irradiated and 48(64) unirradiated fuel assemblies in Unit 5(6).

Fuel in the Units 5 and 6 pools was undamaged by the accident and subsequent hydrogen explosions. The Unit 5 (6) RPVs were defueled in 2014 (2013). These spent fuel assemblies currently reside in the respective unit's pool.

3.3.2.6 Common Spent Fuel Pool

In addition to pools at each of the six units at Fukushima Daiichi, the facility has a common use spent fuel pool. This common pool contains spent fuel from the six FDNPS reactors that has cooled for at least 18 months. The common pool has a capacity of 6840 assemblies and contained 6291 assemblies in March 2010. No issues with fuel integrity, pool integrity, and pool cooling capability have been reported.

3.3.3 Spent Fuel Pools Impacts

Spent fuel needs to be cooled and shielded. At Fukushima Daiichi, this is accomplished in spent fuel pools and dry storage casks. The decay of fission products in the spent fuel generates heat that must be removed or fuel damage can occur. This fuel is cooled by water that is circulated by electric pumps through external heat exchangers that cool the spent fuel or by naturally circulating air that cools the dry storage casks. A reliable supply of onsite and offsite power is required to ensure the capability to cool fuel residing in the spent fuel pools. Given the possibility that the hydrogen explosions weakened the affected unit's pool structural integrity, preserving the pool boundary and maintaining fuel cooling are high priority recovery tasks.

In addition to hydrogen explosion damage, the earthquake may have produced structural degradation that will be investigated as the recovery proceeds. Damage could also have been caused by explosion induced debris falling into the pools and striking fuel assemblies [43,49,52,66]. To limit the impact of these issues, large scale defueling operations have been conducted in Units 4, 5, and 6.

3.3.4 Issues Associated with the Event

The Fukushima Daiichi accident is unique in that it was caused by a natural event (e.g., massive earthquake and subsequent tsunami) that was addressed in the facility licensing basis. Unfortunately, the licensing basis underestimated the design basis earthquake/tsunami. As a result, the issues associated with the Fukushima Daiichi accident have a significant radiological impact and are addressed in subsequent discussion [23,24,43,45,49,52,66]. These issues include the adequacy of the emergency preparedness program, effective risk communications, public impacts, environmental effects, emergency response actions, and emerging issues including public and worker emergency dose limits

4.0 Emergency Preparedness Programs

The accidents at TMI-2, Chernobyl-4, and Fukushima Daiichi clearly illustrated the importance of robust emergency preparedness programs [1-56]. Emergency preparedness programs have two primary objectives [58-80]. First, they develop plans and implementing procedures that provide the capability to mitigate the consequences of severe events in order to protect the health and safety of the public and site personnel. In addition, these programs ensure the operational readiness and capability of a facility's emergency response organization.

Emergency preparedness programs utilize dedicated organizations that manage the event and coordinate response actions with government agencies. State, county, and municipality governments have integrated roles and responsibilities and their respective emergency plans are coordinated with the operating utility. For the most serious events, protective action recommendations and their implementation require close coordination of the utility, government, and regulatory authorities [68-80].

4.1 Emergency Classification

An emergency classification is defined by a set of plant conditions that indicate a level of public risk resulting from a degraded facility state. In the US, degraded plant conditions are defined in terms of a set of four emergency classifications. In order of increasing severity, these are the Unusual Event, Alert, Site Area Emergency, and General Emergency [22,71]. Declaration of an emergency condition requires the activation of the facility's emergency response organization to respond to the degraded plant state.

The four classes are mutually exclusive groupings that are based on the spectrum of nuclear power plant emergencies. Each emergency classification has associated actions that must be performed including notification of offsite agencies and support organizations, and mobilization of the applicable portions of the emergency response organizations to assess, mitigate, and eventually terminate the event. The emergency classes represent a hierarchy of events based on potential or actual hazards. Emergencies may be initially assigned a lower classification and then escalated to a higher classification if the plant condition deteriorates. De-escalation to a lower emergency classification also occurs as the situation improves.

Each of the four emergency classifications is determined by defined, plant-specific emergency action levels (EALs). These levels consist of specific sets of plant parameters (e.g., radiation monitoring system values, fission product barrier status, and cooling system flow capability) that are used to activate the emergency response organization [13,22,68-80]. The emergency response actions include emergency classification designation, notification of government organizations, and mobilization of the facility's emergency response organization.

Emergency action levels facilitate rapid assessment and accident classification. The EALs are not selected to predetermine the necessity to implement protective actions, but ensure sufficient time is provided to confirm initial plant parameter values by implementing additional onsite and offsite assessment actions. Upon declaration of a Site Area Emergency or General Emergency, protective action recommendations are determined utilizing radiological field team measurements, dose projections, or assessed plant conditions. Radiological information, relevant plant conditions, and the projected event duration are communicated to government officials as part of the utility's protective action recommendations [22,69,71].

In the US, utilities adopt specific methodology to relate the effective dose and thyroid equivalent dose to the EAL values associated with an emergency classification [69]. EAL radiation related parameters could be chosen such that an individual exposed to these levels would receive a dose corresponding to a fraction of the Environmental Protection Agency's (EPA) lower limit protective action guides (PAGs) [22,69]. For example an Alert, Site Area Emergency, and General Emergency could be declared when the thresholds of 0.01, 0.05, and 1.0 times the PAG lower limit values are reached, respectively [22,69,71].

The lower limit Protective Action Guides, defined in subsequent discussion, are used as part of the basis for declaring radiological emergencies. The emergency classification philosophy is to promptly declare the highest class for which an emergency action level has been exceeded. For example, a Site Area Emergency is declared if one of its corresponding EALs is exceeded even if the lower Alert class was not previously declared. The emergency classification system facilitates timely evaluation of plant conditions based on comparison to defined EALs. These EALs are specific values or conditions determined by the plant's design [61,69,71].

A number of the key decisions in emergency classification often require calculations of the projected dose as well as the extent of the deposition of radioactive materials in the environment. The projected dose calculations incorporate computer models that utilize plant and field team data.

Computer models (e.g., MIDAS [81] and RASCAL [82] are often used for performing a dose projection and determination of ingestion pathway contamination following a power reactor accident. Many utilities develop facility specific models to calculate projected doses. These codes are consistent with regulatory requirements [67,69,71].

The Meteorological Information and Dose Assessment System (MIDAS) [81] models the atmospheric dispersion of releases of radioactive materials during routine and accident conditions. MIDAS has a graphical user interface that facilitates data entry to define accident conditions. This code also provides critical protective action information during an incident. The model has the capability to provides real-time emergency dose assessment, routine operation 10CFR50 [67] Appendix I environmental analysis, radiological effluent assessment, and automatic meteorological and radiological data collection.

The Radiological Assessment System for Consequence Analysis (RASCAL) code [82] evaluates releases from nuclear power plants, spent fuel storage pools and casks, fuel cycle facilities, and radioactive material handling facilities. RASCAL is designed to be used by the NRC in the independent assessment of dose projections during the response to radiological emergencies. The code has the capability to calculate power reactor source terms, the airborne transport of radioactive materials using both Gaussian plume and puff models, and the associated doses. The output of RASCAL and MIDAS is often used as part of the basis for determining the classification of an emergency event.

A brief description of the four FEMA emergency classifications is provided in subsequent discussion. This discussion is based on US requirements summarized in Ref. 79.

4.1.1 Unusual Event

The lowest level (least severe) of the four emergency classifications is the Unusual Event. An Unusual Event is an event that defines plant conditions that are in process or have occurred which indicates a potential degradation in the level of safety. In an Unusual Event, no release of radioactive material requiring offsite response or monitoring has occurred or is expected unless further degradation occurs. Unusual events are low-level events that can include activation of plant safety systems, adverse plant radiological or operating conditions, explosions, chemical events, fires, flooding, loss of facility systems, loss of electrical power, security events, and weather conditions.

Unusual Events are based on the potential for the plant conditions to degrade to a more serious situation. An Unusual Event emergency declaration considers any uncertainty in the status of plant safety systems, the time the uncertainty may exist, and the expectation these uncertainties can be resolved in a reasonable time.

4.1.2 Alert

The next level of emergency classification is an Alert. An Alert classification is used to define an event that is in process or has occurred that involves an actual or potential substantial degradation in the level of safety of the plant. The Alert classification includes emergencies that are more severe than an Unusual Event. With the increased severity of an Alert classification, additional offsite emergency response agencies are notified and a larger portion of the facility's emergency response organization is activated.

Any radioactive material releases resulting from an Alert are expected to be limited to a small fraction of the EPA's protective action guide values [69]. However, the Alert classification indicates a decrease in plant safety with potentially more severe consequences than the Unusual Event.

Alerts occur less frequently than unusual events. This classification includes the same general categories as noted in the Unusual Event class, but their consequences are more severe.

4.1.3 Site Area Emergency

The next emergency classification is the Site Area Emergency. A Site Area Emergency involves events that are in process or which have occurred that involve actual or likely major failures of plant systems needed for protection of the public. Releases of radioactive material are not expected to exceed the EPA PAGs except near the site boundary. Site Area Emergencies include significant events including loss of coolant accidents, steam generator tube ruptures and security breaches.

Protective actions are considered with the declaration of a Site Area Emergency. This emergency classification also activates onsite and offsite utility and government resources that are required to perform protective actions. If the declaration is based on radiological considerations, field teams are dispatched to perform air and direct radiation monitoring. These radiological data provide utility managers the relevant information to make protective action recommendations. Unlike the Unusual Event and Alert levels, the Site Area Emergency may involve some radiation release to the environment with subsequent public exposure. Many accidents included in this class have the potential to degrade further to the General Emergency classification.

4.1.4 General Emergency

The most severe emergency classification is the General Emergency, and protective actions are implemented with this event type. A General Emergency involves actual or imminent substantial core damage or melting of reactor fuel with the potential for loss of containment integrity. Radioactive releases during a General Emergency are expected to exceed the EPA PAGs beyond the site boundary. Accidents having a large radioactive release potential (e.g., loss of coolant accidents and major security events or sabotage) can damage multiple fission product barriers. Only one General Emergency has been declared in the US. This event was the 1979 TMI-2 loss of coolant accident.

4.2 Emergency Preparedness Effectiveness

To be effective, utility emergency preparedness programs must be coordinated with government organizations. The operating utility activates its emergency response organization to mitigate the accident. Utility emergency response personnel determine the nature of the accident and the capability of available safety systems to mitigate the event. The operating utility provides accurate information regarding the current as well as projected plant status to government emergency management officials. This information includes the (1) availability of core cooling systems and emergency power supplies, (2) status of the fission product barriers and their long-term capability to mitigate a release of fission products to the environment, (3) nature of radioactive materials releases and their projected duration, (4) protective action recommendations, and (5) capability of the utility to terminate the release.

Government officials utilize plant information to activate their emergency response organizations and implement protective actions. Coordination with various government agencies and communication with the public are required to successfully implement protective actions.

Unfortunately, the three major power reactor accidents at Three Mile Island, Chernobyl, and Fukushima Daiichi clearly demonstrate operating utilities have not been completely successful in (1) ascertaining the nature of the accident in a timely manner, (2) developing a strategy to minimize its effects, (3) applying that strategy to mitigate the event, and (4) communicating the accident characteristics, consequences, and anticipated duration to the public. In addition, government organizations have not adequately communicated the nature of the event to the public or fostered confidence in their capability to oversee the event. These issues complicated the subsequent protective action decisions and their effective implementation.

The Fukushima Daiichi accident was exacerbated by the earthquake/tsunami that disrupted communications and evacuation routes. The severe loss of life from the tsunami and fears of the release of radioactive material would challenge any emergency organization. Reactor accidents are difficult to manage even under ideal conditions. They become extremely difficult when a coincident natural disaster occurs.

5.0 Risk Communication

Risk communication is a complex process based on trust, clear and accurate information, and honesty. Challenges range from communicating the hazards of facility incidents (e.g., equipment failures, injuries, and small fires) to the consequences of a major reactor event such as the Three Mile Island or Fukushima Daiichi accidents. Individuals responsible for communicating risk information to the public face two key challenges. First, risk must be communicated in a manner that acknowledges the emotional aspect of the event and provides information to alleviate public concerns. Second, communication must also be done in a manner that engages the public to become an effective partner in addressing and understanding the event's risks.

Risk communication is complicated because the public does not have a complete understanding of radiation and radioactive materials and their associated biological effects. Radioactive materials and radiation also tend to be regarded negatively by the public. The public is more accepting of radiation if it is received in a voluntary medical procedure. Public reaction to radiation following a power reactor accident is much less acceptable since it is a non-voluntary or imposed exposure situation [83]. Voluntary and imposed situations are particular risk attribute types. Other risk attributes and associated risk types are listed in Table 3.

Table 3
Risk Preference Types[a]

Risk Attribute	Risk Type	
	Preferred	Undesired
Situation	Voluntary	Imposed
Required Action	Controlled by the individual	Controlled by others
Benefit	Clearly positive	Little or none
Consequence	Distributed uniformly	Distributed unfairly
Event type	Natural	Man-made
Nature	Statistical	Catastrophic
Origin	Caused by a trusted source	Caused by a source that is not trusted
Hazard	Familiar	Exotic
Group	Adults	Children
Impact	Affects the individual	Affects others

[a] Adler and Kranowitz [83].

In general, radiation risks are characterized by a set of undesirable types. For example, the radiation dose received following a power reactor accident is imposed, controlled by others, perceived to have little benefit, affects individuals in the vicinity of the nuclear facility, is man-made, is not well understood, and affects children more severely than adults. As summarized in Table 3, all of these factors contribute to the difficulty associated with communicating risks associated with ionizing radiation. In addition, the public is more suspicious of communications coming from a representative of the nuclear facility (not a trusted source) than a physician or university professor (trusted source). The individual delivering the message is often as important as the message itself.

With radiation, the associated benefit relative to the risk strongly influences public perception. The public views radioactive material or radiation used in medical applications as having a high benefit and low risk, and an acceptable practice. The high degree of trust in physicians also influences the acceptability of the medical use of radiation. However, the public regards industrial uses of radiation as less desirable. This perception is influenced by the public's general belief that the government and nuclear industry management are not completely trustworthy. These perceptions have been reinforced by government and industry risk communications following the Three Mile Island and Fukushima Daiichi accidents.

The evaluation of risk is always personal. As such, effective communication with the public requires an understanding of how risks affect people individually and as part of stakeholder groups.

Risk communication is interactive and dynamic. It involves information exchange between individuals, groups, and institutions. Risk communication can be defined as the approach used to inform the public of the potential issues and benefits of specific projects, programs, or events. It includes all communication with the government, media, stakeholders, and public regarding controversial programs or events. Risk communication is most important when it involves topics that are controversial or not fully understood.

Effective risk communication between a facility operator and the public should incorporate a number of elements. These include acceptance of the public as a full partner having an interest in the facility and its operations. Public input is relevant and dialogue is important. Interactions with the public and other stakeholders must be open, frank, and honest. Communications must be clear and unambiguous.

Risk communications should be carefully planned and reviewed by facility management. The effectiveness of these exchanges is routinely evaluated to improve the risk communications process. Communications must also meet the needs of media and involve credible individuals who facilitate dialogue between the operating organization and stakeholder groups.

These general guidelines have not always been followed. The TMI-2 and Fukushima Daiichi accidents provided recent examples of weaknesses associated with risk communication. These issues are addressed in subsequent discussion.

The author also notes that understanding public norms and acceptable practices is also important in communicating radiation risk to individuals. During a public tour of Three Mile Island Unit 2 a few years following the accident, the author was asked about a radiation posting encountered along the tour route. The purpose of the posting and the radiation levels in the area were noted and compared to the dose received from cigarette smoking. An elderly female individual, who was a smoker, informed the author in an emotional, expletive laced outburst that it was her choice to smoke, but the radiation from the accident was imposed on her without consent. Since that event, the author has not used the smoking example in discussing radiation doses and their associated risk.

5.1 TMI-2 Accident

One of the most challenging aspects of the TMI-2 accident was communicating timely, accurate, and complete information to news outlets, regulators, and the public. This was difficult to achieve in the complex, evolving situation that occurred during the TMI-2 accident. As a result, some of the plant information provided during the first few days of the accident was conflicting and confusing. With changing plant conditions, the various utility spokespersons offered opinions that reflected personal insights rather than a coordinated, accurate response. As a result, the utility's credibility as a reliable source of information quickly eroded. In a rapidly unfolding event, it is not surprising that some initial statements would later prove to be inaccurate as more information was obtained [7]. Other organizations including the Nuclear Regulatory Commission encountered similar problems in their communications with the public [7].

The utility was accused of not acknowledging the severity of the accident during the height of the event. Part of the blame for this confusion was the initial judgment that there was no immediate public danger and that the accident was not serious. Since events were rapidly unfolding, it was difficult to have timely communications while addressing plant conditions during the first few days of the accident. The utility's emphasis was maintaining the plant in a safe condition, and minimizing the radioactive releases and off-site exposures to the public [7]. In pursuing these objectives, the utility sometimes had to place communications with the public in a secondary role. In addition, individuals responsible for accident management also were briefing the media. These individuals were well versed in plant operations, but not in risk communications.

These conditions also contributed to inconsistent media reports. At times, the utility and government provided differing accident descriptions [7]. When this occurred, media representatives gave conflicting reports, which further added to public confusion. Nuclear jargon, competing nuclear experts, and the communications differences between the various government agencies also contributed to media inconsistencies.

Inaccuracies and erroneous information have serious emergency management consequences. The discovery of hydrogen in the reactor coolant system and the possibility of additional releases of radioactive material triggered another series of missteps [7]. Unfounded concern of a hydrogen explosion in the reactor vessel caused the Pennsylvania's Governor to issue an advisory that pregnant women and pre-school children living within a five-mile radius of the plant be evacuated. The Governor also closed all schools in the area and suggested that people living within 16 km miles of TMI-2 remain indoors. Subsequent information proved there was never a danger of an explosion within the reactor vessel. These actions were a direct result of inadequate communication and the lack and availability of accurate and timely information. For example, the fact that pressurized water reactors use hydrogen gas for reactor coolant system oxygen control was not effectively communicated to stakeholders and would have assisted in placing the perceived hazard into a proper risk context.

Throughout the TMI-2 accident, the public, press, government, and the utility had different impressions of the event because information conveyed by the utility and regulator did not always meet the recipient's expectations. These communications affected subsequent actions and led to the impression that the utility was not providing a complete, accurate description of events, offsite releases, and associated plant conditions. In hindsight, the utility did not have sufficient communications staff to satisfy the media's demands, which reinforced the impression that information was being withheld from the public.

From a practical perspective, the operating utility is in the best position to manage the event. External group assistance may be beneficial to provide technical assistance, logistical support, and infrastructure support after the initial event is under control, but operating utility personnel hold the specific plant knowledge needed to manage the early phase of an event. Government officials do not have an equivalent level of plant specific knowledge, and should not attempt to micromanage the utility's accident response. The government licenses and regulates a facility to operate safely and manage off normal events. Micromanagement suggests the licensing and regulatory process was less than adequate.

5.1.1 Enhanced Communications Organization

Given the communications issues that emerged during the accident, an expanded Communications organization was subsequently developed at TMI to facilitate the dissemination of information to the public, press, government organizations, and other stakeholders. This aggressive action was implemented to ensure that the public was informed of recovery events in a complete, timely, and accurate manner.

The TMI operating utility supplemented its expanded communications organization with an active Speakers Bureau that facilitated staff and manager presentations to stakeholders and conducted public tours to ensure the recovery process was viewed as open and transparent. Numerous public meetings were held to ensure recovery activities were understood. Although challenging to implement with a skeptical public, continued communications efforts have a positive, lasting benefit to a long-term recovery plan.

5.1.2 Offsite Monitoring Network

Following the TMI-2 accident, public distrust of utility radiological information prompted the installation of an array of pressurized ion chambers around the site. These ion chambers included the capability for the real-time display of the local radiation level. Remote displays were located at TMI-2, at the emergency operations centers (EOCs) of the five risk counties, and at the State of Pennsylvania EOC in Harrisburg [13]. In addition, the radiation levels were published on a daily basis in local newspapers. These actions restored a measure of credibility and improved the public's understanding of the radiation effects of TMI-2 recovery activities.

The public received the availability of these data in a very positive manner. Many members of the public monitored the daily radiation levels as a means to measure the impact of recovery activities. When the radiation levels failed to increase and continued to represent background levels, public confidence in the recovery process increased.

5.2 Chernobyl

When the Chernobyl accident occurred in the Ukraine, the Soviet Union was a closed society and did not operate under the same communications rules as the United States and Japan. However, even in a closed society a nuclear accident cannot be hidden from the public.

Public notification was intentionally delayed because the accident occurred at night and the initial protective action was to shelter in place. When public notification was made in the morning, it occurred by door-to-door visits. Public evacuation was permitted by private auto at noon on April 27 and notification to evacuate by bus occurred a few hours later. The government did not use a siren system or television for public communications [26-28].

The NRC in NUREG-1251 [28] comments that the extent of the Soviet Union's public education and information program on radiological emergency response was uncertain. For example, farmers refused to evacuate unless their animals were evacuated. The refusal of some farmers to destroy contaminated milk may have resulted from a lack of public education regarding radiation risk. However, the public was reported to have taken potassium iodide. Public education programs directed at the 45,000 residents of the local village of Pripyat were likely given the fact that the village was evacuated in a 3-hour period.

The Ukrainian Health Minister provided protective action information to the Kiev residents through television broadcasts [26-28]. These broadcasts were used to advise city residents of wind shifts that redirected the radioactive plume toward the city. As with the TMI-2 accident, many rumors were spread and government officials and newspapers were used to refute those rumors. In addition, there was considerable public uncertainty and concern during the first few days of the Chernobyl accident because information from the site was not disseminated to the public.

In terms of risk communication, the TMI-2 and Chernobyl accidents have similar themes related to providing accurate and timely information. This commonality is remarkable in view of the different systems of government that regulated these facilities.

5.3 Fukushima Daiichi

The Fukushima Daiichi accident further illustrates the consequences of poor risk communications. Although many of the communications issues encountered during the TMI-2 accident were repeated, the Fukushima Daiichi event was significantly exacerbated by a massive earthquake and subsequent tsunami that devastated the facility and the surrounding geographical area [23,43,66].

The communications errors exhibited at TMI-2 and Fukushima Daiichi caused the public to question the capability and trustworthiness of utilities and governments to safely manage and regulate nuclear power facilities [23,24,43,66]. This is important since the history of nuclear power operations has fostered public suspicions created by previous accidents and events. A brief history of these events and their associated regulatory implications is summarized in Ref. 24.

At Fukushima Daiichi, these suspicions were raised by the response of the government and facility to the accident and their communications with the public. In particular, the utility and government failed to inform the public in a timely and consistent manner regarding the release of radioactive material and associated radiation levels as the accident unfolded. There was also a lack of coordination since radiation maps were available, but not disseminated [43]. The availability of these radiation maps would have assisted in directing the public to the optimum evacuation routes.

The consistent message from the three major reactor accidents is that nuclear power facilities do not operate in a vacuum, and their effects on the environment have significant consequences for the individual facility as well as the nuclear industry. Public confidence is essential if nuclear power is to have a sustainable future. One of the keys to achieving public confidence is a well-supported risk communication organization based on honesty, candor, and the flow of accurate, timely information [23,24,43].

Reviews of the Fukushima Daiichi accident suggest that a number of options exist for improving the relationship with the public. In addition to the activities taken following the TMI-2 accident, communications enhancements could include improving systems to disseminate plant and radiological data in a timely and consistent manner [23,24]. Data quality must be improved to avoid corrections and revisions of earlier reports [43]. Such corrections and revisions do not inspire public confidence, and are often interpreted in a negative manner. Needed improvements in the Fukushima Daiichi communications area are also noted in the 2012 Japanese Diet Report [43].

The availability of consistent radiological data (e.g., dose rates, facility contamination levels, and radioactive material content in milk, fish, water, plants, and other foodstuffs) and its timely communication to the public should be improved. A possible improvement item was utilized as a response action at TMI-2.

As noted in Section 5.1.2, an array of pressurized ion chambers installed around the TMI site provided the capability for the real-time display of the local radiation level. An extension of the TMI-2 remote display approach could be a useful addition to the Fukushima Daiichi risk communication effort. In addition to providing direct radiation levels, the display of plant parameters including effluent monitor readings could be provided on a real-time basis. The availability of these data would foster informed public debate and improve understanding of the environmental impact of recovery activities. Improved information dissemination is a necessary step in fostering public debates associated with the risks and benefits of nuclear power facilities.

Real-time reporting of contaminated ground water activity levels and the extent of underground liquid plume migration at the Fukushima Daiichi site would also improve confidence in the operating utility's ability to manage the recovery effort. This is particularly important in view of the worldwide interest in liquid releases from the Fukushima Daiichi facility and its radioactive liquid waste storage tanks [48-53].

6.0 Public Impacts

The licensing of nuclear facilities should provide a well-defined process that holds the operator and the regulator accountable for safe facility operation. Stakeholders must have confidence that the facility will operate safely and not have a negative impact on the environment. This is a reasonable expectation that is often met with suspicion because the accidents at TMI-2, Chernobyl-4, and Fukushima Daiichi reinforce concerns that facilities are not always operated in a safe manner. The process of licensing and operating nuclear facilities must permit all stakeholders, especially host communities, to participate and ensure that their interests and concerns have been completely addressed. Public involvement in nuclear licensing is important for all facilities including power plants, industrial facilities using radioactive materials, and high-level waste storage facilities.

6.1 Emergency Response

The evacuations during the Fukushima Daiichi accident renewed the public's interest and focused concern on the emergency preparedness activities associated with nuclear facilities including power plants [23,24,42,43,49,52,66,80]. Evacuations are common events resulting from floods, hurricanes, tornados, fires, industrial accidents, and transportation accidents. However, evacuations associated with a nuclear emergency engender a more significant public reaction.

Although emergency response actions are an integral aspect of nuclear power reactor licensing, the Nuclear Regulatory Commission reexamined the role of emergency preparedness programs following the accidents at the Three Mile Island, Chernobyl, and Fukushima Daiichi. The TMI-2 accident showed the need for improved planning, response, and communication by federal, state, and local governments to deal with reactor accidents. Emergency preparedness revisions related to Fukushima Daiichi include expanded response organizations, improved availability of equipment and supplies, enhanced emergency response procedures, increased availability of backup core cooling systems and power supplies, and improved spent fuel pool level instrumentation. As such, emergency preparedness is a dynamic aspect of nuclear facility licensing and is required to adapt to changing natural and man-made threats to the facility.

6.2 Stakeholder Involvement

Diverse stakeholder views and interests must be considered in the licensing process. Including stakeholders in this process is more stressful, but results in a facility license that has a broader range of support. Although it may not be possible to satisfy the concerns of all groups, the licensing process benefits from the participation of a wide range of stakeholders. The task of communicating information and engaging different interest groups should be a significant consideration in facility licensing. Stakeholders and the public should understand how decisions were reached, different options and opinions considered, and issues and concerns resolved. As discussed Ref. 24, this was an early failure of the US nuclear power facility licensing process. This failure is one of the factors that led to stakeholder suspicions and public mistrust in the nuclear power reactor licensing process and in the oversight of operating facilities.

Stakeholder and public involvement in the licensing process has a number of potential advantages. One possible benefit is that stakeholder participation could increase confidence and acceptance of the licensing decision. A second possible benefit is that well-qualified public intervenors introduce valid concerns that require agency staffs to be more thorough and articulate in their analyses and justifications for decisions. The third possible benefit is the introduction of substantive recommendations, new information, or additional viewpoints not previously considered in the regulatory process. In general, the presentation of new information and viewpoints constitutes the public's primary contribution. Stakeholders also have the potential to provide technical insight and guidance. In hindsight, underestimating the design basis earthquake/tsunami assumptions was a major contributor to the Fukushima Daiichi accident. These assumptions could have been challenged by either the public or stakeholder groups, and that action could have precluded the occurrence of the Fukushima Daiichi accident. Any delay in the licensing of the Fukushima Daiichi facility to accommodate more credible design basis assumptions would have been well justified based on the accident severity and its aftermath.

6.2.1 Public and Media Communications

The Fukushima Daiichi accident again demonstrated that communications between the operating utility and government and between the government and public are in significant need of improvement. Poor radiation risk and dose communications affected the public's perception of the accidents at Three Mile Island, Chernobyl and Fukushima Daiichi.

These issues were magnified during the Fukushima Daiichi accident since it involved international media. The demands of the international media during a major accident and the continuous sharing of accurate information are significant challenges when an accident involves multiple nations. International guidance is needed to ensure the coordination of information dissemination during a nuclear accident affecting multiple nations. This guidance should address the dissemination of accurate and timely radiological data in an understandable format.

The use of social networks and smart electronic devices should be incorporated into international communications and emergency plans as timely methods for distributing information. In addition, groups having public credibility and trust (e.g., university professors and physicians) should be included in international communications plans as a method to enhance information exchange with the public and media. Accurate and timely information dissemination would have partially alleviated the stress and some of the challenges associated with the Fukushima Daiichi accident particularly if it was consistently delivered by a trusted source.

7.0 Environmental Impacts

Nuclear power is judged by its failures. The extensive, positive operating experience and the economic and environmental benefits of this technology are negated by the three major power reactor accidents. The release of fission products to the environment, forced evacuations, and relocation of individuals from their homes are issues that are difficult to overcome. These environmental impacts are a major consideration in future nuclear power growth. Accordingly, the environmental aspects of the 1979 Three Mile Island Unit-2, 1986 Chernobyl Unit-4, and 2011 Fukushima Daiichi Units 1, 2, 3, and 4 accidents are addressed in this section.

7.1 TMI-2

The TMI-2 accident had a very limited impact on the local environment and minimal impact on any area outside the immediate reactor location [7,12,23,24]. This environmental effect is assessed by examining the radionuclides released from the TMI-2 accident. The TMI-2 releases to the environment are summarized in Table 4.

During the TMI-2 accident, the release pathway included transfer of radioactive material from the reactor coolant to the containment building, transfer from containment to the auxiliary building, and release to the environment through the auxiliary building waste gas system.

Table 5 provides a summary of a portion of the core inventory released during the TMI-2 and Chernobyl-4 events. Minimal amounts of Cs, Te, and other particulate fission products were released from TMI-2. As a comparison, less than 25% of the available particulate inventory was released during the Chernobyl-4 accident.

Table 4

Airborne Radioactivity Released to the Environment During the Three Mile Island Unit 2 Accident[a]

Radionuclide	Quantity (PBq)	Half-Life
Noble Gases		
^{133}Xe	310	5.2 d
^{133m}Xe	6.3	2.2 d
^{135}Xe	56	9.1 h
^{135m}Xe	5.2	15.3 min
^{85}Kr	1.8[b]	10.8 y
^{88}Kr	2.3	2.8 h
Radioiodine		
^{129}I	1.1×10^{-10}	1.6×10^{7} y
^{131}I	$<1.1 \times 10^{-3}$	8.02 d
^{133}I	1.5×10^{-4}	20.8 h
Cesium and Strontium		
^{134}Cs	3.7×10^{-10}	2.1 y
^{136}Cs	1.1×10^{-11}	13.1 d
^{137}Cs	1.5×10^{-9}	30.1 y

Table 4 Airborne Radioactivity Released to the Environment During the Three Mile Island Unit 2 Accident[a]		
Radionuclide	Quantity (PBq)	Half-Life
^{138}Cs	$7.4x10^{-10}$	32.2 min
^{89}Sr	$2.2x10^{-9}$	50.6 d
^{90}Sr	$2.2x10^{-9}$	28.8 y
Activation Products		
^{3}H	$5.4x10^{-3}$	12.3 y
^{58}Co	$1.5x10^{-8}$	70.9 d
^{60}Co	$3.3x10^{-9}$	5.3 y
Alpha-emitting Radionuclides		
Gross Alpha	$3.0x10^{-9}$	[c]

[a] Behling and Hildebrand [12].
[b] Includes the 1980 reactor building purge.
[c] Varies with radionuclide.

Table 5 Comparison of the Chernobyl and TMI-2 accident source terms[a]		
Constituent	Percent of inventory released from the core	
	Chernobyl	TMI -2
Noble gases	100	<8
Iodine	40	$<2 \times 10^{-5}$
Cs	25	---
Te	>10	---
Particulates	3-6	---

[a] Knief [17].

A number of public effective dose assessments were performed to determine the radiological impact of the TMI-2 accident [4,6-8,12]. There is general agreement that the effective dose was primarily derived from noble gases. Noble gases also contributed to the skin dose. Skin doses, excluding the shielding provided by clothing, were approximately four times the corresponding whole-body doses [12].

The maximum individual dose was calculated using the highest off-site environmental thermoluminescent (TLD) dosimeter output. This TLD was located about 0.8 km east-northeast of the plant and recorded a dose of 0.83 mSv for the period March 28 through April 7, 1979. Since no member of the public resided closed than this TLD, its output represents an upper bound for the public dose.

Individual and population doses were calculated from dosimeter and meteorological data and population distributions around TMI-2. The population dose was calculated by summing each individual dose for the 2 million people that resided within an 80 km radius of the plant [12]. The radiation dose received by the public from the TMI-2 accident is summarized in Table 6.

Table 6

Summary of Radiation Doses Resulting from the TMI-2 Accident[a]

Exposed Group	Dose			
	Whole Body		Thyroid	
	Individual (mSv)	Collective (person-Sv)	Individual (mSv)	Collective (person-Sv)
Highest Individual	< 1	16 – 53[b]	< 0.2	14 - 28
Average Dose to an individual within a 16 km radius	0.08	---	0.01	---
Average Dose to an individual within a 80 km radius	0.015	---	---	---

[a] Behling and Hildebrand [12].
[b] Most probable estimate is 33 person-Sv.

The accident description provided in Section 3.1 and the offsite release consequences presented in this section illustrate that TMI-2 was less severe in comparison to the Chernobyl-4 and Fukushima Daiichi accidents. Although the TMI-2 accident involved an evacuation, it was not based on actual offsite radiological doses. The evacuation was based on elevated containment radiation levels and concerns regarding conjectured hydrogen accumulation within the reactor vessel. However, there was considerable confusion during the accident that created uncertainty regarding the future radiological conditions and the utility’s ability to control and mitigate the accident.

Based on advice from the NRC and concern for the public, the Pennsylvania Governor advised those individuals most susceptible to the effects of radiation (e.g., pregnant women and children) to leave the area within an 8 km radius of TMI-2. In addition, schools within the 8 km radius were closed. The Governor noted that he was exercising caution based on the continued presence of radioactive material in the area and the possibility of further radioactive material releases [7].

7.2 Chernobyl-4

Chernobly-4 was the most serious accident in the history of the nuclear industry and the first to have major international ramifications. Although the effects from the TMI-2 accident were confined to the immediate area surrounding the facility, Chernobyl-4 affected portions of Asia and Europe. The reactivity excursion that ruptured the Chernobyl-4 reactor vessel ejected radioactive material into the environment [26-32].

Major accident releases of radioactive gases, condensed aerosols, and fuel particles from Chernobyl-4 continued for ten days following the April 26, 1986, accident. The total release of radioactive material was 5 - 10 EBq, which included 1.8 EBq of ^{131}I, 0.085 EBq of ^{137}Cs, 0.01 EBq of ^{90}Sr and 0.003 EBq of plutonium radioisotopes [84]. Noble gases comprised about 50% of the total release activity. Release estimates vary [84-87] due to the nature of the Chernobyl-4 accident, its duration, and variety of mitigation methods used to minimize its impact. These releases are summarized in Table 7.

Table 7

Airborne Releases from Chernobyl-4 and TMI-2[a]

Isotope(s)	Activity Released Offsite (EBq)	
	Chernobyl-4	TMI-2
Kr and Xe	1.9[b]	0.38
Cs	0.089	2.6×10^{-12}
Iodine	1.8	1.3×10^{-6}
Other Fission Products	0.11	4.4×10^{-12}

[a] IAEA [84].
[b] The noble gas release quantity was estimated to be 6.5 EBq in IAEA [85]. Other airborne release estimates are noted in Table 10.

The Table 7 values illustrate that the release pathway has a profound impact on the isotopes that reach the environment. At TMI-2, the release pathway involved a tortuous path that limited the quantity of iodine released. The Chernobyl-4 accident was a direct atmospheric release since the facility had no containment fission product barrier. For a severe accident, Refs. 20 and 58 suggested a large iodine release. This prediction was validated at Chernobly-4, but TMI-2 illustrated the weaknesses in applying the assumed source term to all accident scenarios.

The released radioactive materials contaminated significant portions of land surrounding the Chernobyl site. Over 200,000 km^2 of Europe were contaminated with ^{137}Cs with levels above 37 kBq/m^2. Greater than 70 percent of this area was in Belarus, Russia, and Ukraine which were the areas most affected by the accident [84-87]. Contamination levels varied significantly, and were elevated in locations that received precipitation when the radioactive plume traversed these areas. Most of the strontium and plutonium radionuclides were depleted from the plume within 100 km of the facility since they tended to have a larger particle size.

An estimated 350,000 emergency and recovery operation workers supported mitigating and recovering from the accident during 1986–1987. About 240,000 recovery workers participated in mitigation activities at the site and within the 30-km exclusion zone surrounding the reactor. In later years, the numbers of recovery personnel or *liquidators* increased to 600,000, but only a small fraction of these were exposed to high levels of radiation [84-87].

In 2006, the IAEA [84] reported that more than 5 million people resided in Belarus, Russia, and Ukraine in areas that are classified as contaminated with ^{137}Cs levels above 37 kBq/m^2. About 400,000 people lived in more contaminated areas with ^{137}Cs levels above 555 kBq/m^2 that required radiological control. Within this population, 116,000 people were evacuated in the spring and summer of 1986 from the 30 km Exclusion Zone. In addition, 220,000 people were relocated in subsequent years.

The average accumulated doses from recovery workers and affected populations are summarized in Table 8. Natural removal processes and recovery countermeasures have reduced affected area radiation levels by a factor of several hundred. The majority of the contaminated areas are now available for resettlement and economic activity. However, some restrictions have been retained in the Chernobyl Exclusion Zone and in other limited areas.

Table 8

Summary of Average Accumulated Doses to Affected Populations from Chernobyl Fallout[a]

Population category	Number	Average dose (mSv)
Liquidators (1986–1989)	600,000	~100
Evacuees from highly-contaminated zone (1986)	116,000	33
Residents of “strict-control” zones (1986–2005)	270 000	>50
Residents of other ‘contaminated’ areas (1986–2005)	5,000,000	10–20

[a] IAEA (2006) [84].

Table 9 provides a summary of radiation levels that also includes doses beyond the immediate Chernobyl area. This table lists whole-body, skin, and child thyroid doses for village residents 2 km from the facility and to farmers within 3 – 15 km of the facility. As an illustration of the wide ranging effects of the Chernobyl-4 accident, average doses to individuals within Europe and Asia are also provided. The 50 year committed doses to the population of Europe and Asia represent a significant fraction of the annual background effective dose.

Table 9

Summary of Radiation Doses Resulting from the Chernobyl Accident to the General Population[a]

Exposed Group	Dose (Sv)		
	Average Individual Whole Body	Average Individual Skin Dose	Maximum Child Thyroid Dose
Village residents 2 km from plant	0.014	0.1 – 0.2	2.0
Farmers within 3 to 15 km of the plant	0.43[b]	---	---
Average Dose to a individuals within Europe and Asia	0.002[b]	---	---

[a] Refs 28 and 32.
[b] 50 year dose commitment

7.3 Fukushima Daiichi

The Fukushima Daiichi accident involved the loss of all power, degraded core and spent fuel pool cooling capability, core damage, high dose rates, and the release of fission products to the environment [33-56,66]. These conditions required that protective actions be initiated to protect the public. Protective Action implementation was challenging because the accident was initiated by a massive earthquake and tsunami that damaged critical infrastructure.

7.3.1 Protective Actions

During the course of the accident, a number of protective actions were issued including orders for evacuation, sheltering, and administration of stable iodine. These orders had a significant impact on public perceptions of the accident both within Japan and throughout the world. Subsequent remediation actions included top soil removal. Each of these actions is addressed in subsequent discussion.

7.3.1.1 Evacuation Orders

The Fukushima Daiichi and Fukushima Daini nuclear power stations were affected by the earthquake and subsequent tsunami [40-43,49,52,66,85]. Fukushima Daiichi is located about 12 km North of Fukushima Daini. Although the accident consequences were more significant for Fukushima Daiichi, both power stations were involved in evacuation orders.

Nuclear emergency declarations were made at the Fukushima Daini and Fukushima Daiichi Nuclear Power Stations [40-43,49,52,66,85]. The events at Units 1, 2, and 4 at Fukushima Daini were classified as Level 3 (Serious Incident) INES [57] events, and these units were successfully placed into a cold shutdown condition. Units 1, 2, and 3 at Fukushima Daiichi were classified as INES Level 7 (Major Accident) events, and Unit 4 was classified as a Level 3 INES event.

The initial evacuation order for residents within a 3 km radius of Fukushima Daiichi was issued on March 11 at 9:23 p.m. This order also included sheltering in place for residents between 3 and 10 km of the FDNPS. Three separate orders were issued on March 12:

1. At 5:44 a.m., residents within a 10 km radius of Fukushima Daiichi were directed to evacuate.
2. At 5:39 p.m., residents within a 10 km radius of Fukushima Daini were directed to evacuate.
3. At 6:25 p.m., the evacuation radius around Fukushima Daiichi was extended to 20 km.

Sheltering in place for residents within 20 – 30 km of Fukushima Daiichi was ordered on March 15 at 11:06 a.m. On March 25, the government of Japan advised the residents within a 20 – 30 km radius of Fukushima Daiichi to voluntarily evacuate.

As a matter of comparison, the U.S. government on March 16 advised its citizens within 80 km of the Fukushima Daiichi facility to leave the area. On April 15, the U.S. State Department lifted its voluntary evacuation advisory for families of government employees in Tokyo and other Japanese cities. The U.S. recommendation to avoid travel within 80 km of Fukushima Daiichi was inconsistent with the Japanese government recommendations [43,49,66].

On April 22, 2011, the Japanese government announced the expansion of the evacuation zone to selected areas beyond the 20 km radius. Residents of the new areas were asked to evacuate by the end of May. The decision was made since residents could be exposed to effective dose rates of 20 mSv/y if they stayed in their homes. This area included five municipalities NW of the FDNPS. Evacuation of families with babies and children up to kindergarten age and pregnant women living outside the 20 km zone from the FDNPS began on May 15.

The Japanese government also established a no entry zone within 20 km of the FDNPS, and designated parts of areas within 20 – 30 km of the facility as areas in which residents should remain indoors and be prepared to evacuate on limited warning. This order replaced the previous 20 – 30 km voluntary evacuation order. In addition, the Japanese government restricted rice farming in designated areas during 2011.

The evolving accident, expanding evacuation zone, restrictions on agricultural products, and inconsistency between US and Japanese evacuation orders fostered public uncertainty and confusion [43,49,66]. These conflicts added to public stress and did little to engender confidence in the nuclear industry or the regulatory process.

7.3.1.2 Administration of Stable Iodine

On March 14, 2011, Japan distributed 230,000 units of stable iodine to evacuation centers around the Fukushima Daiichi and Fukushima Daini nuclear power plants [43]. The Japanese government recommended that local authorities instruct evacuees leaving the 20 km zone to ingest stable iodine. This order was made on March 16 and recommended a single administration with an amount dependent on age: babies (12.5 mg), 1 month – 3 years (25 mg), 3 – 13 years (38 mg), and 13 – 40 years (76 mg). The government recommended no administration for evacuees 40 years of age or older [43].

7.3.1.3 School Topsoil Removal

Cities in Fukushima prefecture removed the top 1 – 2 cm of topsoil from school grounds to permit children to resume outdoor activity. Soil removal was requested by parents and teachers to limit student radiation doses [43,49,66].

In May 2011, the Japanese government decided that burying contaminated soil was an effective disposal approach. Burying the soil 50 cm underground reduced that radiation level by 90%. Removal of soil is a significant remediation action that requires a disposal facility. Licensing the soil disposal facility is a regulatory action requiring stakeholder input.

7.3.2 Releases of Radioactive Material

The Fukushima Daiichi evacuations were ordered because significant quantities of radioactive materials were released from the damaged reactors. A summary of the Fukushima Daiichi accident radiological releases is provided in Tables 10 and 11. The fission products released during the accident provided an early indication that significant core damage had occurred. Table 10 summarizes airborne releases of radioactive materials. Liquid releases to the ocean are provided in Table 11.

Table 10

Estimated Releases into the Air from the March 2011 Fukushima Daiichi Accident[a]

Organization	Released amount (PBq)			
	Noble Gas	^{131}I	^{134}Cs	^{137}Cs
IAEA	~ 500	~ 500	~ 10	~ 10
IRSN	2000	200	30	
Chernobyl-4[b]	6500	1800	not reported	85

[a] IAEA [85] and IRSN [86].
[b] Chernobyl-4 data provided as a comparison.

The airborne releases include contributions from noble gases, ^{131}I, ^{134}Cs, and ^{137}Cs. Releases of ^{137}Cs are particularly important since its 30 y half-life ensures an extended environmental impact on food, water, and land use.

Table 10 illustrates the severity of the Chernobyl-4 accident relative to Fukushima Daiichi. Although the Chernobyl-4 radioactive material releases are significantly larger than the FDNPS emissions, public discussions often focus on Fukushima Daiichi. This is likely attributed to the fact that it is a more recent event. However, videos of the upper levels of three reactor buildings being destroyed by hydrogen explosions are powerful images that trigger a significant emotional reaction. When coupled with protracted media reports regarding radiation, radioactive materials releases to the air, leakage of contaminated water to the ocean, displaced populations, and contamination of food and water, nuclear power proponents have significant issues to overcome to fully restore public confidence in this electrical generation technology.

The Fukushima Daiichi accident releases to the sea are summarized in Table 11. Sea release values for ^{131}I, ^{134}Cs, and ^{137}Cs are provided. The activity released to the ocean was considerably less than the corresponding air activity. However, these releases affected the international sale of food that was potentially contaminated with radioactive materials. Moreover, these releases have continued for years following the accident. In 2013 and 2014, significant public attention was directed at releases of contaminated water that leaked from above-ground storage tanks.

Table 11

Estimated Releases into the Sea from the March 2011 Fukushima Daiichi Accident[a]

Organization	2011 Period of Assessment	Released Activity (PBq)		
		^{131}I	^{134}Cs	^{137}Cs
IAEA	26 March to 30 September	11	3.5	3.6
IAEA	21 March to 30 April 3	11.4	[b]	3.6
IRSN	21 March to mid-July	[b]	[b]	27

[a] IAEA [85] and IRSN [86].
[b] Not reported.

The air and ocean releases of radioactive material heightened the international reaction to the Fukushima Daiichi accident. For example, the World Health Organization (WHO) issued an advisory regarding travel to Japan. During the early phase of the accident, individuals were advised by the WHO to avoid travel to the areas most affected by the earthquake and tsunami [40-43,49,52,66]. Japanese authorities prohibited travel within the evacuation and exclusion zones surrounding the Fukushima Daiichi site. The size of these zones was determined by local dose rates and contamination levels and was reduced as mitigation activities were performed.

The contaminated areas include agricultural lands and fishing grounds. Agricultural products and fish were contaminated with low levels of fission products. Although these levels do not present a significant health hazard, their presence led to restrictions on international commerce with Japan.

Restrictions on food were imposed following the accident [40-43,49,52,66]. Many of these restrictions remained in place well beyond the termination of major releases from the Fukushima Daiichi facility. Even a year after the Fukushima Daiichi accident, foreign import restrictions were imposed on Japanese food items due to lingering radiation concerns. At that time, 16 countries and regions banned the import of Japanese-produced food. Only four countries (Canada, Chile, Mexico and Myanmar) lifted restrictions including requirements for Japanese exporters to submit radiation screening certifications. Kuwait and Mauritius in southern Africa imposed total embargos on Japanese-made food items. Fourteen other countries and regions, including China and Taiwan, continued to suspend the imports of some Japanese food items. In addition, 57 countries and regions required Japanese exporters to submit government certificates of origin and radiation screening. At one year post-accident, 73 countries and regions maintained import controls on Japanese food. Using the Chernobyl-4 and Fukushima Daiichi accidents as a guide, it will take an extended period for agricultural restrictions to be removed following a future reactor accident involving a significant fission product release.

8.0 Emergency Response

This section focuses on issues that affect emergency response actions following a major power reactor accident involving core damage. The TMI-2, Chernobyl-4, and Fukushima Daiichi accidents involved unique events that outpaced the capability of the operating utility to simultaneously manage the onsite accident and provide timely information to support emergency response actions by governments. This weakness is ultimately a regulatory issue because the regulator licenses a facility and certifies to stakeholders that the utility is capable of addressing all normal and emergency issues in a manner that protects the health and safety of the public.

The TMI-2 accident was the first major commercial power accident that revealed emergency preparedness weaknesses. Accident response and failure to recognize that a loss of coolant accident was in progress were major weaknesses that led to core damage and the escalation of the event to a General Emergency classification. The resulting release of noble gas fission products, and uncertainty regarding the accident's severity led to conflicting communications with the public [7]. These conflicts were attributed to a number of factors including timely, accurate communications with regulatory bodies.

Following the TMI-2 accident, emergency preparedness programs were required to perform immediate NRC notifications for a specified set of events. Drills and response plans were upgraded. The licensee was also required to evaluate drills and exercises several times a year and implement corrective actions for identified weaknesses [1-7]. A portion of these exercises include participation by state and local agencies, the Federal Emergency Management Agency, and the NRC. In order to enhance emergency performance, additional equipment and monitoring instrumentation were installed to enhance accident identification and mitigation. Additional instrumentation was also installed to monitor radiation levels. These modifications improved response capability and their effectiveness was evaluated through drills and exercises.

As noted by the Nuclear Energy Agency [87], the Chernobyl-4 accident was a unique event that should not be utilized as the reference accident for future emergency planning purposes. However, the Chernobyl-4 accident did reveal a number of deficiencies in emergency preparedness and radiation protection. In addition, it was the first major reactor accident to affect multiple nations and to cause radiation related fatalities in the workforce [26-28].

Initial response actions suggested that emergency preparedness organizations were unprepared for the scope and magnitude of the Chernobyl-4 accident. The emergency procedures did not contain sufficient decision criteria to effectively manage the event as the accident evolved. In addition, clear lines of authority were not defined and too many organizations were involved in the decision process [26-28]. These deficiencies suggested that enhancements to the Chernobyl-

4 emergency planning infrastructure were needed. In particular, enhancements were needed to improve emergency communications systems, intervention team response, worker dose control and limitation, and radiation monitoring network capability. Mobile ground monitoring teams, aerial monitoring, and plume tracking were also in need of significant improvement. The Fukushima Daiichi accident revealed additional radiological response weaknesses and the need for further improvements in a number of the aforementioned areas [26-28].

International evaluations of the Chernobyl-4 accident concluded that the intervention plans were too complex and time-consuming to be efficiently implemented [26-28]. Intervention actions and criteria for their initiation should have an international basis to ensure emergency plans involving multiple nations are implemented in a timely, efficient, and consistent manner.

The Chernobyl-4 radioactive material release was large and energetic, and dispersed fission products over multiple continents. Since radioactive material was dispersed over large areas, the Chernobyl-4 accident demonstrated the need to include the multiple nations in the emergency response plans. Chernobyl-4 also demonstrated that a nation could be affected by nuclear accidents occurring within its borders and from foreign sources. This situation was repeated at Fukushima Daiichi. The international impact of the released fission products prompted cooperation and coordination of emergency response actions and activities. The Fukushima Daiichi accident also fostered the development of international emergency exercises.

Characterizing the accident severity and communicating the hazards to the public in a clear, well-defined manner was a significant Chernobyl-4 challenge. This issue was resolved by developing the International Nuclear Event Scale [57]. The INES scale facilitates communication with the public on the severity of nuclear accidents and is currently adopted by a large number of countries to characterize nuclear events. Its effectiveness was illustrated as a consistent means of characterizing the Fukushima Daiichi accident.

Chernobyl-4 provided motivation for international agreements involving food items and their import following a major reactor accident. Monitoring imported food to ensure its safety was one of the first control measures instituted following the Chernobyl-4 accident and continued to be performed during Fukushima Daiichi.

The Fukushima Daiichi accident was exacerbated by a major earthquake/tsunami that complicated emergency response actions. Shortcomings in emergency response were highlighted in the National Diet of Japan Report [43] on the Fukushima Daiichi accident.

The Diet report noted that emergency response issues existed because roles and responsibilities were not well defined. This continues to be a common theme in major power reactor events. Resolution of role responsibilities can be addressed through national and international exercises that challenge and stress the full extent of emergency response plans and procedures and the capabilities of their emergency organizations.

At Chernobyl-4 and Fukushima Daiichi, regulators failed to implement adequate evacuation plans, and an inadequate crisis management system contributed to public confusion during the evacuation [28,43]. In the case of Fukushima Daiichi, the nuclear evacuation was further complicated by earthquake and tsunami damage [43].

At Fukushima Daiichi, the government and regulators were not fully committed to protecting the health, safety, and welfare of the evacuees. This is an incredible admission in the Japanese Diet Report [43] which invalidates a basic premise of emergency planning; namely that the government acts for the benefit of its citizenry.

The Diet report concluded that the safety of nuclear energy in Japan cannot be assured unless the regulatory process is changed by eliminating its insular attitude of ignoring international safety standards [43]. This was also a key lesson from the Chernobyl-4 accident [18].

9.0 Emerging Issues

Nuclear power proponents as well as opponents express varied opinions regarding the proper dose limits for workers and the public. These discussions are often fueled by changing national and international recommendations that have been proposed by the International Commission on Radiological Protection (ICRP). ICRP recommendations [68] are often accepted by regulators and become national requirements. Concerns regarding appropriate dose limits for workers and the public intensify in the aftermath of a power reactor accident. The most recent example of these concerns is associated with the Fukushima Daiichi accident and the allowable dose limit for workers during accident response, appropriate dose limit for the public during an evacuation, the appropriate dose limit for the public to reoccupy their homes, and the acceptable dose for children to return to their schools [23,24,43,45,47,49,52,53,66].

9.1 Public Dose Limit Considerations

Dose limits are traditionally established for the whole body and specific organs for an individual year or for a specified period. These limits are established for normal conditions. Additional limits are also established for emergency conditions associated with protective action recommendations.

9.1.1 Normal Conditions

During normal operations, public dose limits are often based on a fraction of the occupational values. The most recent guidance for dose limits for occupational and public exposures are provided in ICRP 103 [68]. These ICRP dose recommendations are summarized in Table 12. Occupational limits have steadily declined and the question arises regarding the appropriateness of limits when they appear to be continually reduced. This has been apparent as the ICRP has progressed in its evaluations through Reports 2 [88], 26 [89], 60 [90], and 103 [68]. In the US, public effective dose limits for NRC licensed activities are limited to 1 mSv/y following 10CFR20 [70]. Associated public concern and confusion regarding declining dose limits remain a stakeholder concern associated with the operation and safety of nuclear facilities.

Table 12

ICRP 103 Recommended Dose Limits in Planned Exposure Situations[a]

Type of Limit	Occupational	Public
Effective Dose	20 mSv / y, averaged over defined periods of 5 years[e]	1 mSv in a year[f]
Annual Equivalent Dose:		
Lens of the eye[b]	20 mSv / y, averaged over defined periods of 5 years[e]	15 mSv
Skin[c,d]	500 mSv	50 mSv
Hands and feet	500 mSv	---------

[a] Limits on effective dose are the sum of the relevant effective dose from external exposure, and the committed effective dose from intakes of radionuclides. For adults, the committed effective dose is computed for a 50-year period after intake. For children, it is calculated for the period up to age 70.
[b] The occupational limit was revised in an April 2011 ICRP Statement [91].
[c] The limitation on effective dose provides sufficient protection for the skin against stochastic effects.
[d] Averaged over 1 cm^2 of skin regardless of the area exposed.
[e] With the provision that the dose does not exceed 50 mSv in any year.
[f] In special circumstances, a higher value of effective dose could be allowed in a single year. However, the average over 5 years is limited to 1 mSv/y.

Occupational limits are also provided for pregnant women. As with the aforementioned limits, the pregnancy limits vary with the specific ICRP report. For example, ICRP 60 [90] limited the effective dose to 2 mSv to the surface of the mother's abdomen or 1 mSv from the intake of radionuclides. The ICRP 103 [68] pregnancy limit is based on limiting the fetal dose to 1 mSv. In contrast, the NRC's pregnancy limit is 5 mSv during the term of the pregnancy [70]. These inconsistencies lead to public confusion and do not inspire confidence in the dose limits established by regulators when these various values are cited in licensing discussions [24].

9.1.2 Emergency Conditions

Emergency dose limits influence public evacuation and sheltering decisions, and the administration of thyroid blocking agents. Following these initial protective actions, limits are established to restrict the dose from intakes of food and water and to determine if evacuated individuals are permitted to return to their homes. These limits are more than academic interest. As demonstrated by the Fukushima Daiichi accident, dose limits have a profound impact on evacuated individuals and the ability to return to their homes and resume normal lives [43].

In the US, the EPA establishes public limits for emergency conditions [69]. These limits have been adopted by the NRC and applied to commercial power reactor accidents and are addressed in subsequent discussion.

9.1.2.1 EPA Guidelines

Upon classification of a Site Area or General Emergency, protective actions are usually implemented [71]. Protective actions are guided by actual or projected offsite doses and plant conditions. These actions include sheltering, evacuation, and the administration of radioprotective chemicals. Table 13 summarizes the EPA protection action guidelines (PAGs) for the early, intermediate, and late phases of a nuclear incident [69].

Projected dose is the dose to be delivered to the public given a set of existing plant conditions and the anticipated release duration. Protective actions are governed by a number of considerations including the projected dose. If plant conditions change (e.g., the release rate, core conditions, equipment status, or meteorological conditions), the projected doses are updated.

9.1.2.2 ICRP Guidelines

Emergency exposures are unexpected situations that occur during the operation of a planned situation or from a malicious act. Before describing the ICRP guidelines, it is necessary to define terminology specific to that methodology. In an emergency exposure situation, the reference level is the total residual dose an individual would not exceed during a single acute exposure or during a protracted exposure (annual basis). For example, in emergency exposure situations the criteria in ICRP 60 [90] are specified in terms of averted dose (intervention levels), but the ICRP 103 [68] recommendations are defined in terms of incremental dose (reference levels).

The dose that is expected to occur from the emergency event, should no protective actions be utilized, is called the projected dose. Residual dose is the dose that results following the implementation of a protection strategy. Each protective measure eliminates or avoids a certain dose, which is called the averted dose. As noted in Table 14, optimization of protective measures that comprise the overall protection strategy is a complex process that includes a number of considerations.

For emergency exposure situations, ICRP 60 [90] and ICRP 63 [93] recommend no response below the action levels. Recommend action level values for the averted dose are appropriate for protective actions where intervention is usually justified. These protective actions include sheltering, administration of stable iodine, evacuation, and relocation. ICRP 103 recommends optimization below the reference levels. The ICRP recommends an upper value of the projected dose or reference level received from all pathways below which optimization is applied. Specific ICRP 60 [90], 63 [93], 96 [94], and 103 [68] recommendations are summarized in Table 14.

Table 13

EPA Planning Guidance and Protective Action Guides for Radiological Incidents

Phase	Protective Action Recommendation	Protective Action Guide or Planning Guidance
Early	Sheltering-in-place or evacuation of the public[a]	10 mSv to 50 mSv projected dose/4 days[b]
	Administration of prophylactic drugs (e.g., KI)	50 mSv projected child thyroid dose from radioactive iodine
	Limit emergency worker effective dose	50 mSv/year (or greater under exceptional circumstances)[c]
Intermediate	Relocation of the public	20 mSv projected dose first year[b] Subsequent years, 5 mSv/year projected dose
	Food interdiction	5 mSv/year projected dose, or 50 mSv/year to any individual organ or tissue, whichever is limiting
	Limit emergency worker effective dose	50 mSv/year[b]
	Reentry	Operational Guidelines[d] (Stay times and concentrations) for specific activities
Late	Cleanup	The planning process (including stakeholder participation) sets priorities and actions.
	Waste Disposal	The planning process (including stakeholder participation) sets priorities and actions.

[a] Should begin at 10 mSv. Sheltering may begin at lower levels if advantageous.
[b] Projected dose is the sum of the effective dose from external radiation exposure (i.e., groundshine and cloudshine) and the committed effective dose from inhaled radioactive material.
[c] Doses to emergency workers above 50 mSv may be approved by competent authority.
[d] DOE/HS-0001; ANL/EVS/TM/09 [92].

Table 14

ICRP Emergency Exposure Situations

Categories of Exposure	ICRP 60 Intervention Levels[a,b,c]	ICRP 103 Reference Levels[a,c]
Occupational exposure[d,e]		
• Life-saving (informed volunteers)	• No dose restrictions[d]	• No dose restrictions if benefit to others outweighs the rescuer's risk[e]
• Other urgent rescue operations	• ~500 mSv; ~5 Sv (skin)[d,g]	• 1000 or 500 mSv[e]
• Other rescue operations	• Not provided	• ≤ 100 mSv[e]
Public exposure[e,f]		
• Foodstuffs	• 10 mSv/y[f]	• -----
• Distribution of stable iodine	• 50-500 mSv (thyroid)[f,g]	• -----
• Sheltering	• 5-50 mSv in 2 days[f]	• -----
• Temporary evacuation	• 50-500 mSv in 1 week[f]	• -----
• Permanent relocation	• 100 mSv first year or 1000 mSv[f]	• -----
• All countermeasures combined in an overall protection strategy	• -----	• Typically between 20 – 100 mSv/y according to the situation.

[a] Effective dose unless otherwise specified.
[b] Averted dose.
[c] Intervention Levels refer to averted dose for specific countermeasures, and remain valuable for optimization of individual countermeasures when planning a protection strategy. As a supplement to Reference Levels for evaluation of protection strategies, these levels refer to residual dose.
[d] ICRP 60 [90].
[e] ICRP 96 [94]. Effective doses below 1000 mSv should avoid serious deterministic effects, and effective doses below 500 mSv should avoid other deterministic effects.
[f] ICRP 63 [93].
[g] Equivalent dose.

The application of the ICRP 103 reference levels [68] involves (1) characterizing the exposure situation, (2) setting a reference level, and (3) optimizing protection accounting for the specific circumstances. This is an iterative process, and yields an improvement in the level of protection for existing and emergency situations.

The ICRP emphasizes the need for optimization and justification of protection strategies for application during an emergency. Optimization is influenced by the reference levels. Protective actions and dose evaluations are part of the optimization process.

9.2 Radiation Worker Dose Limits

The issue of radiation worker dose limits was raised during the early phase of the Fukushima Daiichi accident when a number of workers exceeded the 250 mSv effective dose limit [43]. Worker dose limits are a topic of interest because efforts have been made to harmonize national radiation protection regulations [24]. As noted previously, there are a variety of national and international approaches to establishing worker dose limits [24].

Radiation workers have established dose limits for normal operations, planned special exposures, and emergencies. Normal operations doses are specified in national regulations (e.g., 10CFR20 [70] and 10CFR835 [95] in the US) and in National Council on Radiation Protection and Measurements (NCRP) (e.g., NCRP 116 [96]) and ICRP (ICRP 60 [90] and 103 [68]) publications. Planned special exposures are unique to the US regulatory environment, allow workers to receive additional dose for non-emergency situations, and are defined in the Code of Federal Regulations for US Nuclear Regulatory licensees in 10CFR20 [70] and for US Department of Energy licensees in 10CFR835 [95]. Emergency dose limits and recommendations are specified by national as well as international organizations, and are addressed in subsequent discussion.

9.2.1 Normal Operations

The ICRP 103 dose limit recommendations are summarized in Table 12**.** These limits provide a dose framework for normal operations and operating conditions. In the US, regulatory limits follow ICRP recommendations, but the adoption of the most recent ICRP publications are often delayed by years. Current NRC regulations are based on ICRP 26. The USDOE utilizes a combination of ICRP 26 and ICRP 60 recommendations, but ICRP 26 dose limits are used.

9.2.2 Emergency Operations

Three major power reactor accidents have occurred and evacuations were implemented for each event [1-56]. The TMI-2 accident involved a voluntary evacuation, but did not result in significant offsite doses or levels of contamination. Chernobyl-4 and Fukushima Daiichi led to mandatory evacuations and areas outside the facility boundary were contaminated with fission products. In addition, worker exposures at Chernobyl-4 and Fukushima Daiichi were significantly higher than encountered during the TMI-2 accident.

During an emergency, decisions are made that affect the health and safety of workers and the public. In order to facilitate these decisions, guidelines are needed to quantify dose limits for life saving activities and for the protection of facility equipment and property. Table 14 summarizes emergency worker dose guidance provided by the ICRP. US Environmental Protection Agency guidance is provided in Tables 13 and 15 [69]. It is interesting to note that the NRC provides no specific emergency guidance. The NRC uses the EPA guidance that is applied to all US commercial nuclear power events.

Table 15

EPA Response Worker Guidelines[a]

Effective Dose Guideline (mSv)	Activity	Condition
50	All occupational exposures	All reasonably achievable actions have been taken to minimize dose
100[b]	Protecting valuable property necessary for public welfare (e.g., a power plant)	Exceeding 50 mSv is unavoidable and all appropriate actions are taken to reduce dose Monitoring is available to project or measure dose
250[c]	Lifesaving or protection of large populations	Exceeding 50 mSv is unavoidable and all appropriate actions are taken to reduce dose Monitoring is available to project or measure dose

[a] EPA [69].

[b] For potential doses >50 mSv, medical monitoring programs should be considered.

[c] In the case of a very large event, incident commanders may need to consider raising the property and lifesaving response worker guidelines to prevent further loss of life and massive spread of destruction.

The EPA limits emergency worker effective doses to 50 mSv/y during the early accident phase, which is assumed to last 4 days. Higher effective doses can be incurred under exceptional circumstances. The EPA notes that protecting valuable property necessary for public welfare (e.g., a power plant) can utilize worker limits of 100 mSv and lifesaving activities can be authorized up to 250 mSv. In the case of a very large incident, such as a multiunit nuclear accident with severe core damage, incident commanders may raise the property and lifesaving response worker guidelines to prevent further loss of life and massive spread of destruction. In the US, a dose authorized by incident commanders in excess of 250 mSv would likely be voluntary.

The Fukushima Daiichi accident emergency worker dose limit was established at 250 mSv. This value is consistent with ICRP recommendations.

The possibility of worker doses in excess of 250 mSv in a severe power reactor event introduces an emergency management concern. Since doses above 250 mSv are likely, emergency managers may face a lack of volunteers during a high dose event. The US guidelines are inconsistent with the most recent ICRP 103 guidance noted in Table 14. For example, ICRP 103 imposes no dose restrictions if the benefit to others outweighs the rescuer's risk for lifesaving activities. Emergency management decisions and worker activities can take very different paths when using ICRP 103 or EPA guidance. Based on the doses likely to be encountered following a severe core melt event, it appears that more definitive US guidance is required for emergency workers and emergency managers to avoid delays encountered in addressing voluntary exposure situations. The ICRP 103 approach offers a more realistic view of the possible consequences of a severe reactor accident. Training and emergency exercises should reflect situations encountered in events where worker effective doses exceed 250 mSv. A number of Fukushima Daiichi workers exceeded 250 mSv which suggests that planning for these high doses is more than an academic exercise [43,49,50,52,66].

Inconsistency between ICRP and US emergency worker doses is a regulatory issue that should be reconciled. These discrepancies are most apparent for severe core damage events that have resulted in higher worker doses. Severe power reactor accidents have the potential to create confusion and possible litigation regarding reasonable and prudent worker dose values and actions that produced the conditions leading to these exposures.

9.3 Future Considerations

The issues that facilitated the TMI-2, Chernobyl-4, and Fukushima Daiichi accidents are mitigated through advanced reactor designs [24,97,98]. Generation IV reactors [97] incorporate existing operating experience to enhance safety and minimize the probability of a severe accident. However, considerable development is required for Generation IV reactors to reach their potential and become an operational reality.

Nuclear generation is receding in the Western world, but Asia, Africa, and the Middle East will likely see a significant expansion [98]. The expansion of nuclear power to nations with less technical capability and infrastructure presents a challenge to reactor safety and offers the potential for future accidents. Sustained, safe operation of these nuclear units presents a significant challenge and requires a dedicated effort to ensure their success [24].

10.0 Summary and Conclusions

This paper reviewed selected aspects of the TMI-2, Chernobyl-4, and Fukushima Daiichi power reactor accidents with a focus on their radiological significance. These events have had a profound impact on radiation safety, nuclear safety, nuclear regulation, and the future development and implementation of nuclear power production. The key aspects of the three major accidents are summarized in Table 16.

Table 16

TMI-2, Chernobyl-4, and Fukushima Daiichi Accident Summary

Specific Feature	TMI-2 (1979)	Chernobyl-4 (1986)	Fukushima Daiichi (2011)
Reactor Type	PWR	RBMK	BWR
Location	US	USSR (Ukraine)	Japan
Units Involved / Units at Site	1/2	1/4	4/6
Spent Fuel Pools Effected	0	0	4
Event Type	Loss of Coolant Accident	Reactivity Excursion	Station Blackout / Loss of Coolant Accident
INES Classification	5	7	7
Event Affected Other Nations	No	Yes	Yes
Radiation Related Fatalities	No	Yes	No
Cause	Valve closure failure Operator errors Human factors - control room design Regulatory failures – Design weaknesses and operating experience not distributed	Inadequate test evaluation and performance Unforgiving reactor design Safety systems bypassed Operator errors	Regulatory failures – Design Basis Event underestimated Reactor design – inadequate power design to manage a station blackout condition Possible operator errors
Hydrogen Detonation	Yes	Uncertain due to rapid accident progression	Yes (Multiple Units)
Fission Product Barrier Status - Fuel - Reactor Coolant System - Containment	 Failed Intact (following PORV closure) Intact	 Failed Failed Not applicable for the RBMK design	 Failed Failed Failed

Table 16

TMI-2, Chernobyl-4, and Fukushima Daiichi Accident Summary

Specific Feature	TMI-2 (1979)	Chernobyl-4 (1986)	Fukushima Daiichi (2011)
Release Pathway	Reactor coolant system to reactor building sump to auxiliary building sump to auxiliary building waste gas system	Direct atmospheric release	Through failed fission product barriers
Nuclides Released	Noble Gas Minimal Iodine	Noble Gas Iodine Particulates including Cs and Sr	Noble Gas Iodine Particulates including Cs and Sr (Total release about 10-20% of Chernobyl-4)
Evacuation Order	Yes (Voluntary)	Yes (Mandatory)	Yes (Mandatory)
KI Administered to Evacuees	No	Yes	Yes
Offsite Areas Require Contamination Remediation	No	Yes	Yes
Recovery Status	The reactor vessel is defueled and the facility is stabilized. Final cleanup is to be accomplished with the decontamination and decommissioning of the TMI site.	The site is essentially stabilized with the accident unit enclosed by a sarcophagus. A New Safe Containment is to be completed by the end of 2017.	Units 1, 2, and 3 are in cold shutdown. Unit 4 is defueled. Significant decontamination efforts have yet to be accomplished. Defueling approaches are under evaluation.

All three accidents damaged one or more fission product barriers. Failure of the fission product barriers led to releases of radioactive material to the environment and public evacuations.

Emergency preparedness plans and program weaknesses were highlighted during these evacuations. The evacuations and relocation of the public present a continuing issue and challenge to the advancement of nuclear power.

Control of worker doses during emergencies remains a concern, and the basis for public dose limits requires clear communication to stakeholders. Stakeholder relations and communications during emergencies remain continuing issues.

Nuclear power appears to have a bright future in Africa, Asia, and the Middle East, but the ramifications of the three major accidents has a lingering impact on its advancement in the US and European Union. Unless the issues associated with the TMI-2, Chernobyl-4, and Fukushima Daiichi accidents are fully resolved, future power reactor accidents are possible.

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