13th International Conference on CANDU Fuel
Holiday-Inn Waterfront Hotel
Kingston, Ontario, Canada, 2016August 15-18

CANDU FUEL:
Evolution towards Optimal Performance

Causes and Radiological Consequences of the Chernobyl and Fukushima Nuclear Accidents

L. Sihver[1] and N. Yasuda[2]

[1]Technische Universität Wien, Atominstitut, Vienna, Austria
(Stadionallee 2, 1020 Vienna, Austria+43 2622 26100 950, lembit.sihver@tuwien.ac.at)
[2]Research Institute of Nuclear Engineering, University of Fukui, Tsuruga-shi, Japan

ABSTRACT – In this paper the causes and the radiological consequences of the explosion of the Chernobyl reactor occurring at 01:23 h (local time) on April 26, 1986, and of the Fukushima Daiichi nuclear disaster following the huge Tsunami caused by the Great East Japan Earthquake at 14:46 h. (local time) on Friday 11, March, 2011 will be discussed.The need for better severe accident management (SAM), and severe accident management guidelines (SAMGs), are essential in order to increase the safety of the existing and future operating Nuclear Power Plants (NPPs). In addition to that, improved radiation release barriers, including low corrosive fuel and cladding, should be developed. Stress tests should on a regular basis be performed to assess whether the NPPs can withstand the effects of natural disasters and man-made failures and actions.The differences in safety preparations at the Chernobyl and Fukushima Daiichi will therefore be presented, as well as recommendations concerning improvements of safety culture, nuclear fuel performance, decontamination and disaster planning. The need for a high-level national emergency response system in case of nuclear accidents will also be discussed. The emergency response system should include fast alarms, communication between nuclear power plants, nuclear power authorities and the public people, as well as well prepared and well established evacuation plans and evacuation zones. The experiences of disaster planning and the development of a new improved emergency response system in Japan will be presented together with training and education program, in order to ensure that professional rescue workers, including medical staff, fire fighters, police, etc., as well as the normal populations including patients, have sufficient knowledge about ionizing radiation and are informed about the meaning of radiation risks and safety.

Introduction

The Chernobyl and Fukushima accidents highlighted that both in-depth understanding of nuclear accident scenarios and improvement of existing, or development of new, severe accident management guidelines (SAMGs) are essential in order to further increase the safety of the existing and future operating Nuclear Power Plants (NPPs).The main objectives of severe accident management (SAM) are preventing significant core damage; terminating the progress of core damage once it has started; maintaining the integrity of the containment as long as possible; minimizing releases of radioactive material; and achieving a long term stable state. To achieve these objectives, a number of strategies mustbe developed. From these strategies, suitable and effective measures for accident management should be derived. Such measures include plant modifications and personnel related actions. To reduce the risk that future nuclear accidents will occur, as well as mitigate the consequences of an accident if it would occur, it is important that improvements made to severe accident management programs are shared between nuclear facilities, that regulatory related issues are discussed, and that training and education of personal are improved at all nuclear facilities.It is also essential that on-site and off-site emergency response plans, for a potential severe nuclear accident, are closely linked to each other and that they are regularly discussed, improved and updated. Gaps in knowledge related to the implementation of SAMGs, and how these gaps may be addressed,must be identified and potential priority areas for research and development recognised. In this paper, SAM, SAMGs, and the causes and the radiological consequences of the Chernobyl and the Fukushima nuclear disasters arediscussed.

1. Severe Accident Management (SAM)

Accident management consists of both "preventive" and "mitigative” parts to minimize the risk for accidents, and if an accident would occur minimize the consequences of the accident. A common tool for promptly and consistently communicating to the public the safety significance of events associated with sources of ionizing radiation is by grading the event by using the International Nuclear and Radiological Event Scale (INES), shown in Figure 1. Another way of labelling an accident in a nuclear facility is by the division into design basis accident (DBA),or maximum credible accident (MCA), and beyond design basis accident (BDBA). A DBA or a MCA is a postulated accident that a nuclear facility must be designed and built to withstand, without loss of the systems, structures, and components necessary to assure public health and safety.Accident conditions more severe than a DBA are conditions with deviations from normal operation more severe than anticipated operational occurrences, which may arise owing to multiple failures of safety systems leading to significant core degradation and may jeopardize the integrity of many or all of the barriers to the release of radioactive material. These conditions couldinvolve significant core degradation and are then termed severe accidents [1].

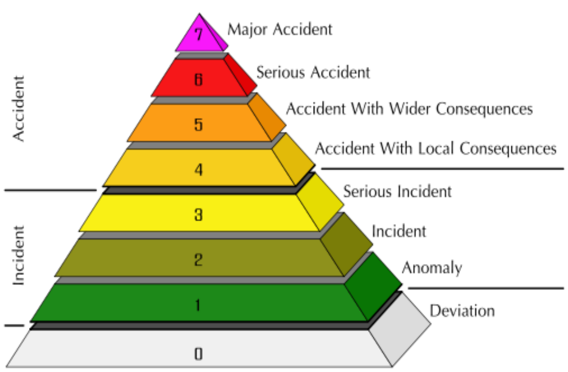

Figure 1. The International Nuclear and Radiological Event Scale (INES).

In a NPP, nuclear accident management is the set of actions to be performed during the evolution of a beyond DBA:

- to prevent the escalation of the event into a severe accident;
- to mitigate the consequences of a severe accident;
- to achieve a long term safe stable state [1].

The second aspect of the accident management listed above (to mitigate the consequences of asevere accident) is also termed severe accident management (SAM). Accidentmanagement is essential to ensurethat both thelikelihood of an accident entailing significant core damage (a severe accident) and themagnitude of a release of radioactive material, following a severe accident, are kept aslow as reasonably achievable and, thereby, reduce the risk for a severe accident.

Based on the SAM, severe accident management guidelines (SAMGs) should be implemented to certify that a knowledge based response strategy exist to increase the safety of the existing and future NPPs. Such a response strategy should rely on the operators´ understanding of the performance of the NPP and its systems to decide on an appropriate course of action. This approachis to be compared with a rule based response strategy which requires operatorsto follow prescriptive procedural guidance in response to an accident. Theknowledge based strategy allows for more flexibility and the application of responsestrategies that are adaptable to the events at hand. The Chernobyl disaster, which is discussed in paragraph 2.is an example of aDBA becoming a non DBA largely due to failures to follow the written operating procedures. In comparison, the Fukushima nuclear accident was caused by a combination of BDBA and human caused errors, which is discussed in paragraph 3.

When dealing with risk, risk perception, risk assessment and risk management must be considered, as shown in Figure 2. Risk perception is the subjective judgment about the characteristics and severity of a risk, i.e. using imagination to foresee possible risks. Risk assessment contains quantitative or qualitative estimations of the risks, i.e. using current knowledge to make a decision how to handle the risk. Risk management, is how different risk scenarios are handled in practice, which also include the safety culture at each specific facility.

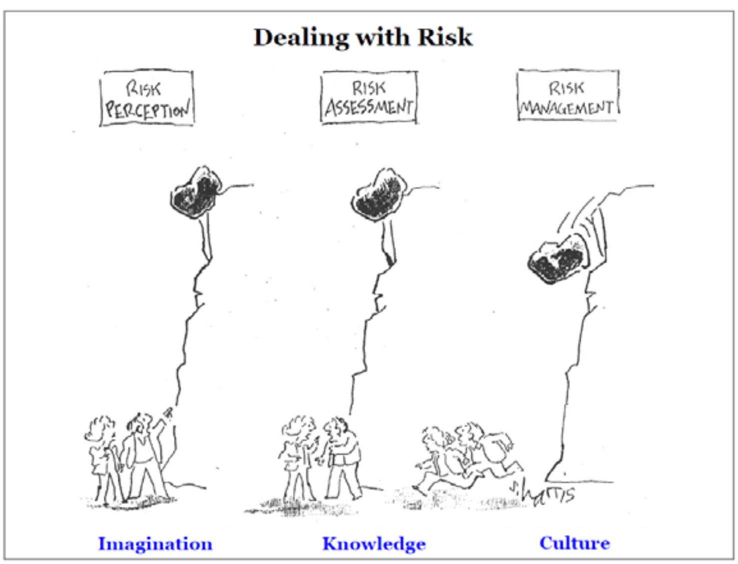

Figure2. Dealing with risk.

The prevention/mitigation of risk can be handled in different ways. The accident management guidance could e.g. be developed as a structured top-down approach, as suggested in ref. [2]. This approach should begin with the objectives andstrategies, and result in procedures and guidelines, and should cover both thepreventive and the mitigatory domains, as shown in Figure 3.To achieve the objectives, a number of strategies should be developed and from the strategies, suitable and effective measures for accidentmanagement should be derived [2].

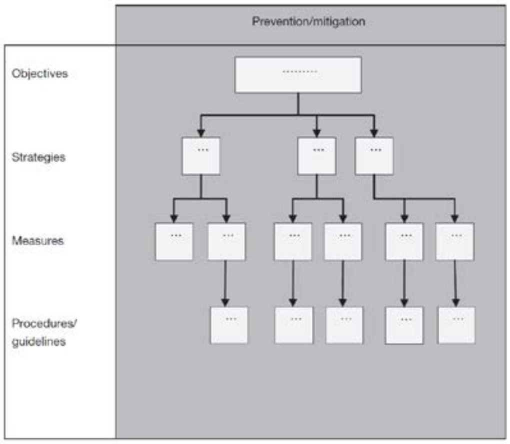

Figure3.Accident management guidance as a structured top-down approach[2].

2. The Chernobyl accident

The Chernobyl power station is situated at the settlement of Pripyat, 16 km northwest of the city of Chernobyl and 104 km north of Kievin Ukraine. The station consist of four Reaktor Bolshoi MoshnostyKanalny (RMBK) reactors, which each was capable of producing 1,000 megawatts of electric power when they came online in 1977–83. Two more reactors were under construction at the time of the accident,April 26, 1986,On April 25, 1986, prior to a routine shut-down, the reactor crew at Chernobyl Unit 4 began preparing for a test to determine how long the turbines would spin and supply power to the primary pumps following a loss of the main electrical power supply. A number of events followed by each other lead to that around 01:23 h local time, Friday, April 26, 1986, the largest nuclear power accident ever happened occurred at the Unit 4 at the Chernobyl nuclear power plant.

2.1 Causes leading to the Chernobyl accident

Immediately prior to the accident, the reactor had for many hoursbeen driven off permissible operating conditions. The reason for that was that on April 15, 1986, prior to a routine shut-down, the reactor crew at ChernobylUnit 4 began preparing for a test to determine how long the turbines would spin and supply power to the primary pumps following a loss of main electrical power supply. The turbine energy should bridge the electricity gap until the emergency diesel generators reach full power (40 - 60 seconds). The test should be carried out between 700 and 1000 MWth, even if it was well known that the reactor is extremely unstable at a low power levels. First the power level was decreased slowly from 3200 MWth to 1600 MWth, when one of the two turbine-generators was stopped. However, the network distributor in Kiev requested a stop of the power decrease due to electricity demand in the network. The reactor was therefore kept at operation at 1600 MWth for around 10 hours, and then the power was decreased further. The operators were however unable to stabilize the reactor due to Xenon poisoning around 1000 MWth, so the power decreased down to 30 MWth. The operators tried to bring the reactor back to the necessary power level by removing all but 6 control rods out of the core as far as possible.With more than 200 control rods removed only 200 MWth was reached. Then additional coolant pumps switched on, core subcooled by cold water and the experiment started. The turbine inlet valve closed, turbine-generator and coolant pumps run down. Soon the water started to evaporate in the core and the power increased slowly, but the remaining 6 CR could not compensate the power increase so the shift supervisor ordered insertion of all CR.The insertion speed was however too slow, so there was a prompt nuclear transient and an explosion,which brought the temperature above 3000 °C. Thisled to that the graphite in the reactor caught fire and a second explosion followed that tore down the reactor and caused 1000 ton reactor cover lifted away and all coolant channels were destroyed, and that a large part of the reactor contentof volatile substances were released.

2.2 Radiological consequences of the Chernobyl accident

The Chernobyl accident caused many severe radiation effects almost immediately. Of the 600 workers present on the site during the early morning of 26 April 1986, it is estimated that 134 received high doses (0.8-16 Gy) and suffered from radiation sickness. Of these, 28 died in the first three months and another 19 died in 1987-2006 of various causes not necessarily associated with radiation exposure. In addition, according to the UNSCEAR 2008 Report [3], the majority of the 530,000 registered recovery operation workers received doses of between 0.02 Gy and 0.5 Gy between 1986 and 1990. That cohort is still at potential risk of late consequences such as cancer, cardiovascular and other diseases, and their health are followed closely.

Two radionuclides, ^{131}I, with a half-life of 8 days, and ^{137}Cs, with a half-life of 30 years, were significant for the radiation dose delivered to the members of the public. For the short lived ^{131}I, the main transfer pathway of human exposure was via pasture grass to cow´s milk, which were then drank by people, especially children. Many children weretherefore exposed to high doses of ^{131}I, which in particular caused thyroid cancer. By 2005, more than 6,000 thyroid cancer cases had been diagnosed in those who were children and adolescents in Belarus, Ukraine and the most affected Russian regions. An increased occurrence of breast cancer, as well as different solid cancer types, have also been reported in the most contaminated areas. Since no information was given to the residentsimmediately after the accident, and only on the second day after the disaster (after 36 hours) did theSoviet authorities start evacuating people from the area around Chernobyl, many children drank milk with high levels of ^{31}I iodine. Soviet did not admit that there had been an accident at Chernobyl until 60 hours after the disaster, afterthat the Swedish authorities had alerted other European countries about the detected radioactive falloff from Soviet Union and warned the Soviet authorities that Sweden was going to file an official alert with the IAEA.

Among the Russian recovery operation workers who received higher doses, there is emerging evidence of some increase in the incidence of leukemia [3]. However, based on other studies, the annual incidence of radiation-induced leukemia would be expected to fall within a few decades after exposure. In addition, recent studies of the recovery operation workers indicate that opacities of the eye lens might be caused by relatively low radiation doses.Among the 106 patients surviving radiation sickness, complete normalization of health took several years. Many of those patients developed clinically significant radiation-induced cataracts in the first few years after the accident.

For the long-lived radionuclides, such as ^{137}Cs, the long-term transfer proceeds through the environment and is still followed.

The Chernobyl accident resulted in widespread radioactive contamination in areas of Belarus, the Russian Federation and Ukraine inhabited by several million people. In addition to causing radiation exposure, the accident caused long-term changes in the lives of the people living in the contaminated districts, since the measures intended to limit radiation doses included resettlement, changes in food supplies and restrictions on the activities of individuals and families. More than 200,000 km^{2}in Europe received a surface contamination of morethan 37 kBq/m^{2}of^{137}Cs. During the first day of the accident, high winds brought radioactive substances northwards towards the Nordic countries. Where it rained during the cloud passage was the fallout on the ground large and estimations showed that e.g. the central and northernpart of Sweden absorbed around 5% of the ^{137}Cs that Chernobyl released into the air.

2.3 Design and safety flaws of RMBK reactor in Chernobyl

The RBMK reactors have a number of negative design features that strongly influence the safety of their operation. Some of them were eliminated after the Chernobyl accident. However, below is discussed the negative features of the RBMK reactors that existed at the time of the accident. One of them is an enhanced sensitivity of neutron fields to the moving of control rods. This effect is caused through a big number of absorbers in the core for compensation of a large reactivity surplus. By withdrawal of some absorbers, especially absorbers in peripheral zones, a local criticality can occur.These features of the corecause significant problems in controlling the RBMK reactors in comparison to PWRs and BWRs. Another significant problem was that the Chernobyl'sRMBK reactor had a dangerously large positive void coefficient due to that the reactorused solid graphite as a neutron moderator, and the coolant water actedlike a neutron absorber. The neutrons were therefore slowed down even if steam bubbles were formed in the water. Furthermore, because steam absorbs neutrons much less readily than water, increasing the intensity of vaporization means that more neutrons are able to fission the uranium atoms, increasing the power output of the reactor. This makes the RBMK design very unstable at low power levels, and prone to suddenly increasing energy production to a dangerous level. This behavior is counter-intuitive, and this property of the reactor was unknown to the crew.Aneven more significant flaw was that the lower part of each control rod was made of graphite and was 1.3 meters shorter than necessary, and in the space beneath the rods were hollow channels filled with water. The upper part of the rod, the truly functional part that absorbs the neutrons and thereby halts the reaction, was made of boron carbide. With this design, when the rods are inserted into the reactor from the uppermost position, the graphite parts initially displace some water (which absorbs neutrons, as mentioned above), effectively causing fewer neutrons to be absorbed initially. Therefore for the first few seconds of control rod activation, reactor power output is increased, rather than reduced as desired. This behavior is also counter-intuitive and was not known to the reactor operators.Human factors also contributed to the conditions that led to the disaster. Those included:

- operation of the reactor at a very low operative reactivity surplus (ORS),
- conducting of the experiment at a power level below the level provided for test,
- blocking of the protection system relaying on water level and steam pressure in
- steam-separators,

- blocking of the protection system relaying on shutdown signal from two turbo-generators,
- connection of all the main circulating pumps to the reactor,
- switching off the emergency core cooling system (ECCS).

3. The FukushimaDaiichi accident

The Fukushima Daiichi(I) Nuclear Power Plant comprise six BWRs originally designed by General Electric (GE) and maintained by the Tokyo Electric Power Company (TEPCO). At the time of the Great East Japan Earthquake (Tōhoku Earthquake) at 14:46 h Japan Standard Time (JST)on 11 March 2011, reactors 4, 5 and 6 were shut down in preparation for re-fueling.However, their spent fuel pools still required cooling.The Great East Japan Earthquake wascaused by a sudden release of energy at the interface where the Pacific tectonicplate forces its way under the North American tectonic plate. A section of theEarth’s crust, estimated to be about 500 km in length and 200 km wide, wasruptured, causing a massive earthquake with a magnitude of 9.0 on the Richter scale and a tsunamiwhich struck a wide area of coastal Japan, including the north-eastern coast,where several waves reached heights of more than ten metres. The floodingfrom the tsunami waves resulted in the failure of the power supplies necessaryto maintain the fundamental safety functions, including the cooling of the reactorsand the spent fuel. This failure led to severe core damage in three reactors and therelease of radioactive material to the atmosphere.The radionuclides in the atmosphere were then deposited both on land and in theocean. People within a radius of 20 km of the site and in other designated areas were evacuated, and those within a radius of 20–30 km were instructed to shelter before later being advised to voluntarilyevacuate. Restrictions were placed on the distribution and consumption of food and the consumptionof drinking water. The earthquake and tsunami caused great loss of life and widespread devastation in Japan. More than 16,000 people died in the disaster and more than 470,000 were displaced from their homes, and over 2,500 people are still missing and presumeddead. This was a tragedy beyond imagination.

3.1 Causes leading to the FukushimaDaiichi accident

At the time of the Earthquake at 14:46 h JST on 11 March 2011, reactors 4, 5 and 6 were shut down in preparation for re-fueling. The tsunami waves started reaching the Fukushima Daiichi NPP site about 40 minutes after the earthquake. The site was protected from the first wave, which had a 4–5 m run-up height, by the tsunami barrier seawalls that were designed to protect against a maximum tsunami height of 5.5 m. However, about 10 minutes after the first wave (between 15:36 h and 15:37 h), the second and largest tsunami wave (with a run-up height of 14–15 m), reached the plant. The wave overwhelmed the seawalls and inundated the site. It engulfed all structures and equipment located at the seafront, as well as the main buildings (including the reactor, turbine and service buildings) at higher elevations. As a result of a number of events following the huge wave, Units 1–5 lost all AC power, a situation referred to as a station blackout (SBO). Only Unit 6, with its one remaining air cooled EDG supplying emergency AC power, did not experience a SBO. The Fukushima Daiichi NPP units, similar to other plants of the same age, had design provisions to withstand an SBO for eight hours, with response procedures for operators. All units at the Fukushima Daiichi NPP were equipped with on-site DC sources as an emergencypower supply in an SBO situation, but the flooding also affected this equipment in Units 1, 2 and 4,inundating the DC batteries, power panels or connections. Consequently, the DC power was graduallylost in Units 1, 2 and 4 during the first 10–15 minutes of the flooding, making it difficult to cope withthe SBOs.Due to the loss of all electrical (AC and DC) power, the operators of Units 1 and 2 could no longer monitor essential plant parameters, such as reactor pressure and reactor water level, or the status ofkey systems and components used for core cooling. The heat removal capabilityfor the spent fuel pools (SFPs) in all units was already lost following the loss of offside power (LOOP). The additional loss of DC power inUnits 1, 2 and 4 lead to that the operators could no longer monitor the water temperature and levels in theSFPs of these units.In the absence of procedures addressing the loss of all AC and DC power, the operators of Units 1, 2and 4 did not have specific instructions on how to deal with an SBO under these conditions.

3.2 Radiological consequences of the Fukushima Daiichi accident

The total amount of radioactive materials released into the atmospherefrom the Fukushima Daiichi accident has been estimated and reported from various organizations in Japan, including the Nuclear and Industrial Safety Agency (NISA), the Nuclear Safety Commission (NSC), and Tokyo Electric Power Company (TEPCO).The averages of the published estimates were about 10% of the corresponding releases to the atmosphere estimated for the Chernobyl accident. As for the Chernobyl accident described previously in paragraph 2.2 in this paper, ^{131}I and ^{137}Cs are the two most important radionuclides from the perspective of public exposures. The estimates of the released amount of these radionuclides are 100 – 500 PBq for ^{131}I, and 6 – 20 PBq for ^{137}Cs [4]. Those were finally deposited on land and sea, or direct released into the sea from the site of the accident. The area in Japan contaminated with more than 37 kBq/m^{2}of ^{137}Cs has been estimated to be 8,900 km^2, which is less than5% of the area which was contaminated with same activity level from the Chernobyl accident[5-16].

After the Fukushima Daiichi accident on March 11, 2011, the government ordered that residents within 3 km radius around the Fukushima Daiichi NPP should be evacuated. As the significance of the accident became apparent, the evacuation area was gradually expanded to include all residents living within a 20 km radius around the NPP. The government finally designated the contaminated areas into 1) restricted area (within a 20 km radius of the accident); 2) deliberate evacuation areas (where the annual cumulative dose was expected to be 20 mSv); and 3) evacuation prepared areas in case of emergency. The Japanese government has gradually lifted the evacuation orders after that decontamination has been performed, and after confirmation of radiation level, infrastructure and security. As a consequence of these countermeasures, 154,000 people (109,000 people lived in the contaminated areas) of the Fukushima residents were evacuated at the peak time. Additional 150,000 voluntary evacuees,who lived at other places in Japan but were seriously concerned about health damage caused by the radioactive material, moved to cities distant from the Fukushima Daiichi. At present, around 160,000 people (including 50,000 residents of Fukushima) are still evacuated[17].

In December 2012, TEPCO reported statistics on doses received by about 25,000 workers at the Fukushima Daiichi site. The accumulative doses received by the workers who were engaged in the emergency work from March 11, 2011 to November 30, 2012, based on the integrated value measured by their alarm pocket dosimeters (external exposure),were verified by whole body counter measurements (internal exposure). The average effective dose, the workers had been exposed to over the time period written above, was around 12 mSv. Among the 25,000 workers, 167 persons had received effective doses larger than 100 mSv. The highest measured effective dose was 679 mSv. The same worker had received the highest reported effective dose due to internal exposure (590 mSv). The UNSCEAR Committee independently evaluated the doses for the twelve workers who had received effective doses higher than 100 mSv,based on full body counting. It was estimated that they had received absorbed doses to the thyroid, due to inhalation of ^{131}I, in the range of 2 to 12 Gy [18-20].

The Fukushima Health Management Survey, which includes the Basic Survey for external dose estimation and four detailed surveys (Thyroid Ultrasound Examination, Comprehensive Health Check, Mental Health and Lifestyle Survey and Pregnancy and Birth Survey), started from May 2011. The Basic Survey consisted of a questionnaire that askedthe residents in Fukushima Prefecture about their location and movements during the first four months after the accident. The individual external doses were then estimated by using the results from the questionnaire,together with a daily dose map drawn based on monitored air dose rates in the prefecture. Based on this survey 62.0% of the 421,394 residents (radiation workers excluded) received < 1 mSv, 94.0% <2 mSv, and 99.4%<3 mSv during the first four months after the accident. The arithmetic mean and maximum for the individual external doses were verified to be 0.8 and 25 mSv, respectively [21].

In July 2012, Hirosaki University reported on the^{131}I activity in the thyroid of 46 out of the 62 residents and evacuees who were subject to a detailed investigation in April 2011. The median thyroid equivalent dose was estimated to be 4.2 and 3.5 mSv for children and adults, respectively. The highest thyroid equivalent doses for children and adults were 23 mSv and 33 mSv, respectively. This is consistent with screening tests, performed by health authorities, on 1080 children who lived in areaswhere it was expected that the children should get the highest thyroid dose within two weeks after the accident. The estimated highest district-average absorbed dose to the thyroid was about 52 mGy for 1-year-old infants, which is only about one tenth of what was received by the infants of the Chernobyl evacuees [22-23].

3.3 Design and safety flaws of FukushimaDaiichi

Because the reactor buildings of the Fukushima 1-5 BWRs were small, the backup diesel generators were locatedin turbine buildings between reactor no. 6 and the older reactors 1-5, as well as in buildings located higher on the mountainside next to the reactors. The Fukushima 6 reactor building had enough space for the backup generators to go inside, but no backup generator was located in that reactor building so all six reactors were given access to generators housed outside of the vulnerable turbine buildings. Since the backup power generators are critical safety equipment, they should have been inside the reactor buildings or located high enough so they could survive a large tsunami since there had been warnings that a large tsunami could happen at the Fukushima Daiichi site. However, these warnings were ignored by TEPCO. In 2001, when the original 30-year operating permit for Fukushima Daiichi's reactor no. 1 was set to expire, TEPCO applied for and received a 10-year extension. Five weeks before the accident in 2011, the same reactor receive a new extension. However, the abbreviated minutes of government deliberations show that regulators never reviewed whether the basic blueprint of the older reactors was flawed. The extension was based on the premise that design reviews were undertaken before the plant was ever built, so there was no discussion of fundamental design and construction specifications

On July 5, 2012, the Japanese National Diet-appointed Fukushima Nuclear Accident Independent Investigation Commission (NAIIC) submitted its inquiry report to the Japanese Diet.The Commission found that the nuclear disaster was "man-made", and that the direct causes of the accident were all foreseeable prior to March 11, 2011. The report also found that the Fukushima Daiichi Nuclear Power Plant was incapable of withstanding the magnitudes of the earthquake and tsunami which caused the accident. TEPCO, the regulatory bodies (NISA and NSC), and the government body promoting the nuclear power industry (METI), all failed to correctly develop the most basic SAMGs, such as assessing the probability of damage, preparing for containing collateral damage from such a disaster, and developing evacuation plans for the public in the case of a serious radiation release. A separate study,performed by researchers at Stanford,found that Japanese plants operated by the largest utility companies were particularly unprotected against large potential tsunamis.

4. Countermeasures and disaster planning in Japan

After the Fukushima Daiichi accident, countermeasures on inhibiting accidents and on protecting the public from exposure to ionizing radiation have been developed in Japan. In parallel with this, the nuclear regulatory system has been reformed. The emergency preparedness and response systems have also been improved based on the experiences from the Fukushima accident and the resident’s reactions on the disaster.Especially, the Nuclear Emergency Preparedness and Response Guidelines have been revised, the basic concepts and the criteria of the IAEA’s safety standards have been adopted, andthe Nuclear Regulation Authority (NRA) has been renewed. The new response guidelines differ much from the prior ones. The arrangement of emergency response systems, resources and the operational procedures are currently being adapted to the new guidelines in municipalities where the NPPs are located, as well as in municipalities surrounding those areas.

In order to perform urgent protective action, the safety standards require that the settings of the conditions of the measures should be specified for off-site emergency zones, for which arrangements shall be made. The initial conditions will also be specified and deviations from that specified as an emergency classification system with different action levels related to the level in deviation.

The precautionary action zone (PAZ) is defined as an area around a nuclear facility for which arrangements will be made to take urgent protective actions in the event of a nuclear or radiological emergency to reduce the risk of severe deterministic health effects to the public. Protective actions within this area will be taken before or shortly after a release of radioactive material on the basis of the prevailing conditions at the facility. The urgent protective action planning zone (UPZ) is defined as an area around a facility for which arrangements will be made to take urgent protective actions in the event of a nuclear or radiological emergency to prevent doses outside the site. Protective actions within this area will be taken on the basis of environmental monitoring or, as appropriate, prevailing conditions at the facility. The NRA has adopted the PAZ and UPZ as indications of the distances from the nuclear facilities. The municipalities within 5 km radius of a NPP have assigned to be PAZ and within a 5 to 30 km radius have assigned to be UPZ, respectively.

In Japan, an emergency classification system is used to classify and group off-normal events and conditions according to the potential or actual effects or consequences, and resulting onsite and offsite consequences and response actions. This enable a common understanding about the extent of the emergency situation in between responders, such as the operations staff, the emergency personnel, offsite authorities and functions for offsite disaster prevention. The emergency classification is set to three categories, Alert Level (AL), Site area Emergency (SE) and General Emergency (GE). The SE and GE are directly linked to the Article 10 in the Japanese law: Obligation to Notifya Nuclear Emergency Preparedness Manager and to the Article 15: Declaration of a Nuclear Emergency Situation, etc. on the "Act on Special Measures Concerning Nuclear Emergency Preparedness"[24].

The emergency action level (EAL), is defined as a specific, predetermined, observable criterion used to detect, recognize and determine the emergency classification. According to the guidance from NRA, the nuclear operators have listed conceivable events, and assigned different numbers with an emergency classification level for each kind of event. For example, "AL21" denotes "Leakage of reactor coolant". "AL21" will be common classification level for all reactor types in Japan (BWR, PWR, ATR and FBR). Thus the EAL is a reference to determine the status of the facility in combination with an emergency classification. Some implementations and/or preparations of protective measures will be performed based on the EAL when the emergency level becomes higher, so that it is also a criterion what protective measures should be implemented.

The operational intervention level (OIL) is defined as an estimated level, measured or determined by laboratory analysisthat corresponds to an intervention level or action level. OILs are typically expressed in terms of dose rates or of activity of released radioactive material, e.g. time integrated air concentrations, ground or surface concentrations, or activity concentrations of radionuclides in environmental, food or water samples. An OIL is a type of action level that is used immediately and directly (without further assessment) to determine the appropriate protective actions on the basis of an environmental measurement.

The new improved emergency response system in Japan is developed together with a training and education program, in order to ensure that professional rescue workers, including medical staff, fire fighters, police, etc., as well as the normal populations including patients, have sufficient knowledge about ionizing radiation and are informed about the meaning of radiation risks and safety.

5. Summary and conclusions

When evaluating and comparing the Chernobyl and Fukushima accidents, it is clear that the human factor played a role in both accidents. The accident at Chernobyl RMBK reactor was the product of a lack of safety culture, in combination with a poor and unforgiving reactor design from the point of view of safety, which provoked the dangerous operating. The operators had not the required information and knowledge, and were therefore not aware that the test performed could bring the reactor into an explosive condition. In addition, they did not comply with operational procedures. The combination of these factors provoked a nuclear accident of maximum severity in which the reactor was totally destroyed within a few seconds. Immediately after the accident, no information was given to the residents around the Chernobyl NPP, and there was no evacuation of people until

36 hours after the accident. Due to that many children drank milk contaminated with ^{131}I, which later lead to thyroid cancer.After the accident, the occurrence of other cancer forms, e.g breast cancer, have also increased in the contaminated areas. In addition, many recovery operation workers were exposed to very high doses of ionizing radiation which caused different health problems.

The Fukushima Daiichi BWR was obviously incapable of withstanding the magnitudes of the earthquake and tsunami which caused the accident even if warnings had been made that earthquakes and tsunamis of that magnitude could occur. Insufficient attention was paid to evidence of large tsunamis inundating the region surrounding the plant about once every thousand years. Five weeks before the accident in 2011, the NPP received an operation extension without taking necessary safety steps that might have prevented the accident. Such a safety steps should have included:

- protecting emergency power supplies, including diesel generators and batteries, by moving them to higher ground or by placing them inwatertight bunkers;
- establishing watertight connections between emergency power suppliesand key accident systems; and
- enhancing the protection of seawater pumps (which were used to transferheat from the plant to the ocean and to cool diesel generators) and/or constructing a backup means to dissipate heat.

The Fukushima Daiichi nuclear power accident was therefore, as Chernobyl, caused by a combination of human errors and construction safety flaws, even if the radiological consequences of the Fuksushima accident was minor in comparison to the accident in Chernobyl due to better reactor design and much faster actions.

In addition to the above mentioned safety steps, it is important to handle and reduce, the hydrogen which is formed by radiolytic decomposition of the coolant water in light-water NPPs. This needs to be dealt withto avoid the potential for explosion with the present oxygen. One method is replacing external recombiners,that need to be connected and powered, with passive autocatalytic hydrogen recombiners in the containments. Hydrogen monitoring devices should also be installed, as well as equipment for immediate injection of nitrogen into the containment, if needed. However, in aloose of coolant accident, such as at Fukushima, where the fuel became very hot, a lot of hydrogen is also formed by the oxidation of zirconium fuel cladding in the steam.The removal of thisamount of hydrogen is beyond the capability of the normal hydrogen recombiners. It is therefore important that automatically pressure release valves, to enable venting to the surrounding through filters and scrubbers, are installed. The option to inert the containment with nitrogen should also be available. Better fuel cladding, with zirconium preplaced by silicon carbide, molybdenum alloys, molybdenum-zirconium alloys, or iron-chromium alloys should also be considered and tested. To reduce the hydrogen production of overheated uranium oxide fuel, more research and testing should be performed on low corrosive alternatives, e.g. low swelling uranium nitride or uranium carbide fuel.

In Table 1, a schematic comparison of perception, assessment and management before and during the Chernobyl and Fukushima accidents is tabulated.

Table 1. Comparison of perception, assessment and management before and during the Chernobyl and Fukushima accidents.

	Perception	Assessment	Managment
Chernobyl	Reactivity behavior is complicated and requires control systems and well trained operators.	Reactivity analysis leads to technical an administrative barriers.	Insufficient safety culture and administrative barriers were broken.
Fukushima	Tsunamis can occur.	Amplitde exceeded assessment.	Extremyly difficult to do anything wich such a total loss of instrumentation and equpment.

These two accidents show that, based on SAM, there is a strong need for implementations of SAMGs to certify that a knowledge based response strategy exist to increase the safety of the existing and future NPPs. Such a response strategy should rely on the operators´ understanding of the performance of the NPP and its systems to be able to decide on an appropriate course of action. In addition to that, stress tests should on a regular basis be performed to assess whether the NPPS can withstand the effects of natural disasters and man-made failures and actions.

6. Acknowledgements

The authors acknowledge very much valuable information provided by Anders Henoch, Ringhals NPP, Sweden.

7. References

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safety Glossary,Terminology Used in Nuclear Safety and Radiation Protection, 2007 Edition,IAEA, Vienna (2007).
[2] Severe Accident Management Programmes for Nuclear Power Plants, Safety Guide, No. NS-G-2.15, IAEA, 2009.
[3] Sources and Effects of Ionizzing Radiation. UNSCEAR 2008 Report, Volume II (2008); ISBN-13: 978-92-1-142280-1.
[4] SOURCES, EFFECTS AND RISKS OF IONIZING RADIATION, United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR 2013 Report to the General Assembly with Scientific Annexes, 2014.
[5] INTERNATIONAL ATOMIC ENERGY AGENCY. The International Chernobyl Project: Technical Report, IAEA, Vienna (1991).
[6] EUROPEAN COMMISSION, INTERNATIONAL ATOMIC ENERGY AGENCY, WORLD HEALTH ORGANIZATION, One Decade after Chernobyl: Summing up the Consequences of the Accident, IAEA, Vienna (1996).
[7] Chernobyl: Looking Back to Go Forward (Proc. Int. Conf Vienna, 2005), IAEA, Vienna (2005).

[8] Eslinger, P.W., et al., Source term estimation of radioxenon released from the Fukushima Dai-ichi nuclear reactors using measured air concentrations and atmospheric transport modeling, J. Environ. Radioact. 127 (2014) 127–132.
[9] Stohl, A., et al., Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Daiichi nuclear power plant: Determination of the source term, atmospheric dispersion, and deposition, Atmos. Chem. Phys. 12 5 (2012) 2313–2343.
[10] Bowyer, T. W., et al., Elevated radioxenon detected remotely following the Fukushima Nuclear accident, J. Environ. Radioact. 102 7 (2011) 681–687.
[11] Schöpper, M., et al., Estimation of the time-dependent radioactive source-term from the Fukushima nuclear power plant accident using atmospheric transport modelling, J. Environ. Radioact. 114 (2012) 10–14.
[12] Terada, H., Katata, G., Chino, M., Nagai, H., Atmospheric discharge and dispersion of radionuclides during the Fukushima Dai-ichi nuclear power plant accident. Part II: Verification of the source term and analysis of regional-scale atmospheric dispersion, J. Environ. Radioact. 112 (2012) 141– 154.
[13] SCIENCE COUNCIL OF JAPAN, A Review of the Model Comparison of Transportation and Deposition of Radioactive Materials Released to the Environment as a Result of the Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Plant Accident (2014), http://www.jpgu.org/scj/report/20140902scj_report_e.pdf
[14] Chino, M., et al., Preliminary estimation of release amounts of 131I and 137Cs accidentally discharged from the Fukushima Daiichi nuclear power plant into the atmosphere, J. Nucl. Sci. Technol. 48 7 (2011) 1129–1134. 170
[15] Buesseler, K., Aoyama, M., Fukasawa, M., Impacts of the Fukushima nuclear power plants on marine radioactivity, Environ. Sci. Technol. 45 23 (2011) 9931–9935.
[16] United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR 2000 Report to the General Assembly,with scientific annexes.
[17] Annual Report on the Environment, the Sound Material-Cycle Society and Biodiversity in Japan 2013, white paper 2013, Ministry of the Environment, and http://www.reconstruction.go.jp/topics/main-cat2/sub-cat2-1/hinanshasuu.html
[18] http://www.tepco.co.jp/en/press/corp-com/release/index1110-e.html
[19] http://www.tepco.co.jp/en/press/corp-com/release/2012/12/index-e.html
[20] Developments since the 2013 UNSCEAR report on the levels and effects of radiation exposure due to the nuclear accident following the Great East-Japan Earthquake and Tsunami, A 2015 white paper to guide the Scientific Committee's future programme of work, UNSCEAR 2015.
[21] Ishikawa, T., et al., The Fukushima Health Management Survey: estimation of external doses to residents in Fukushima Prefecture, Scientific Reports 5, Article number: 12712 (2015).
[22] Tokonami, S., et al., Thyroid doses for evacuees from the Fukushima nuclear accident, Scientific Reports 2, Article number: 507 (2012).
[23] UNSCEAR 2013 Report, Annex A - Levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami, 2013.
[24] Genshiryokusaigaitaisakutokubetsusochihō [Act in the Japanese law on Special Measures Concerning Nuclear EmergencyPreparedness], Act No. 156 of 1999, last amended by Act No. 114 of 2014. Old version of English translation (amended by Act No. 118 of 2006) is available on JapaneseLaw Translationmaintained by the Ministry of Justice, athttp://www.japaneselawtranslation.go.jp/law/detail_main?id=106&vm=&re.