

# **WORLD MAJOR NUCLEAR ACCIDENTS AND THEIR NEGATIVE IMPACT IN THE ENVIRONMENT, HUMAN HEALTH AND PUBLIC OPINION**

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The paper describes ten major nuclear accidents that have been reported since 1979 in five countries. Three of them had serious negative consequences for the environment, human health, and public opinion. The first nuclear accident occurred in the USA in 1979 during the normal operation of a nuclear power plant; the second nuclear accident occurred in Ukraine in 1986 during a test designed to assess the reactor's safety margin in a particular set of circumstances; and the third nuclear accident occurred in Japan in 2011 as the result of an earthquake of magnitude 9 and a tsunami.

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## ABSTRACT

Since 1959, ten major nuclear accidents have been reported by five countries. Three of them had serious negative consequences for the environment, human health, and public opinion. Each of these three major nuclear accidents is different. The first nuclear accident occurred in the USA in 1979 during the normal operation of a nuclear power plant; the second nuclear accident occurred in Ukraine in 1986 during a test designed to assess the reactor's safety margin in a particular set of circumstances; and the third nuclear accident occurred in Japan in 2011 as the result of an earthquake of magnitude 9 and a tsunami.

**Keywords:** nuclear accidents; IAEA; Three Miles Island nuclear accident; Chernobyl nuclear accident; Fukushima Daiichi nuclear accident

## INTRODUCTION

Nuclear power plants must operate in the most secure manner respecting all safety measures and principles adopted at national, regional, and international levels. When safety measures and principles are ignored or are not properly observed by nuclear plant operators, a nuclear accident can occur with serious consequences for the environment, human health and public opinion. For this reason, nuclear assessment of the operation of nuclear power plants should be carried out periodically by governments and nuclear power plant owners. The aim of this assessment is to determine whether an adequate level of safety has been achieved and whether the safety objectives and criteria as specified by the plant designer, the operating organization, and the regulatory body have been met. Safety assessment should be a systematic process that has to be carried out throughout the lifetime of the nuclear power plant, with the aim of identifying radiation risks that arise for workers, the impact on the public and on the environment during the normal operation of a nuclear power plant.

The aim of safety assessment is to determine whether adequate measures have been taken by governments and nuclear power plant operators to control radiation risks to an acceptable level, with account taken of both the prevention of abnormal events and the mitigation of their consequences.

Since 1959, ten major nuclear accidents have been reported by five countries. These nuclear accidents are the following:

- Fukushima, Japan - March 2011;
- Kashiwazaki, Japan - July 2007;
- Mihama, Japan - August 2004;
- Blayais, France - December 1999;
- Tokaimura, Japan - September 1999;
- Tokaimura, Japan - March 1997;
- Chernobyl, Ukraine - April 1986;
- Three Mile Island, USA - March 1979;
- The Urals, USSR - October 1958;
- Windscale, UK – October 1957.

It is important to stress that out of these ten major nuclear accidents registered during the period 1957-2011, five were reported by one country: Japan. Among these ten major nuclear accidents, three had serious negative consequences for the environment, human health, and public opinion. These accidents are the following:

- Three Miles Island;
- Chernobyl;
- Fukushima.

The first accident occurred during the normal operation of the nuclear power plant and was caused by serious malfunctioning of equipment and serious human errors; the second accident occurred during a test designed to assess the reactor's safety margin in a particular set of circumstances and it occurred due to serious errors in the reactor design and a lack of appropriate training of the staff; and the third accident occurred as result of a natural disaster (an earthquake of magnitude 9 and a tsunami) in addition to an inappropriate selection of the plant site.

In the following paragraphs the main events associated to these three nuclear accidents are described and the consequences and lesson learned identified.

### **THE THREE MILE ISLAND NUCLEAR ACCIDENT**

A combination of equipment failure, human error, and bad luck, the nuclear accident at Three Mile Island (TMI) stunned the nation and permanently changed the nuclear industry in the USA and Europe. The TMI nuclear accident had a devastating impact on the US nuclear power industry - the Nuclear Regulatory Commission (NRC) has not reviewed an application to build a new nuclear power plant in the USA until recently. It also brought about sweeping changes involving emergency response planning, increase safety measures, reactor operator training, human factors engineering, radiation protection, and many other areas of nuclear power plant operations (Powell).

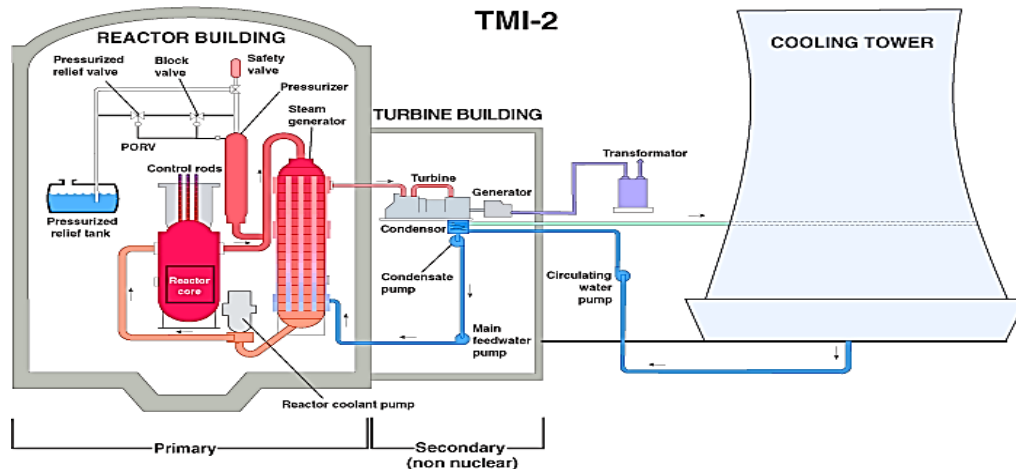
The TMI nuclear accident was the most significant nuclear accident in the history of the US commercial nuclear power generating industry. It resulted in the release of limited amount of radioactive noble gases and iodine to the environment. However, there have been no deaths or injuries to plant workers or members of the nearby community, which can be attributed to the accident.

The Three Mile Island (TMI) power plant is located near Harrisburg, Pennsylvania, in the USA. It had two pressurized water reactors (PWRs). One PWR was of 800 MWe (775 MWe net) and entered service in 1974<sup>2</sup>. It remains one of the best-performing units in USA. Unit 2 was of 906 MWe (880 MWe net) and almost brand new<sup>3</sup> and was the unit in which the accident occurred.

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<sup>2</sup> TMI-1 was shut down for refueling at the time of the accident.

<sup>3</sup> TMI-2 was operating online only three months before the accident.



Source: NEI (Nuclear Energy Overview 8/5/2000).

Figure 1. Unit 2 Three Mile Island power plant.

According to Morales Pedraza (2012), the accident at the Three Mile Island Unit 2 (TMI-2) occurred on March 28, 1979 when the unit was operating at 97 % power (see Figure 2). It led to no deaths or injuries to plant workers or members of the nearby community and the negative impact of the accident in the environment was very small. However, the impact of the TMI-2 nuclear accident in the public opinion was very high forcing the government to cancel all plans already adopted for the construction of new nuclear power reactors in the country.



Source: Photograph courtesy of Ohio Citizen Action.

Figure 2. Three Mile Island nuclear power plant after the accident.

What caused this serious nuclear accident? It was caused by a sequence of events during which equipment malfunctions, design-related problems, and worker errors occurred, which

led to a partial meltdown of the TMI-2 unit core but with very small off-site releases of radioactivity. In summary, it was a series of apparent errors and equipment malfunctions, coupled with some questionable instrument readings, resulted in loss of reactor coolant, overheating of the reactor core damaging the fuel with a partial melting, and limited releases outside the plant of radioactive noble gases and iodine<sup>4</sup> (Corey, 1979).

What really happens? The accident began about 04:00 hours with a failure in the secondary non-nuclear section of the nuclear power plant. The main feed water pumps stopped running, caused by either a mechanical or electrical failure, which prevented the steam generators from removing heat. First the turbine and then the reactor automatically shut down (the process to shut down the nuclear power reactor took about one second). Immediately, the pressure in the primary system, which is the nuclear portion of the nuclear power plant, began to increase. In order to prevent that pressure from becoming excessive, the pilot-operated open a valve located at the top of the pressurizer. The valve should have closed when the pressure decreased by a certain amount but for unknown reason it did not. As a result, cooling water poured out of the stuck-open valve and caused the core of the reactor to overheat.

As coolant flowed from the core of the reactor through the pressurizer, the instruments available to reactor operators provided confusing information. There was no instrument that showed the level of coolant in the core of the reactor. Instead, the operators judged the level of water in the core of the reactor by the level in the pressurizer, and since it was high, they assumed that the core of the reactor was properly covered with coolant. In addition, there was no clear signal that the pilot-operated relief valve was open. As a result, as alarms rang and warning lights flashed, the operators did not realize that the plant was experiencing a loss-of-coolant accident, and took a series of actions that made conditions worse by simply reducing the flow of coolant through the core of the reactor.

The problems were complicated by the failure of the backup system. Following the loss of the main feed pumps, three emergency feed water pumps had started automatically, but two valves on the emergency feed water lines were closed, preventing the feed water from reaching the steam generators. It is important to stress that the emergency feed water system had been tested 42 hours prior to the accident; as part of the test, these valves were closed. They should have been reopened at the end of the test, but they were not, through an administrative or human error<sup>5</sup>. The valves were discovered closed about eight minutes into the accident. Once they were reopened, emergency feed water was restored to the steam generators.

At 06:00 hours, there was a shift change in the control room. A new arrival noticed that the temperature in the holding tanks was excessive and used a backup valve called “a block valve” to shut off the coolant venting, but around 950 m<sup>3</sup> (250 000 US gallons) of coolant had already leaked from the primary loop. It was not until 165 minutes after the start of the problem that radiation alarms activated as contaminated water reached detectors — by that

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<sup>4</sup> According to the NRC, the maximum total increase in radiation measured at ground level, just outside the plant boundaries, was lower than 100 millirem. While hardly anyone was stationed just outside the plant, 24 hours a day for that entire week, anyone so stationed would have received a radiation dose roughly equivalent to the amount by which annual background radiation in Denver or Manhattan exceeds that in Boston or Chicago (Corey, 1979).

<sup>5</sup> It is important to stress that this lack of emergency feed water for eight minutes did not have a significant effect on the outcome of the accident, but did add to the confusion faced by the operators.

time, the radiation levels in the primary coolant water were around 300 times expected levels, and the plant was seriously contaminated. At 09:00 hours, the hydrogen within the reactor building ignited and burned, but this was largely unnoticed. After 16:00 hours, the primary loop pumps were turned on once again, and the core temperature began to fall. Because adequate cooling was not available, the nuclear fuel overheated to the point at which the long metal tubes which hold the nuclear fuel pellets ruptured and the fuel pellets began to melt.

Although the TMI-2 unit suffered a severe core meltdown, the most dangerous kind of nuclear power accident that can occur in a nuclear power reactor, it did not produce the worst-case consequences that nuclear experts had long feared. In a worst-case accident, the melting of nuclear fuel would lead to a breach of the walls of the containment building and release massive quantities of radiation to the environment. Hopefully, this did not happen in the Three Mile Island accident.

Finally, it is important to stress the following: Various studies on health effects, including a 2002 study conducted by the University of Pittsburgh<sup>6</sup>, have determined the average radiation dose to individuals near Three Mile Island power plant site at the time of the meltdown was about 1 milligram, much less than the average annual natural background dose for residents of the central Pennsylvania region. Twenty-five years later, there has been no significant rise in cancer deaths among residents living near the Three Mile Island nuclear power plant site<sup>7</sup>. A new analysis of health statistics in the region conducted by the Radiation and Public Health Project has, however, found that death rates for infants, children, and the elderly soared in the first two years after the Three Mile Island nuclear power plant accident in Dauphin and surrounding counties (Powell). It is important to stress also that research conducted on the health effects of the Three Mile Island accident has been rather minimal, even though more than 25 years have passed since the accident. Meanwhile, official bodies like the NRC still assert that radiation from the accident had “negligible effects on the physical health of local residents”. It is likely that a full accounting of health effects will never be made (Mangano, 2004).

Today, the TMI-2 reactor is permanently shut down and defueled, with the reactor coolant system drained, the radioactive water decontaminated and evaporated, radioactive waste shipped off-site to an appropriate disposal site, reactor fuel and core debris shipped off-site to a Department of Energy facility, and the remainder of the site being monitored<sup>8</sup>. The owner of the nuclear power plant will keep the facility in long-term, monitored storage until the operating license for the TMI-1 unit expires on April 1, 2014, at which time both plants will be decommissioned. The cleanup of the damaged nuclear power reactor system at TMI-2 took nearly twelve years was carried by around 1 000 skilled workers and cost approximately US\$ 973 million.

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<sup>6</sup> See Talbott et al. (2003).

<sup>7</sup> The Kemeny Commission, which was established by President Jimmy Carter after the TMI nuclear accident, stated that the only health threat posed to the local population was mental distress (Mangano, 2004).

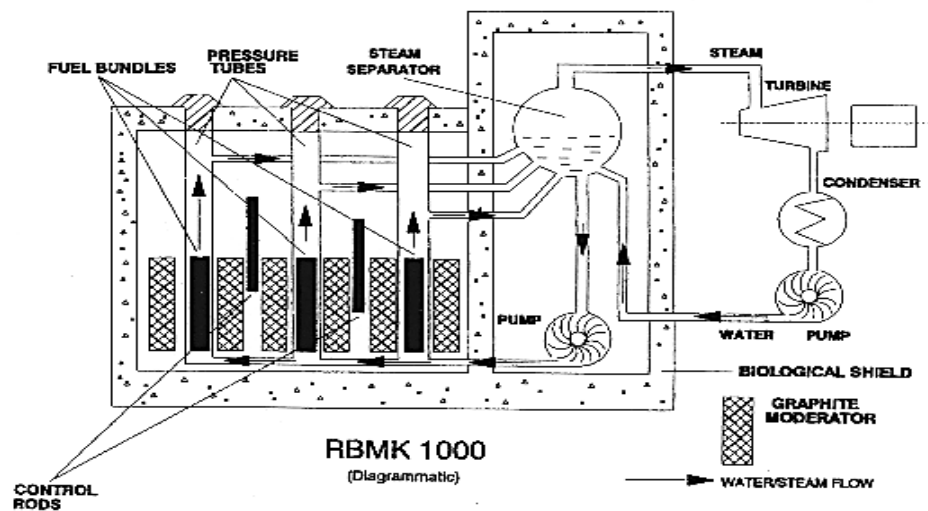
<sup>8</sup> The cleanup of the TMI 2 began in August 1979, with the first shipments of accident-generated low-level radiological waste to Richland, Washington. In the cleanup's closing phases, in 1991, final measurements were taken of the fuel remaining in inaccessible parts of the reactor vessel. Approximately 1 % of the fuel and debris remains in the vessel. Also in 1991, the last remaining water was pumped from the TMI 2 reactor. The cleanup ended in December 1993, when Unit 2 received a license from the NRC to enter Post Defueling Monitored Storage.

## THE CHERNOBYL NUCLEAR ACCIDENT

The Chernobyl nuclear power plant is located in Ukraine, near the town of Pripyat, which had been built to house power plant employees and their families. The nuclear power plant was constructed in a wooded, marshy area near the Ukraine-Belarus border, approximately 18 km northwest of the city of Chernobyl and 100 km north of Kiev, the capital of Ukraine. The Chernobyl nuclear power plant included four nuclear power reactors (RMBK type), each capable of producing one gigawatt of electric power. At the time of the accident, the four reactors produced about 10 % of the electricity used in Ukraine.

Construction of the Chernobyl nuclear power plant began in the 1970s. The first of the four reactors was commissioned in 1977, and Unit 4 began producing power in 1983. When the accident occurred in 1986, two other nuclear reactors were under construction.

According to Morales Pedraza (2012), the Chernobyl nuclear accident is the worst nuclear accident ever occurred in a nuclear power plant, considering the area contaminated, the number of countries involved, and the amount of people affected by the accident. What caused this terrible accident from the environment and human health point of view? Initially, the accident at Unit 4 of the Chernobyl nuclear power plant was considered as resulted from a combination of design and technical deficiencies with a grave operator error. However, in a later report the IAEA put the main cause of the accident to the reactor's design. What really happens? According to WNAO's report, on 25 April prior to a routine shut down, the reactor crew at Unit 4 of the Chernobyl nuclear power plant began preparing for a test to determine how long turbines would spin and supply power to the main circulating pumps following a loss of main electrical power supply.



Source: WANO.

Figure 3. RBMK reactor type.

This test had been carried out at Chernobyl nuclear power plant the previous year, but the power from the turbine ran down too rapidly, so new voltage regulator designs were to be tested.

Which was the purpose of the test to be performed in Unit 4 of the Chernobyl nuclear power plant in April 1986? It is well known that nuclear power plants not only produce electricity, they also consume electricity, for example to power the pumps that circulate the coolant. This electricity is usually supplied from the grid. If the source of electricity failed, most nuclear power reactors are able to derive the required electricity from their own production. However, if the reactor is operating but not producing power, for example when the reactor is in the process of shutting down, some other sources of supply are required. Generators are generally used to supply the required power, but there is a time delay while they are started. The test carried out at Unit 4 of the Chernobyl nuclear power plant was designed to demonstrate that a coasting turbine would provide sufficient power to pump coolant through the reactor core while waiting for electricity from the diesel generators. The circulation of coolant was expected to be sufficient to give the nuclear power reactor an adequate safety margin.

A summary of the main events associated to the nuclear accident in Unit 4 of the Chernobyl nuclear power plant is described in the following paragraphs.

On April 25 at 01:06 hours, the scheduled shut down of Unit 4 and the preparation of the test started. Gradual lowering of the power level of the unit began. At 03:47 hours, lowering of Unit 4 halted at 1 600 MWt. At 14:00 hours, the emergency core cooling system was isolated as part of the test procedure to prevent it from interrupting the test later<sup>9</sup>. The power was due to be lowered further, however, the controller of the electricity grid in Kiev requested the reactor operator to keep supplying electricity to enable demand to be met. Consequently, the reactor power level was maintained at 1 600 MWt and the experiment was delayed. At 23:10 hours, power reduction recommenced and 50 minutes later a shift change was took effect.

On April 26 at 00:05 hours, power level of Unit 4 had been decreased to 720 MWt and continued to be reduced<sup>10</sup>. At 00:28 hours, power level of Unit 4 was 500 MWt. The control was transferred from the local to the automatic regulating system. Either the operator failed to give the hold power at required level signal or the regulating system failed to respond to this signal, something that has not yet totally clarified. This led to an unexpected fall in power, which rapidly dropped to 30 MWt. At approximate 00:32 hours and in respond to the loss of power the operator retracted a number of control rods in an attempt to restore the power level<sup>11</sup>. At 01:00 hours, the reactor power had risen to 200 MWt and three minutes later an additional pump was switched into the left hand cooling circuit in order to increase the water flow to the core of the reactor<sup>12</sup>. At 01:07 hours, as part of the test procedure an additional pump was switched into the right hand cooling circuit. Operation of additional pumps removed heat from the core more quickly. This reduced the water level in the steam separator.

At 01:15 hours, automatic trip systems to the steam separator were deactivated by the operator to permit continued operation of the reactor and three minutes later the operator increased feed water flow in an attempt to address the problems in the cooling system. One

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<sup>9</sup> It is important to stress that the fact that the emergency core cooling system was isolated did not contribute to the accident; however, had it been available it might have reduced the impact slightly.

<sup>10</sup> It is now recognized that the safe operating level for a pre-accident configuration RBMK was about 700 MWt because of the positive void coefficient of this type of reactors.

<sup>11</sup> According to the nuclear power plant safety procedures it required that approval of the chief engineer be obtained to operate the reactor with fewer than the effective equivalent of twenty six control rods. It is estimated that there were less than this number remaining in the reactor at 00.32 hours of April 26, 1986.

<sup>12</sup> This action was part of the test procedure.

minute later some manual control rods withdrawn to increase power and raise the temperature and pressure in the steam separator. It is important to stress that operating policy required that a minimum effective equivalent of fifteen manual control rods be inserted in the reactor at all times. At this point, it is likely that the number of manual rods was reduced to less than this<sup>13</sup>. However, automatic control rods were in place, thereby increasing the total number. At 01:21 hours, feed water flow rate reduced to below normal by the operator to stabilize steam separator water level, decreasing heat removal from the core of the reactor and thirty seconds later spontaneous generation of steam in the core of the reactor began. At 01:22 hours, indications received by the operator, although abnormal, gave the appearance that the reactor was stable.

The preparation of the test started at 01:23 hours. Turbine feed valves closed to start turbine coasting and ten minutes later automatic control rods withdrawn from the reactor core. An approximately ten second withdrawal was the normal response to compensate for a decrease in the reactivity following the closing of the turbine feed valves. Usually, this decrease is caused by an increase in pressure in the cooling system and a consequent decrease in the quantity of steam in the core of the reactor. The expected decrease in steam quantity did not occurred due to reduced feed water to the core of the reactor. At 01:23 hours, steam generation increased to a point where, owing to the reactor's positive void coefficient, a further increase of steam generation would lead to a rapid increase in power. Fourteen minutes later, steam in the core of the reactor begins to increase uncontrollably. At 01:23 hours, the emergency button was pressed by the operator. Control rods started to enter the core of the reactor. The insertion of the rods from the top concentrated all of the reactivity in the bottom of the reactor core. Four minutes later the reactor power rose to a peak of about 100 times the design values and one minute later fuel pellets started to shatter, reacting with the cooling water to produce a pulse of high pressure in the fuel channels. At 01:23 hours, fuel channels ruptured and one minute later two explosions occurred. One was a steam explosion that killed two workers; the other resulted from the expansion of fuel vapor. The explosions lifted the pile cap, allowing the entry of air. The air reacted with the graphite moderator blocks to form carbon monoxide. This flammable gas ignited and a reactor fire started lifting tons of radioactive materials into the atmosphere (there were over 100 radioactive elements released into the atmosphere when Unit 4 exploded without any type of control, including plutonium, iodine, strontium, and cesium)<sup>14</sup>.

There is some dispute among nuclear experts about the character of the second explosion, but it is likely to have been caused by the production of hydrogen from zirconium-steam reactions. What were the immediate consequences of the nuclear accident? Two workers died as a result of these explosions. The graphite and fuel became incandescent and started a number of fires, causing the main release of radioactivity into the environment.

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<sup>13</sup> According to some public information, the number of manual rods at 01.15 hours of April 26, 2013 was probably eight.

<sup>14</sup> Iodine, strontium and cesium were the most dangerous of the elements released, and have half-lives of 8 days, 29 years, and 30 years, respectively. The isotopes strontium-90 and cesium-137 are therefore still present in the area to this day. While iodine is linked to thyroid cancer, strontium can lead to leukemia. Cesium is the element that travelled the farthest and lasts the longest. This element affects the entire body and especially can harm the liver and spleen.



Source: Photograph courtesy of Wikimedia Commons (Elena Filatova).

Figure 4. Chernobyl nuclear power plant with the sarcophagus.

As consequence of the nuclear accident some 150 000 km<sup>2</sup> in Belarus, Russia and Ukraine were contaminated and stretch northward of the nuclear power plant site as far as 500 km. An area of 30 km around the nuclear power plant site was considered the “exclusion zone” and is essentially uninhabited. Radioactive fallout scattered over much of the northern hemisphere via wind and storm patterns, but the amounts dispersed were in many instances insignificant. Cesium and other radioactive isotopes were blown by wind northward into Sweden and Finland and over other parts of Europe and the northern hemisphere. During the first three weeks after the accident, the level of radiation in the atmosphere in several places around the globe was above normal; but these levels quickly receded reducing the consequences of the Chernobyl nuclear accident for many countries.

In January 1993, the IAEA issued a revised analysis of the Chernobyl nuclear accident, attributing the main root cause to the reactor’s design and not to operator error<sup>15</sup>. In 2005, the IAEA and the World Health Organization (WHO) reported that “only 56 people had died directly from the incident, mainly accident workers<sup>16</sup>. They estimated another 4 000 deaths

<sup>15</sup> The IAEA in its 1986 analysis had cited the operators’ actions as the principal cause of the accident.

<sup>16</sup> According to WNAO report (2012) and other sources, the accident destroyed Unit 4 of the Chernobyl nuclear power plant, killing thirty one operators and firemen within three months and several further deaths later (the initial explosion resulted in the death of two workers, one of them was killed immediately and a second died in hospital soon after as a result of injuries received. Twenty-eight of the firemen and emergency clean-up workers died in the first three months after the explosion from Acute Radiation Sickness and one of cardiac arrest). Acute radiation syndrome (ARS) was originally diagnosed in 237 people on-site and involved with the clean-up and it was later confirmed in 134 cases. Of these, 28 people died as a result of ARS. Nineteen more

among workers and local residents”. Some 8 of the 140 tons of fuel, which contained plutonium and other highly radioactive materials (fission products), were ejected from the reactor along with a portion of the graphite moderator, which was also radioactive. These materials were scattered around the nuclear power plant site. In addition, cesium and iodine vapors were released both by the explosion and during the subsequent fire.

After the Chernobyl nuclear accident the pressure of the international community to close nuclear power plants in operation in many countries increased significantly, independently of the type of nuclear power reactors used for the generation of electricity. In 1995, a memorandum of understanding was signed between the governments of the G-7 countries, the EC, and the Ukraine government, agreeing with the closure of all Chernobyl nuclear power reactors. Based on this memorandum, Unit 2 was shut down in October 1991 after a huge fire in the unit, Unit 1 in November 1996, and Unit 3 in December 2000.

Following the Chernobyl nuclear accident, Unit 4 was encased in a giant concrete sarcophagus (See Figure 4), constructed above the destroyed reactor by hundreds of thousands of soldiers and civilian, including nuclear experts, to prevent further leakage of radioactive material<sup>17</sup>. However, the sarcophagus built in 1986 is unstable and could collapse in the future. For this reason, a stabilizing steel structure was extended in December 2006 to spread some of the load on the walls damaged by the explosion. Undoubtedly, the current situation of Unit 4 still represents a serious potential threat to the Ukraine population, if actions are not taken as soon as possible by the government to repair the whole structure of the sarcophagus. But these actions were not enough to stabilize the damage steel structure. Having been seriously damaged by the 1986 nuclear accident and subsequently repaired, the roof of the turbine hall roof adjacent to the reactor building partially collapsed in February this year. This unexpected event released no radiation and had no effect on the shelter that protects the highly radioactive remains of Unit 4. According to some Russian nuclear experts the collapse of the roof has been caused by weight of snow. However, managers of the nuclear power plant requested support from the IAEA in the preparation of the report. For this reason, and IAEA expert team was sent to the plant site in June this year, with the aim of assessing the entire turbine hall where the roof section fell. A full report on the causes of the collapse will be presented to the director general of Chernobyl nuclear power plant in July. Preliminary remarks from the team stress that the incident was dealt with in a way that avoided impact on the ongoing new safe confinement shelter project.

## THE FUKUSHIMA DAIICHI NUCLEAR ACCIDENT

The Fukushima Daiichi nuclear accident, considered the second world major nuclear accident after Chernobyl, is the third major accident that has been affected the world nuclear industry in the last thirty five years. The accident is the result of a severe climate disaster (that kills around 20 000 persons) that was not foreseen that could happen by the constructor of the nuclear power plant, putting out of service important components of the safety system of the

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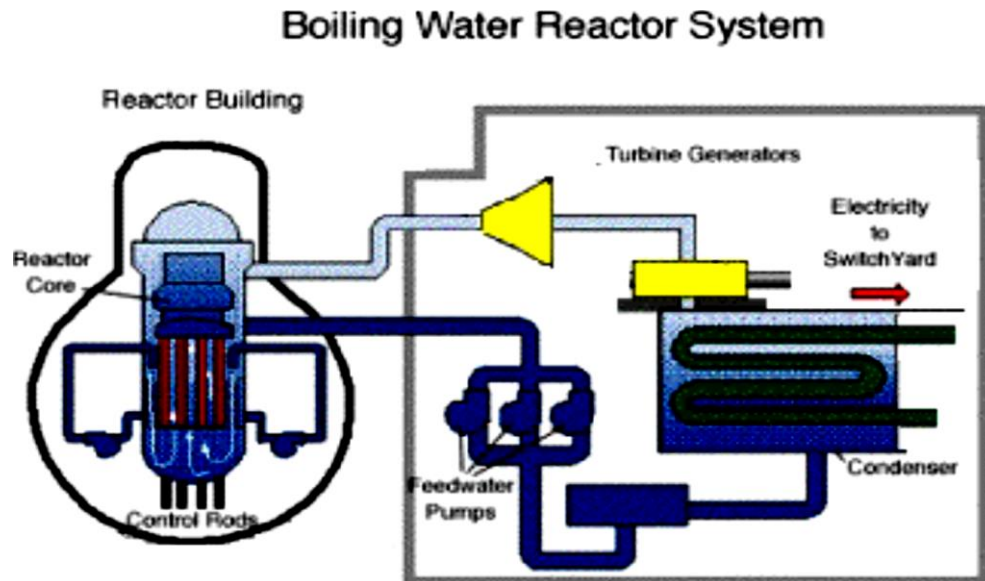
subsequently died between 1987 and 2004 but their deaths cannot necessarily be attributed to radiation exposure.

<sup>17</sup> According to some experts' calculations, the resulting steam explosion and fires released at least 5 % of the radioactive reactor core into the atmosphere and downwind.

plant. The type of nuclear power reactors in operation in the Fukushima nuclear power plant was of the boiling water reactor type (BWR) constructed in the 1970s (Generation II).

According to the IAEA Briefing on Fukushima Nuclear Accident and the Japan's Nuclear and Industrial Safety Agency, the most relevant events associated to the Fukushima Daiichi nuclear accident are described in the following paragraphs.

At 05:46 UTC (coordinated universal time) on 11 March 2011 an earthquake of magnitude 9 occurred off the east coast of Honshu, Japan. At 06:42 UTC, the IAEA Incident and Emergency Centre (IEC) was activated following notification from the Agency's International Seismic Safety Centre (ISSC) of the earthquake and of the potential for damage at four nuclear power plants located on the north-east coast of Japan as well as the potential for a tsunami. At 8:15 CET on the same day, the IEC received information from the ISSC confirming information about the earthquake of magnitude 9 that hit the east coast of Honshu, Japan. The IEC has received information from the Japan's Nuclear and Industrial Safety Agency that a heightened state of alert has been declared at 11:45 hours at Fukushima Daiichi nuclear power plant, as result of the earthquake and the tsunami that hit the east coast.



Source: International Nuclear Safety Center, Argonne National Laboratory, USA

Figure 5. Boiling water reactor components.



Source: Tokyo Electric Power Co.

Figure 6. Fukushima nuclear power plant after the accident.

A second earthquake of magnitude 6.5 has struck Japan near the coast of Honshu and the Tokai nuclear power plant. As result of these meteorological disasters, four nuclear power plants located on the north-east coast of Japan, Fukushima Daiichi and Fukushima Daini nuclear power plants of the Tokyo Electric Power Company (TEPCO), Onagawa nuclear power plant of the Tohoku Power Company, and Tokai nuclear power plant of the Japan Atomic Power Company, could be damaged (IAEA GOV/INF/2011/8, 2011). Based on the information received, the IAEA confirmed the following information about the status of the Fukushima Daiichi nuclear power plant: Unit 4 was shut down for a routine planned maintenance outage on 30 November 2010; after the outage, all fuel from the nuclear power reactor was transferred to the spent fuel pool; Units 5 and 6 were shut down at the time of the earthquake. Unit 5 was shut down as of 3 January 2011. Unit 6 was shut down as of 14 August 2010. Both units are currently loaded with fuel.

Japanese authorities have informed the IEC that the earthquake and tsunami have cut the supply of off-site power to the Fukushima Daiichi nuclear power plant. In addition, diesel generators intended to provide back-up electricity to the plant's cooling system were disabled by tsunami flooding<sup>18</sup>. At Fukushima Daiichi nuclear power plant, officials have declared a nuclear emergency situation, and at the nearby Fukushima Daini nuclear power plant a heightened alert condition.

On March 12 at 12:40 UTC, the Japan's Nuclear and Industrial Safety Agency has informed the IEC, that there has been an explosion at Unit 1 at the Fukushima Daiichi nuclear power plant and that they are assessing the condition of the reactor core. In addition, there has been an explosion at Unit 3. The explosion occurred at 11:01 hours (local time). Unit 1 is

<sup>18</sup> The tsunami hazard for nuclear power plant sites was underestimated by the constructor of the nuclear power plant and that the selection of the site was not the appropriate one to face properly this type of natural disaster, according to some experts' opinions.

being powered by mobile power generators on site, and work continues to restore power to the entire nuclear power plant. There is currently no power via off-site power supply or backup diesel generators being provided to the nuclear power plant. Seawater and boron are being injected into the reactor vessel to cool the reactor.

Due to the explosion on 12 March, the outer shell of the containment building has been lost. Unit 2 is being powered by mobile power generators on site, and work continues to restore power to the entire nuclear power plant. The reactor core is being cooled through isolation cooling, a procedure used to remove heat from the reactor core. The current reactor water level is lower than normal but remains steady. The outer shell of the containment building was intact at Unit 2 at that time.

According to the information released by the Japanese government, Unit 3 does not have off-site power supply or backup diesel generators providing power to the nuclear power plant at that time. As the high pressure injection system and other attempts to cool the nuclear power reactor core failed, injection of water and boron into the reactor vessel commenced. Water levels inside the reactor vessel increased steadily for a certain amount of time but readings indicating the water level inside the pressure vessel were no longer showing an increase. To relieve pressure, venting of the containment started on 13 March at 09:20 hours (local time). Planning to reduce the concentration of hydrogen inside the containment building was carried out. The containment building was intact at Unit 3 at that time.

On March 14 at 06:00 UTC, the Japan's Nuclear and Industrial Safety Agency has provided further information about the hydrogen explosion that occurred at Unit 3 at the Fukushima Daiichi nuclear power plant. Another hydrogen explosion occurred at Unit 3 at 11:01 hours (local time). Six people have been injured as resulted of the explosion. The reactor building exploded but the primary containment vessel was not damaged. The control room of Unit 3 remains operational at that time. At 22:03 hours (local time), Japanese authorities have reported that Unit 2 experienced decreasing coolant levels in the reactor core. Officials have begun to inject sea water into the reactor to maintain cooling of the reactor core. Sea water injections into Units 1 and 3 were interrupted the day before due to a low level in a sea water supply reservoir, but sea water injections were restored at both units. A fire at Unit 4 occurred at 23:54 UTC and lasted two hours.

On March 15 at 00:16 UTC, plant operators considered the removal of panels from Units 5 and 6 reactor buildings to prevent a possible build-up of hydrogen in the future. It was a build-up of hydrogen at Units 1, 2 and 3 that led to explosions at the Fukushima Daiichi nuclear power plant. After explosions at both Units 1 and 3, the primary containment vessels of both units are reported to be intact. However, the explosion that occurred at 21:14 UTC on 14 March at Unit 2 affected the integrity of its primary containment vessel. All three explosions were due to an accumulation of hydrogen gas.

Japanese authorities also informed at 04:50 CET that the spent fuel storage pond at Unit 4 was on fire and radioactivity was released directly into the atmosphere. Dose rates of up to 400 mSv per hour have been reported at the site. According to the Japanese authorities there is a possibility that the fire was caused by a hydrogen explosion and informed that there has been an explosion at the Unit 2. The explosion occurred at around 06:20 hours on 15 March (local time). At 14:10 UTC, sea water injections to cool Units 1, 2 and 3 were continued. Attempts to return power to the entire Fukushima Daiichi nuclear power plant were also carried out.

Japanese authorities reported some casualties to nuclear plant workers. At Fukushima Daiichi nuclear power plant, four workers were injured by the explosion at Unit 1, and there are three other reported injuries in other incidents. In addition, one worker was exposed to higher-than-normal radiation levels that fall below the IAEA guidance for emergency situations. At Fukushima Daini nuclear power plant, one worker died in a crane operation accident and four others have been injured.

On March 19, Japan's Chief Cabinet Secretary said that sea water injection were carried out at Units 1, 2 and 3 at the Fukushima Daiichi nuclear power plant. Preparations were made to spray water into the used fuel pool at Unit 4, and an unmanned vehicle sprayed more than 1 500 gallons of water over seven hours into the used fuel pool at Unit 3. The situation at the Unit 3 fuel pool was stabilized. Some reactor cooling capacity has been restored at Units 5 and 6 after the installation of generators at those units. Progress had been made on a fundamental solution to restore power at the Fukushima Daiichi nuclear power plant, with electricity restored at Units 1 and 2 on March 19 and Unit 3 as early as Sunday.

On March 20 at 14:05 GMT, workers on site succeeded in increasing the stability of the Fukushima Daiichi reactor units with Units 5 and 6 now in cold shut down. Pressure built up within Unit 3 but a more significant venting was not seemed necessary at that time. External power has now been connected to Units 5 and 6, allowing them to use their residual heat removal systems and transfer heat to the sea. This has been used to cool the fuel ponds and bring the units to cold shut down status, meaning that water in the reactor system was at less than 100° C. An extended operation to refill the fuel pond took place at Unit 3. A similar operation is planned for Unit 4. At Units 1 and 2, external power was restored. Tokyo Electric Power Company (TEPCO) said it would restore functions in the central control room shared by the units so that accurate readings could again be taken from the reactor system. Next, workers checked the condition of the water supply systems to the nuclear power reactors and the used fuel pond. External power for Units 3 and 4 was in place a few days later.

The Japanese authorities have initially classified the accident at Fukushima Daiichi nuclear power plant as a level 4 —Accident with Local Consequences on the International Nuclear and Radiological Event Scale (INES) of the IAEA. Later on the nuclear accident was classified by the IAEA as level 7 (the same level of the nuclear accident in the Chernobyl nuclear power plant) due to the characteristics of the accident. However, it is important to stress that the radioactive materials liberated as result of the nuclear accident in the Fukushima nuclear power plant was estimated to be only 10 % of the radioactive materials released by the nuclear accident in the Chernobyl nuclear power plant.

After the Fukushima nuclear accident, the use of nuclear energy for the generation of electricity and its future in Japan have polarized the public opinion, with thousands of protesters<sup>19</sup> demanding its abandonment while some government officials insisting that it remains necessary in order to satisfy, in the most effective and economic manner, the country energy demand.

As result of the Fukushima Daiichi nuclear accident, a total of 35 units of the country's 54 nuclear power reactors were offline – either damaged, halted by the quake and resulting

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<sup>19</sup> Almost 70 % of Japanese say their country should reduce its reliance on nuclear energy, in a poll conducted in 2012 as the country's last nuclear power plant went offline. This is a much larger number taking this position than in the weeks following last year's nuclear meltdown at the quake and tsunami-damaged Fukushima Daiichi nuclear power plant. Just 4 % of Japanese say the country should expand the use of nuclear power in the coming years.

tsunami or down for routine repairs. The approved programme for the construction of 14 new nuclear power reactors was suspended. Since March 11, 2011, Japan has been unable to restart any of its nuclear power reactors that were temporally shut down, scuttled by local opposition and its own meandering policies. That alone has led to nationwide energy shortages, tightening margins for businesses and other activities. But the energy shortages could become more severe in coming months, as the nuclear power reactors that are still operating (two units) now come off-line for scheduled tests<sup>20</sup>. The Ministry of Environment has announced that to clean the areas surrounded the Fukushima nuclear power plant that has been contaminated, around 29 million m<sup>3</sup> of contaminated soil has to be removed. Billions of dollars have been approved by the Japanese government for this work as well as for recovering the contaminant area. It is expected that the process of cleaning the contaminated area needs around forty years to be completed. The damage provoked by the nuclear accident in the Fukushima Daiichi nuclear power plant was estimated to be around € 156,500 million. According to Leonid Bolshov, director of the Institute for the Secure Development of Atomic Energy of the Russian Academy of Science, there are two possibilities that can be considered for the clean-up of the Fukushima Daiichi nuclear power plant site and surrounded areas: a) dismantling and burial of all elements and components of the plant; and b) the construction of sarcophagus for each of the nuclear power reactors damage by the nuclear accident.

## **MAIN PRELIMINARY FINDINGS, CONSEQUENCES, AND LESSONS LEARNED**

The main preliminary findings, consequences, and lessons learned from the three major nuclear accidents described above were the following:

### **Nuclear Accident at Three Miles Island Nuclear Power Plant**

According to WANO sources and reports, including other public sources and experts' opinions, the following are a summary of the main lesson learned from the TMI nuclear accident:

- The adoption of additional safety measures with the aim of strengthening further the level of nuclear safety in all nuclear power plants operating in the country and in other countries as well at that time. In the USA, NRC's regulations became broader in scope and more robust, and management of the nuclear power plants in operation in the country was scrutinized more carefully. Similar measures were adopted by the

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<sup>20</sup> According government sources, utilities had been waiting for the NRA's new regulations to come into force before submitting applications to restart several units idled over the months following the Fukushima Daiichi nuclear accident. The nine units covered by the applications are Kansai's Takahama Units 3 and 4 and Ohi Units 3 and 4; Hokkaido's Tomari Units 1 and 3; Shikoku's Ikata Unit 3 and Kyushu's Sendai Units 1 and 2. Kyushu expects to submit applications for Genkai Units 3 and 4 on 12 July increasing the number of nuclear power reactors in operation to eleven. The new regulations adopted by the government require nuclear operators to show that their nuclear power reactors are prepared to face satisfactorily extraordinary external events comparable to the one affected the Fukushima nuclear power plant.

nuclear regulatory offices in other countries as well, following a group of safety recommendations adopted by the IAEA after the accident.

- Problems identified from careful analysis of the accident have led to permanent and sweeping changes in how NRC regulates its licensees which, in turn, has reduced the risk to public health and safety. Similar actions were implemented in other countries as well.
- In addition to the improved operating training, improvements in quality assurance, engineering, operational surveillance and emergency planning have been instituted. The continued development of new and improved operating procedures requires increased imagination and flexibility on the part of both operators and regulators, a readiness to accept changes for the better, and less emphasis upon procedural requirements (like logging the locking or unlocking of an access door) which are largely unrelated to plant operation but which by their unrelenting inflexibility may occasionally detract from the safety they are intended to enhance (Corey, 1979).
- Improvements in control room habitability, sight lines to instruments, ambiguous indications, and even the placement of trouble tags were made. Improved surveillance of critical systems, structures and components required for cooling the plant and mitigating the escape of radionuclides during an emergency were also implemented.
- Each nuclear power plant must now have an approved emergency plan to direct the evacuation of the public within a ten mile Emergency Planning Zone and to facilitate rapid notification and evacuation. This plan is periodically rehearsed with federal and local authorities to ensure that all groups work together quickly and efficiently;
- Revision of the PWR design in order to improve it with the aim of avoiding that the same type of problems occur in the future;
- Strengthening training programs for the preparation of nuclear power plant operators. According to GPU Nuclear Corporation (1999) and NEI (2000), training reforms are among the most significant outcomes of the TMI nuclear accident. Training became centered on protecting a plant's cooling capacity, whatever the triggering problem might be. TMI nuclear accident has been of interest to human factors engineers as an example of how groups of people react and make decisions under stress. There is consensus that the accident was exacerbated by wrong decisions made because the operators were overwhelmed with information, much of it irrelevant, misleading or incorrect. As a result of the TMI nuclear accident, operator training has been improved. Before the accident it focused on diagnosing the underlying problem; afterwards, it focused on reacting to the emergency by going through a standardized checklist to ensure that the core of the reactor is receiving enough coolant under sufficient pressure. At TMI nuclear accident, the operators turned to a book of procedures to pick those that seemed to fit the event. Now operators are taken through a set of "yes-no" questions to ensure, first, that the reactor's fuel core remains covered. Then they determine the specific malfunction. The TMI nuclear accident led also to the establishment in 1979 of the Atlanta-based Institute of Nuclear Power Operations (INPO) and its National Academy for Nuclear Training (1985). Close to half of the operators' training is in a full-scale electronic simulator

of the TMI control room. The US\$ 18 million simulator permits operators to learn and be tested on all kinds of accident scenarios;

- The accident fostered better understanding of fuel melting, including improbability of a “China Syndrome” meltdown breaching the reactor vessel and the containment structure.
- One of the main consequences of the nuclear accident in the TMI nuclear power plant was the increase of public fear to the use of nuclear energy for the generation of electricity in the USA and in other countries as well and, as consequence of this fear, the increase rejection of the public opinion to the construction of new nuclear plants and to the use of this type of energy for this specific purpose in the future<sup>21</sup>. The TMI accident also had a psychological effect on the US population. To reduce this rejection, nuclear authorities and nuclear industry should provide all necessary information to the public about the operation of a nuclear power plant, the safety measures adopted to avoid the repetition of nuclear accidents, the benefit in the use of this type of energy in order to reduce the emission of CO<sub>2</sub>, among other information.
- Taking into account the strong rejection of the public opinion in the USA and in several other countries to the use of nuclear energy for the generation of electricity, approved plans for the construction of new nuclear power reactors in the USA were stopped until February 2013<sup>22</sup>; in other countries these plans were cancelled, reduced significantly or postponed indefinitely.
- The financial risks, coupled with continuing need for careful management control, suggest that nuclear power plants be operated by substantial organizations having responsible management in depth, which is committed to the development of well-trained personnel and the use of expert control techniques (Corey, 1979).

## **Nuclear Accident at Chernobyl Nuclear Power Plant**

According to WANO sources and reports, including other public sources and experts’ opinions, the following are a summary of the main lesson learned from the Chernobyl nuclear accident:

- The adoption of the so-called “safety culture” by all countries with nuclear power plants in operation. This safety culture was promoted by the IAEA after the accident in order to increase the safety of all nuclear power reactors operating in all countries. In addition, the IAEA promoted the adoption of specific measures to further strengthen nuclear safety regulatory authorities in almost all countries, including the independence of these authorities from other government offices. The IAEA also elaborated new safety documents with the purpose of increasing the safety operation of all nuclear power reactors.

<sup>21</sup> Before the accident, 70 % of the general public approved the use of nuclear energy for the generation of electricity. After it, support for the use of this type of energy source for the generation of electricity across the country fell to about 50 %, where it remained for decades.

<sup>22</sup> At the time of the TMI nuclear accident, 129 nuclear power plants had been approved in the USA but only 53 (which were not already operating) were completed.

- Upgrading was performed on all RBMK units operating in the former Soviet Union and in other former Eastern European socialist countries with the purpose of eliminating all identified design deficiencies that contributed to the Chernobyl nuclear accident, to improve shutdown mechanisms, redesigned control rods, faster control rod mechanisms, changes of fuel enrichment to reduce the effect of positive void coefficient, and heighten general safety awareness among staff. It is important to stress those changes in the design of RBMK reactor type that were introduced with the purpose of avoiding that the same kind of accident occurs in the future<sup>23</sup>;
- Improve current training programs for the preparation of nuclear power plant operators in the former Soviet Union (now Russia) and in other countries with important nuclear power programmes as well;
- In the specific case of the Chernobyl nuclear accident, when the operators noticed the sharp increase in power they attempted to insert the control rods into the reactor core. This did not help because the rods could not move fast enough. When the operators started to push the control rods back in, the boron carbide parts were completely clear of the reactor core. Below the graphite part was a column of water. Inserting the rods initially had the effect of pushing the water away, which meant decreasing the amount of poison which meant increasing “k”. The intense heat deformed the reactor core and the control rods stuck before they could be completely inserted. The control rods were badly designed. Several measures were adopted to redesign the control rods in these types of reactors.
- Strong concrete buildings surround most Western reactors was not in place around Unit 4 or around any other of the three units in the Chernobyl nuclear power plant. If it did, radiation might not have leaked into the environment.
- One of the consequences of the Chernobyl nuclear accident was the decision adopted by Russia and other former European socialist countries of abandonment the use of RBMK reactor type for the generation of electricity and the decision not to construct new nuclear power reactors of this type inside or outside Russia.
- Finally, it is important to stress the following: the accident would not have happened unless the operators had made several serious errors. First of all the test should have been aborted when things were not going as planned. The power level was lower than planned, increasing the importance of the positive void coefficient. The core of the reactor was suffering from severe xenon poisoning, so the control rods had to be almost fully retracted, leaving too small margin of safety. The operators seemed completely unaware of the fact that the effect of xenon poisoning would decrease rapidly, should the power level rise.

Summing up the following can be stated: The nuclear accident at Chernobyl nuclear power plant is the resulted from a combination of external circumstances, engineering design flaws and errors made by badly trained operators. The biggest challenge facing communities

<sup>23</sup>It is important to stress that in almost all types of nuclear power reactors, the multiplication factor decrease when temperature increases. This also holds for the RBMK reactors, with one exception: When running the reactor at a low power level, increasing boiling of water in the reactor core, which means less water around the reactor core, (steam is virtually transparent to neutrons, so it call “void”, hence “void coefficient”) leads to increasing power. It is important to be aware that although light water (as opposed to heavy water) is often used as moderator, it also works as a poison, absorbing neutrons.

affected by the Chernobyl nuclear accident is the psychological damage to five million people in Belarus, Ukraine and Russia. The psychological impact is now considered to be Chernobyl's biggest health consequence because people consider themselves as victims of the accident and are therefore more apt to take a passive approach toward their future rather than developing a system of self-sufficiency.

Finally, it is important to stress the following: The Belarus National Academy of Sciences estimates 270 000 people in the region around the accident site will develop cancer as a result of Chernobyl radiation and that 93 000 of those cases are likely to be fatal. In another report the Russian Academy of Sciences found a dramatic increase in mortality since 1990—60 000 deaths in Russia and an estimated 140 000 deaths in Ukraine and Belarus—probably due to Chernobyl radiation<sup>24</sup>.

### **Nuclear Accident at the Fukushima Daiichi Nuclear Power Plant**

According to the IAEA International Fact Finding Expert Mission report (2011) and other experts' opinions, the following are the main lesson learned from the nuclear accident in the Fukushima Daiichi nuclear power plant:

- The tsunami hazard for nuclear power plant sites was underestimated by the constructor of the plant and there are some experts' opinions that the selection of the site was not the appropriate one to face properly this type of natural disaster. To avoid the repetition of this type of nuclear accident in a nuclear power plant caused by a severe natural disaster, nuclear designers and operators should appropriately evaluate and provide protection against the risks of all natural hazards, and should periodically update these assessments and the methodologies used in light of new information, experience, and understanding. In the future one of the main criteria to be considered for the selection of new sites for the construction of nuclear power plants should be that the site provide sufficient protection from any foreseeable extreme natural disaster similar to the one affected the Fukushima Daiichi nuclear power plant;
- Defense in depth, physical separation, diversity, and redundancy requirements should be applied for extreme external natural events, particularly those with common mode implications such as extreme floods;
- Nuclear regulatory systems should address extreme external natural events adequately, including their periodic review, and should ensure that regulatory independence and clarity of roles and responsibilities are preserved in all circumstances in line with IAEA Safety Standards;
- The nuclear regulatory office should be an independent body within the government structure with the necessary authority and resources to carry out its mandate free of interference from other government offices and the private nuclear industry;

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<sup>24</sup> According to different public sources, the accident at Chernobyl nuclear power plant was approximately 400 times more potent than the atomic bomb dropped on Hiroshima during World War II. However, the atomic bomb testing conducted by several countries around the world during the 1960s and 1970s sent between 100 and 1 000 times more radioactive material to the environment than the Chernobyl nuclear accident.

- Severe long-term combinations of external events should be adequately covered in design, operations, resourcing, and emergency arrangements;
- The Japanese accident demonstrates the value of hardened on-site Emergency Response Centers with adequate provisions for communications, essential plant parameters, control and resources. They should be provided for all major nuclear facilities with severe accident potential. Additionally, simple effective robust equipment should be available to restore essential safety functions in a timely way for severe accident conditions;
- Hydrogen risks should be subject to detailed evaluation and necessary mitigation systems provided;
- Emergency arrangements, especially for the early phases, should be designed to be robust in responding to severe accidents;
- The permanent communication with the public affected or not by a nuclear accident and the supply of accurate information regarding the consequences and the impact of a nuclear accident in the environment and the public health should have a high priority for governments and the private nuclear industry in order to avoid confusion and misunderstanding.

In addition, it is important to stress the following: The types of reactors used in the Fukushima Daiichi nuclear power plant was constructed following an old nuclear technology developed in the 1960s and 1970s with a number of design deficiencies (the so-called Generation II reactors). These deficiencies were detected first by the USA many years ago and changes were made to redesign this type of reactor in a short period of time. Regrettably, Japan did not introduce these changes in the same type of nuclear power reactors used in the country<sup>25</sup>.

## CONCLUSION

One of the available energy sources that can be used for the generation of electricity that has proved that can supply the power that a country need at any time, in the amount desired, in a clean manner, in almost all conditions, and when is required, is nuclear energy. However, the use of nuclear energy for the generation of electricity is not an easy and cheap option and in some countries faces a strong rejection of the public opinion. From the technological point of view, many countries consider the use of nuclear energy for the generation of electricity as a very costly alternative, particularly for those countries with a weak technological development, limited financial resources, lack of qualified personnel or relative small electrical grid.

The majority of the nuclear power reactors today in operation in the world are from the second generation of nuclear power reactors built mostly in the 1970s (the so-called “Generation II”), which were the type of reactors involved in the three major nuclear accidents that occurred since 1979. However, most of the countries that are expanding their nuclear power programmes are constructing nuclear power reactors of the third generation

<sup>25</sup> Japan was one of the two countries in the world with the highest number of BWRs in operation before the Fukushima Daiichi nuclear accident (26 units in operation in 2011).

(the so-called “Generation III”), which are more reliable and with a number of built-in safety features. Advances to third generation of nuclear power reactors are underway, resulting in several near-term deployable reactors that is actively under development and are being considered for deployment in several countries such as France, China and Finland, just to mention a few ones. It is expected that all new nuclear power reactors to be built between now and 2030 will likely be chosen using an improved version of this type of reactor design (the so-called “Generation III +”).

The main questions that need to be asked now are the following: nuclear accidents can be totally eliminated in the future? What types of nuclear technologies are under development now that can increase the safety operation of new nuclear power reactors to be constructed in the future? These new nuclear technologies can eliminate the possibility of a severe nuclear accident in the future?

Six nuclear technologies are now under research in several countries but these technologies will not be in the market before 2050<sup>26</sup>. However, there is and will not be a nuclear technology or any other energy technology that can be 100 % secure and, for this reason, all rational measures should be adopted to reduce to the minimum the possibility that a severe nuclear accident could occur in the future and, if it happens, the consequences should be negligible because if a new nuclear accident occur in the future in any nuclear power plant, then the use of nuclear energy for the generation of electricity will be excluded from the energy mix of all countries.

Finally, it is important to stress the following: after the Three Miles Island nuclear accident the majority of the plans for the expansion of nuclear power programs adopted by some countries were stopped, particularly in the USA and in some other countries in the European region. After the Chernobyl nuclear accident, the fear of the public opinion to the use of nuclear energy for electricity generation increased significantly forcing some governments to stop their plans for the expansion of their nuclear power programs. However, in the Asia region, the Fukushima Daiichi nuclear accident has little negative impact in the expansion of the use of nuclear energy for electricity generation at least in the majority of states within the region. The region interest in the use of nuclear energy for the generation of electricity has reflected in the consideration of around 100 nuclear power projects of various scales approved in several countries of the region. Many of these projects are either under consideration, have already been negotiated and signed off on, or close to implementation. For example, China accounts for the bulk of these projects; it has the largest number of ongoing projects worldwide (24 units), followed by South Korea (6 units), India (4 units), Taiwan (2 units), and Pakistan (1 unit). Other countries such as Iran, which finally completed its Bushehr nuclear power plant (1 000 MW) in 2010 with Russian assistance is continuing with the construction of the 360 MW Darkhovin nuclear power plant in its Khuzestan Province, and it has also announced plans to build enough nuclear capacity to generate 20 000 MW of power over the next twenty years (around 19 new units). In Southeast Asia, Vietnam has embarked on constructing a nuclear power plant consisting of four nuclear reactors (1 000 MW light water reactors) with the assistance of Russia (for two reactors) and Japan (for the other two). Preliminary work has started on one Russian reactor scheduled for completion in 2020.

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<sup>26</sup> For additional information on these new nuclear technologies see Morales Pedraza (2012).

Undoubtedly, the future belongs to the fourth generation of nuclear power reactors (the so-called “Generation IV”). This new generation of nuclear power reactors is a revolutionary type of reactors with innovative fuel cycle technologies and with innovations designed to achieve improved fuel efficiency, including high temperature applications, and designs to be used safely in isolated or remote locations. The use of this type system designs for the generation of electricity will increase nuclear safety and will reduce significantly the possibility of a severe nuclear accident as the ones mentioned in this paper. However, Generation IV nuclear power reactors would be available in the market not before 2050.

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