



The Ontario Society of Professional Engineers' Guide to the Nuclear Accident at the Fukushima Dai-Ichi Plant

The recent tragic events in Japan have captured the attention of professional engineers and citizens worldwide. The thoughts and prayers of all professional engineers in Ontario are with the people of Japan and the TEPCO employees who are working tirelessly to bring the situation at the Fukushima Dai-Ichi nuclear plant under control. OSPE encourages all professional engineers to contribute generously to relief organizations that are helping with the recovery efforts in the various Japanese communities.

The tragedy of a major earthquake is pain enough for any country to bear without the additional devastation of a major tsunami, combined with the risks associated with release of radioactive materials from a major nuclear plant accident. At this time, we must try to remain calm and remember that the worst nuclear accident in history, the Chernobyl accident in 1986, pales in comparison with the death and destruction caused by the Japanese tsunami itself.

The Dai-Ichi nuclear accident is not expected to be as serious as Chernobyl for reasons explained below. We urge our political leaders to refrain from making hasty policy decisions until the official investigation and report of the Dai-Ichi accident is available.

Three obvious questions that many people in Ontario are asking are:

1. How bad can this accident get, and will it affect us in Ontario?
2. Could the same type of accident happen here in Ontario?
3. Is nuclear power really necessary to meet our energy needs, when there are very serious risks involved?

Before we try to answer these questions, let's look at what has already happened at the Fukushima Dai-Ichi Plant and the status of the site as of Saturday evening, March 19, 2011, local Japanese time (Friday evening, March 18, 2011 Toronto time).

We can neither elaborate with any degree of certainty regarding the behaviour of the control systems and operators at the Fukushima Dai-Ichi Plant nor on the degree of equipment damage that will ultimately be incurred before the accident is fully resolved. Such information will need to wait for a full accident investigation and report. We know however, that the accident will be brought under control, if for no other reason than the laws of physics. However, with dedicated human intervention, it should be possible to significantly reduce the time to end the accident and significantly reduce the amount of radioactive material that is released into the environment.

The key to reducing the amount of radioactive material release is to cool and contain the fuel in both the reactor and the spent fuel bays. If the fuel is not cooled, fuel temperatures will rise and the zirconium cladding that seals the fuel and fission products inside the fuel bundles will burn and release some of the fission products. The most likely releases will be of gaseous fission products—products that can vaporize or melt at the temperatures that the fuel reaches when there is inadequate cooling.

On Saturday, March 19, 2011, the highest radioactivity was recorded in Namie Town by one of the 28 monitoring stations located in the area 30 to 60 kilometres from the plant. Located 30 kilometres northwest of the plant, Namie Town had a level of 136 microsieverts per hour around 10:20 a.m. In simple terms, that is the equivalent of about 13.6 millirem, or slightly more than two chest X-rays per hour. This radiation dose rate will fall with time after the accident is brought to an end. This level of exposure is likely to accumulate to a higher value than that outside the Three Mile Island site during the 1979 accident that took place there. That accident created an exposure of 100 millirem, or about six chest X-rays, at the plant site boundary for the entire duration of that accident.

We know that the Dai-Ichi plant was struck with a major earthquake, then by a major tsunami, followed by a series of numerous aftershocks. The plant was designed for a specific level of earthquake and tsunami event. Indications are that the earthquake ground motion and the tsunami wave height exceeded the design of these structural defenses. It is not clear to what extent the units were initially damaged by the earthquake and tsunami. The six units at the plant were placed in service between 1971 and 1979. We know that the Mark I containment building design at Dai-Ichi has been superseded by two more robust Mark II and Mark III containment designs since the plant was built. We are not certain at this stage what upgrades were made to the plant to meet the revised safety standards that emerged after the Three Mile Island and Chernobyl accidents.

About the time the tsunami struck, the plant lost all its electrical power supplies, except for limited battery power. The tsunami appears to have caused more problems than the earthquake because it damaged and shorted out all external plant power sources including the emergency generators. These generators and their fuel supply were outside the main reactor building. All nuclear plants of current design (prior to the latest GEN IV concept) require electrical power to keep the plants safe. Electrical power is needed to keep fission reactors shut down and cooled, to keep radioactive materials contained, and to keep the plant monitored to ensure all conditions remain safe.

Off-site mobile generators were apparently delivered to the site. However, the damaged and salt-water soaked electrical system could not be restored at that time. From the daily reports of explosions and fires at the site, it is clear that the staff is having a difficult time bringing the accident under control. Most of the explosions are believed to have been caused by hydrogen released by the zirconium oxidation in the presence of hot steam, which releases hydrogen gas. Hydrogen is normally managed in a severe accident using electrically powered hydrogen recombiners. Unfortunately, with no electrical power, recombiners are ineffective. The explosions and fires resulted in further damage that frustrated the staff's efforts to contain the accident.

Units 4, 5 and 6 were in a maintenance outage at the time the earthquake struck. The fuel in the unit 5 and 6 spent fuel bay had cooled down, so the water in their spent fuel bay was still capable of cooling the fuel for over a week without additional cooling water. The unit 4 reactor had recently been shutdown for maintenance, so its fuel was still hot in the spent fuel bay. That is the reason for concern about the Unit 4 spent fuel bay and failure of the zirconium fuel cladding as the water boiled off. Units 1, 2 and 3 were operating at the time of the earthquake and were automatically shut down. Units 1 and 2 were using enriched uranium oxide fuel. Unit 3 was using enriched mixed oxide fuel, a combination of uranium and plutonium, developed as part of the world effort to reduce the stockpile of weapons-grade plutonium.

When systems important for safety have been damaged, then the staff must configure other means to provide the necessary safety functions such as cooling and containment. That is why the staff at Dai-Ichi is using fire trucks to try to cool the fuel in the reactor and spent fuel bay. This will remain challenging not only because of the damage incurred by plant equipment and buildings but also because of the devastation in the surrounding areas and demands on emergency personnel around the country to deal with the human side of this tragedy. To date, the earthquake and tsunami have killed 7,000 people, and over 10,000 are missing. Moreover, several coastal communities have been completely destroyed, leaving thousands homeless.

By Saturday evening, the Dai-Ichi staff was successful in restoring emergency generator power to Units 5 and 6 and bringing in a temporary grid power line to units 1 and 2. They are now in the process of determining if that power can be delivered to the cooling equipment and controls and whether that cooling flow will reach the reactors and spent fuel bays. The staff hopes to provide external power to Units 3 and 4 and then Units 5 and 6 by Sunday.

Fortunately, Japan is a sophisticated and technologically advanced society. In time, with support from the world community, its nuclear energy practitioners should be able to overcome these obstacles and end this accident, which continues to keep the rest of the world watching.

Answering Common Questions

1. How bad can this accident get and will it affect us in Ontario?

The severity of the Dai-Ichi reactor accident is expected to lie between the Three Mile Island-2 accident and the Chernobyl-4 accident. Ontario is too far away to be directly affected by Dai-Ichi, except for trace amounts of radioactive materials, which may be carried overseas by winds.

The Dai-Ichi reactors are a Boiling Water Reactor (BWR) design. Unit 1 is 439 net MWe; Units 2, 3 and 4 are 760 net MWe. They are boiling light water-cooled and moderated reactors with enriched uranium fuel or mixed uranium and plutonium fuel. The core is inside a pressure vessel, which is surrounded by a primary concrete containment, which in turn is inside a secondary concrete containment building. The design is an early version (1971 to

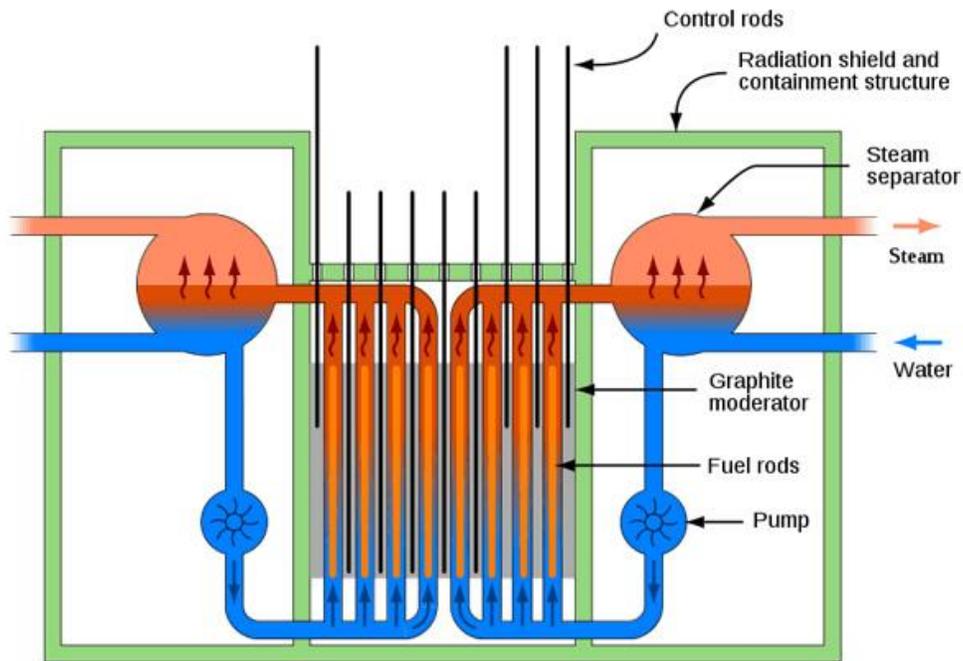
1979 vintage) called a Mark I containment design. The accident has recently been raised to a 5 on the international nuclear and radiological event scale (INES) of 0 to 7. The Dai-Ichi accident is not expected to reach the magnitude of the Chernobyl accident, which was a level 7, because the energy released during the accident is much lower. Even though four reactors and their fuel bays are involved in this loss-of-cooling accident, the reactors are shut down and will gradually release less nuclear energy every day. This accident will likely be worse than the Three Mile Island accident, which was rated a 5 on the INES scale, because hydrogen gas has caused explosions that have damaged all four reactor buildings and equipment and made it more difficult to cool the reactor cores and spent fuel bays. The resulting zirconium fuel cladding oxidation will release additional chemical energy, in addition to the gradually decaying nuclear energy in the fuel bundles.

The worst nuclear power accident to date was the Chernobyl Unit 4 accident in 1986. Thirty operators and firemen died within three months and several more deaths of emergency responders later on could be attributed to the accident. It is estimated that all of the xenon 135 gas, about half of the iodine 131 and cesium 137, and at least 5% (about 10 tons) of the remaining radioactive material in the Chernobyl-4 reactor core (which had 192 tons of fuel) was released in the accident. The core power level reached 100 times the design rating of the reactor due to a runaway reactor power excursion. This was a 3,200 MW thermal reactor that exceeded 300,000 MW thermal for a short period of time. The fuel and graphite moderator became incandescent (white hot). The energy release melted the fuel and the resulting rapid steam pressure buildup blew the steel cover off the reactor. Some of the very hot fuel and graphite was ejected from the core and started a number of fires. The building roof immediately above the reactor core was blown away. Nuclear-grade graphite itself does not burn; but because it was very hot, it caused other materials in contact with it to burn, such as the roof materials and cables. Most of the released radioactive material was deposited close by as dust and debris, but the lighter material was carried by wind over the Ukraine, Belarus, Russia and to some extent over Scandinavia and Europe. Initially 116,000 people were relocated to safer areas and eventually another 220,000 people were relocated. See <http://www.world-nuclear.org/info/chernobyl/inf07.html> for more information.

The Chernobyl-4 reactor was a RBMK design. The reactor was rated 950 net MWe. This reactor is a light-water-cooled, graphite-moderated, vertical pressure tube design with slightly enriched (2%) uranium fuel. The accident was very serious for four major reasons:

- The reactor did not have a reinforced concrete containment building around it.
- The reactor used graphite blocks around the pressure tubes to moderate the nuclear reaction, and graphite is not a coolant.
- The reactor had a very strong tendency to power up rapidly if too much steam was produced too quickly in the pressure tubes.
- The shutdown system was slow acting and could not terminate the fast power increase. See <http://www.world-nuclear.org/info/inf31.html> .

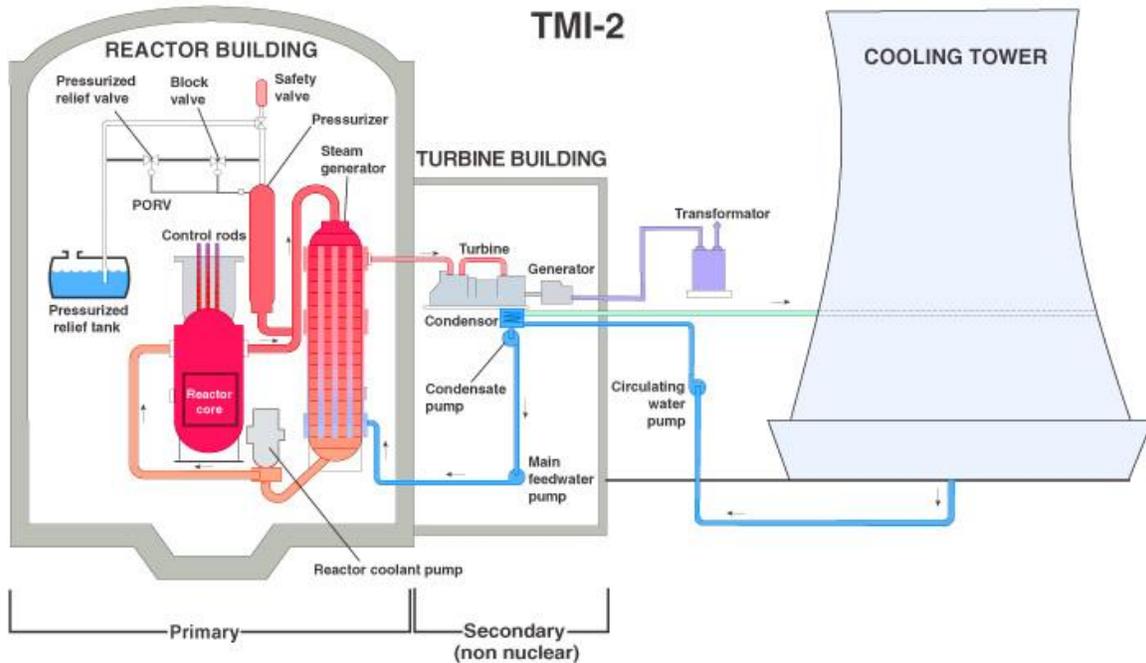
A diagram of the Chernobyl reactor is shown below:



**RBMK Reactor
(courtesy WANO)**

The second worst nuclear power accident prior to Dai-Ichi was the Three Mile Island unit 2 (TMI-2) accident in 1979. It was rated a level 5 on the INES scale. A significant fraction (about 50%) of the reactor core melted; however, very little radioactive material escaped from the containment building. Estimates are that the average dose to about 2 million people in the area was only about 1 millirem each. To put this into context, exposure from a chest X-ray is about 6 millirem, and the natural radioactive background dose is about 100-125 millirem per year for the area. The maximum dose to a person at the site boundary would have been less than 100 millirem. See <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html#glossary> .

The TMI-2 reactor is an 802 net MWe PWR design. It is a pressurized, light-water-cooled and moderated, enriched uranium reactor with the fuel residing in a pressure vessel, which is inside a reinforced concrete containment building. A diagram of the TMI-2 reactor is attached below.



Three Mile Island Unit 2 Reactor
(courtesy US-NRC)

2. Could the same type of accident that happened in Japan happen here in Ontario?

Each type of reactor has significant design differences and significant differences in the local natural risks. Major factors include geology, geography and plant design.

Geology

Japan has some of the highest earthquake ground motions in the world because it is situated on the edge of four different tectonic plates. The Dai-Ichi plant appears to have made it through the initial large Richter 9 earthquake in reasonably good shape, even though the plant was designed for a smaller earthquake.

The geology in Ontario is such that we have relatively low earthquake ground motions because we sit in the middle of the North American tectonic plate. Ontario has some of the lowest earthquake ground motions in the world. Ontario's CANDU reactors are designed for a lower earthquake ground motion because we do not experience Richter 9 earthquakes. The last earthquake experienced in Ontario had no damaging affect at the CANDU plants in Ontario. This is one reason why CANDU plants in Ontario do not automatically shutdown when an earthquake strikes. The CANDU plants here are expected to ride through our relatively mild earthquakes and continue to operate.

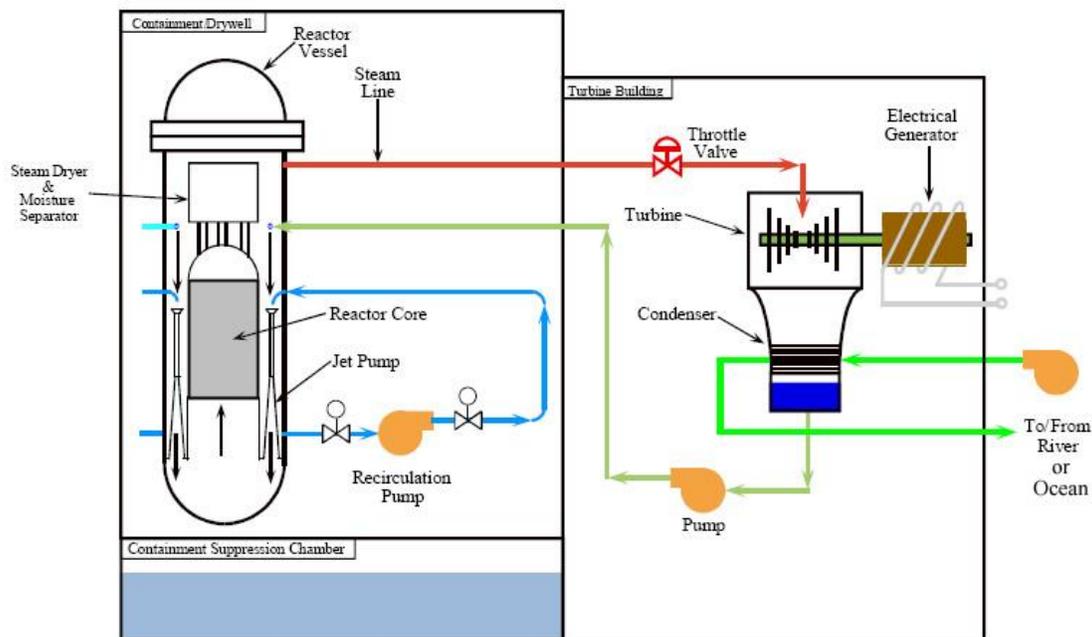
Geography:

Japan is on the coast of the Pacific Ocean, subject to both tides and tsunamis. Tsunamis are expected if an earthquake occurs offshore and the sea floor is displaced vertically: The bigger the earthquake, the bigger the displacement and the bigger the tsunami. Predicting tsunamis and their wave magnitude is not an exact science. The Dai-Ichi plant had a 6.5 metre (22 foot) tsunami barrier, but it was breached. If a tsunami barrier is breached, and the plant is near the ocean, then the peak elevation of the tsunami wave will eventually strike the plant because tsunamis have a very long wave length.

Ontario's CANDU plants are located on the Great Lakes. There are no tsunami or tide effects on the Great Lakes. We can get significant changes in lake levels due to storms (wind induced water accumulation near shore), but these are much smaller than tsunami waves and are factored into the design of the shore line protection for our CANDU plants.

Plant Design:

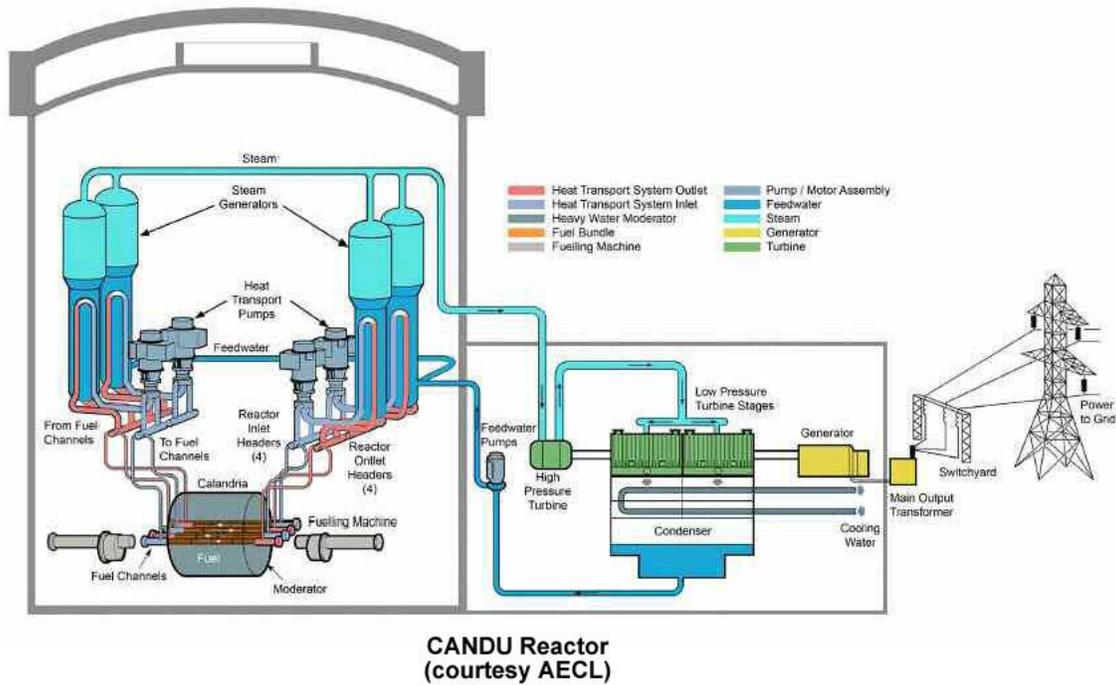
The reactors at Dai-Ichi are Boiling Water Reactors (BWR). They use enriched uranium in most of the units and a mix of enriched uranium and plutonium (MOX) fuel in Unit 3. They have a single pressure vessel that generates the steam that goes to the turbine for electrical production. The reactor core is cooled and moderated by light (ordinary) water. A diagram of the Dai-Ichi Reactor is shown below.



BWR Reactor
(courtesy NRC)

CANDU plants in Canada use hundreds of horizontal pressure tubes within a heavy-water-filled tank called a calandria. Heavy water is used as both a moderator and to cool the fuel in

the heat transport circuit. It is available naturally and contains the heavy isotope of hydrogen. Heavy water is an excellent moderator that does not absorb neutrons, so it permits CANDU reactors to be fuelled by natural uranium (not enriched). In all CANDU reactors built after 1975, the calandria tank sits inside a light water tank called a shield tank. Pressure tubes permit CANDU reactors to be fuelled daily on-line while they operate. This means they do not have to carry additional fuel in the core to last two years between fueling outages. A diagram of a CANDU reactor is shown below.



CANDU reactors are also physically much larger than the equivalent sized BWR or PWR reactor. The reactor core energy density is, therefore, much lower in terms of MW per cubic metre of volume. That means there is a lot of moderator and shield tank water available for severe accident fuel cooling in the event the normal cooling circuit and pressure tubes fail.

All current Ontario reactors are multi-unit plants that use a vacuum building for each four-unit group. The vacuum building automatically sucks pressure and radioactive materials out of the reactor buildings when a leak or loss of coolant accident occurs in any of the reactor buildings. The vacuum building concept was developed for multi-unit CANDU reactors for the Pickering A plant in the mid 1960s. The design engineers and managers at the time were concerned that the public would not accept reactors near large cities like Toronto unless the leakage rate during an accident would be very low. Subsequent operating experience suggested that the vacuum building was an unnecessary additional cost. Also, world standards to make each reactor completely independent of the others on the same site have resulted in a change in design philosophy. The newer CANDU reactors such as the natural-uranium-fuelled CANDU 6 and the slightly-enriched-uranium-fuelled ACR 1000 have more typical reactor containment building designs like those used in the USA, France and Japan. They do not use a vacuum building, but they do have spray headers in the ceiling to help

condense steam and keep the reactor containment building pressure and temperature low following an accident.

To ensure a shutdown, CANDU reactors have two fast-acting, fully capable shutdown systems. One is the traditional shutoff rod system; the other is a chemical poison injection system. The poison is injected into the moderator tank, ensuring the chain reaction cannot restart. In natural uranium CANDU reactors, the operator can also inject light water into the heavy water to downgrade it and prevent the reactor from undergoing any further chain reaction. Natural uranium reactors cannot sustain a chain reaction with light (ordinary) water in either the normal heat transport circuit or in the moderator tank.

These differences mean that ensuring reactor shutdown and fuel cooling for a CANDU reactor in the event of a total loss of electrical power accident such as that at Dai-Ichi should be easier to achieve.

In Ontario we have successfully handled three significant loss-of-coolant accidents: two at Pickering A in 1983 and 1994 and one at Bruce B in 1995. In all three cases, the reactors were returned to service after cleanup and repairs were made. We have also successfully handled a major electrical grid blackout in 2003, with four of the reactors—three at Bruce B and one at Darlington—riding through the blackout and reconnecting to the grid within a few hours. The other reactors, which were shutdown during the blackout, returned to operation over the following several days.

The key to reactor safety for all reactor types include

- well trained, experienced staff at all levels, up to the very top of the organization;
- well developed procedures to help staff perform their duties reliably during both normal and abnormal events, including “beyond design basis accidents”;
- well designed, constructed, operated and maintained plants with a “safety first” culture;
- sufficient defense-in-depth both in the engineered safety-related systems and the roles and responsibilities of the various organizational units at the site.

If these key safety lessons are embraced by the plant management, the plant can be operated safely, with acceptable levels of risk compared to the benefits that nuclear power provides.

All energy systems and human activities involve risk. We don't shut down the car industry because 50,000 people die on our roads every year. We don't shut down the aircraft industry because a few hundred people per year die in plane crashes. And we don't shut down the hydraulic generation industry when a dam breaks. In all these cases, we learn from each event and the industry is permitted to improve its designs and safety record. The nuclear industry did the same after the accidents at TMI-2 and Chernobyl-4. And it will do so again after the Dai-Ichi accident. Statistically, nuclear power has always been safer than all other heavy industries. It's our extreme reaction to the words “radiation leak” that prevents us from enjoying even greater benefits from nuclear power—vast amounts of affordable, greenhouse-gas-free energy.

3. Is nuclear power really necessary to meet our energy needs?

Fossil fuels represent the majority of the world's energy supply. The equivalent of about a cubic mile of oil is burned every year to maintain the higher living standards of about one-quarter of the world's population. If the other three-quarters are to rise to the same standard of living as the developed world, about three times the current energy supply will be needed in the future. This assumes our energy efficiency improves sufficiently to counteract the population increase.

While renewable energy will play an important and growing role, it cannot replace three times the current fossil fuel consumption. Also, some forms of renewable energy require storage to shift the energy in time to when consumers want it rather than when nature provides it. In addition, renewable forms such as wind and solar only produce about 30 per cent of the time, so almost three times as much peak installed capacity is required to produce enough power to meet consumers needs round the clock. The cost of building such large over capacity and associated storage to shift the delivery period makes some forms of renewable energy uneconomical for the bulk of our base load energy needs.

If we want to improve the lives of the less fortunate without burning far greater amounts of fossil fuel we can do one of two things: The developed world must dramatically reduce its energy consumption, or we need a large, dependable, affordable energy supply that is available 24 hours a day, seven days a week. While nuclear fusion energy promises cleaner and safer nuclear plants, it is at least 50 years or more away from widespread adoption. The world needs a carbon-free transition fuel as a bridge between today and when nuclear fusion or another technology is ready to replace it. Nuclear fission is currently the only economical option for additional large-scale energy production in those jurisdictions with limited hydraulic resources, such as Ontario.

Additional Reading:

If you are interested in additional information, the following web sites are recommended:

- American Nuclear Society, Japan Page ansnuclearcafe.org
- Nuclear Energy Institute www.nei.org
- World Nuclear News www.world-nuclear-news.org
- ANS Radiation Dose Chart www.new.ans.org/pi/resources/dosechart/
- NHK Television www3.nhk.or.jp/nhkworld/index.html
- Japan Times www.japantimes.co.jp
- AECL site for CANDU reactor info <http://www.aecl.ca/Reactors.htm>