ASCENTRUST LLC

The POWER of ENGINEERING

HEALTH AND SAFETY IN NUCLEAR SYSTEMS

AN INTRODUCTION TO NUCLEAR POWER PRODUCTION

FOR

STAKEHOLDERS AND CONSULTANTS

OF

NUCLEAR TECHNOLOGY PEBBLE BED MODULAR REACTOR

(NTPBMR) PROJECT

HEALTH AND SAFETY ASPECTS OF NUCLEAR POWER PLANTS

Health and Safety Aspects of Nuclear Power Plants

SECTION 0: INTRODUCTION

0.1. PREAMBLE

This document started off as a short introductory paper on radiation and was part of a large group of introductory papers prepared by the Principal Engineer of the **Nuclear Technology Pebble Bed Modular Reactor (NTPBMR) Project** for the primary stakeholders to the project. This document will attempt to present an integrated, positive view of the safety characteristic of existing nuclear power facilities and make the case for the inclusion of the **NTPBMR** in the energy production of the twenty-first century.

This document is a compilation of a series of white papers undertaken by the Principal Engineer covering many aspects of the production of electrical power with the use of nuclear energy. The objective of these white papers was to provide a knowledge base consisting of factual, up-to-date information on aspects of nuclear power that are needed to make the case for the safety of the existing nuclear power production fleet in the U.S. and overseas.

The method used was a systematic and selective collection, condensation, and presentation of existing information for public dissemination and for the use by generalist as well as by the technical staff associated with our stakeholders and funders. These papers were not intended to provide design guidelines but rather as background sources to support detailed or specialized analyses and reviews of our **NTPBMR** nuclear power project.

The scope of this analysis includes some of the topics and issues deemed importance to the funding and licensing of the **NTPBMR Project.**. Prime among these issues is the safety of nuclear reactors, a subject of intense controversy and debate among technical experts, political groups, and the public at large. This issue, together with those covered in the other papers, was in fact responsible for the near halt in the development of nuclear power in most countries.

Since **AscenTrust, LLC. (The Company)** is now actively involved in the funding of the **NTPBMR Prototype Project,** we are engaged in discussions with an Investment Group and several countries that have a desire to include a nuclear component in their power system. This document was undertaken to familiarize the staff of our stakeholders with the scientific facts, and provide answers to the questions which are often posed:

1. Why nuclear Power?
2. How safe is the operation of your Nuclear Power Technology?
3. What are the radiation hazards of nuclear power?
4. What about Three Mile Island, Chernobyl and Fukushima?
5. How does your reactor technology mitigate the **LOCA** (Loss of Coolant Accident)
6. What is your solution to the nuclear waste problem?
7. What should be done about nuclear proliferation?

This document will provide the reader with a fairly complete answer to the first four question stated above. Section Zero contains the preamble which includes a description of the history of this document. Section Zero contains an introduction to the magnitude of the Nuclear Power generation industry in the world.

Section One includes a description of the three reactor concepts which were involved in nuclear events. The two most important **Light Water reactor technologies** are the pressure water reactor and the boiling water reactor. The third reactor technology which was involved in a major reactor incident is the Russian RBMK. Finally section one also includes an introduction to the Pebble Bed Reactor Technology.

Section Two begins with an elucidation of the public concerns regarding the production of energy with the use of nuclear fuel and then introduces the most important elements of the nature of radiation. Section two then addresses the current state of scientific understanding of the health effects of radiation, both somatic and genetic, originating from routine as well as accidental releases of radioactivity from nuclear power plant operations.

Section Three addresses routine emissions of radioactive material that result from normal plant operations. Operational data shows that the average radiation dose to the general public resulting from normal operation of nuclear power plants is a small fraction of the average individual dose received from natural sources of radiation in the environment, and that average doses resulting from the operation of nuclear power plants are a small fraction of the variation in natural background radiation dose received in different geographic regions of the world. Recent epidemiological studies have produced no statistically significant evidence of an excess rate of cancer incidence as a result of living near nuclear installations; nor have they produced statistically significant evidence of adverse health effects among nuclear power plant workers whose occupational doses (received in normal plant operations) can often exceed natural background radiation levels.

(It must be noted that although these statements are endorsed by the consensus opinion of the medical, scientific and technical communities and by official country and international bodies, there exist dissenting reports and views on the matter.)

Section Four reviews the basic principles of nuclear power plant safety, and describes engineering systems that are designed to prevent or mitigate nuclear accidents in typical pressurized water reactors operating in the U.S. Within this context, the range of possible accidents that could occur in a power plant is discussed together with goals for power plant safety that have been established by regulatory authorities in the United States.

Three major accidents have occurred in the history of commercial nuclear power, **Three Mile Island** (TMI), **Chernobyl** and **Fukushima.** The first accident which occurred in 1979, the reactor core suffered major damage and enormous loss of investment and cleanup cost ensued. However, the releases of radioactivity to the environment were minor (owing to the effectiveness of the containment structure) and no measurable direct health effects were observed other than psychologically induced illnesses.

In the accident which occurred at Chernobyl of the Soviet Union in April of 1986, 31 persons, principally from the firefighting team, died within a month from acute exposure of radiation, large scale evacuation of population was necessitated, and large land contamination resulted. The long-term effects of radiation exposure resulting in increased cancer incidence is a matter of intense debate. The number of cancer deaths in the Soviet Union due to such exposure is estimated to be in the range of 10,000 - 40,000 during the period of the next 30 years but may not be statistically observable among the 70,000,000 deaths from naturally occurring cancer expected in the same time period. The design of the Chernobyl reactor (15 of which were operational at the time of the accident) was not exported by the Soviet Union and is no longer used for future units. About twenty units are still being operated in the USSR.

Section Five reviews the causes and consequences of the **TMI, Chernobyl** and **Fukushima** accidents, as well as those of an accident that occurred at a weapons material production plant in the United Kingdom in 1957.

0.2. CURRENT NUCLEAR POWER ANALYSIS

The American public has become aware that a sharp increase in the number of Nuclear Power Plants is the only viable solution to the global carbon dioxide emission crisis. Interest in nuclear power has recently increased because of the **Global Warming** issue. Nuclear energy is now a mature industry. In 2007, nuclear power provided 16.8% of total worldwide electricity generation, and is expected to increase that contribution in the years to come.

A. Global Nuclear Power Production: Today, there are some 439 nuclear power reactors operating in 30 countries, with a combined capacity of about 370 billion watts of electricity (GWe), which produce about 16.8% of the world's electricity but do so without directly producing any greenhouse gases. These nuclear reactors represent the major portion of green energy produced globally.

B. According to the US **Dept of Energy** (**DOE)** projections, world net electricity generation will nearly double from about 17.3 trillion kilowatt hours (kWh) in 2005 to 24.4 trillion kWh in 2015 to 33.3 trillion kWh by 2030

C. Globally, power generation emits nearly 10 billion tons of Carbon Dioxide (**CO_2)** per year. The United States, with over 8,000 of the more than 50,000 power plants worldwide, accounts for about 25 percent of that total or 2.8 billion tons.

D. More than 67% of electricity generated worldwide is produced by burning fossil fuels, primarily coal (42%), which is the most carbon-intensive fuel. In addition to carbon dioxide, burning fossil fuels also produces oxides of sulfur and nitrogen, and other air pollutants that contribute to problems like acid rain.

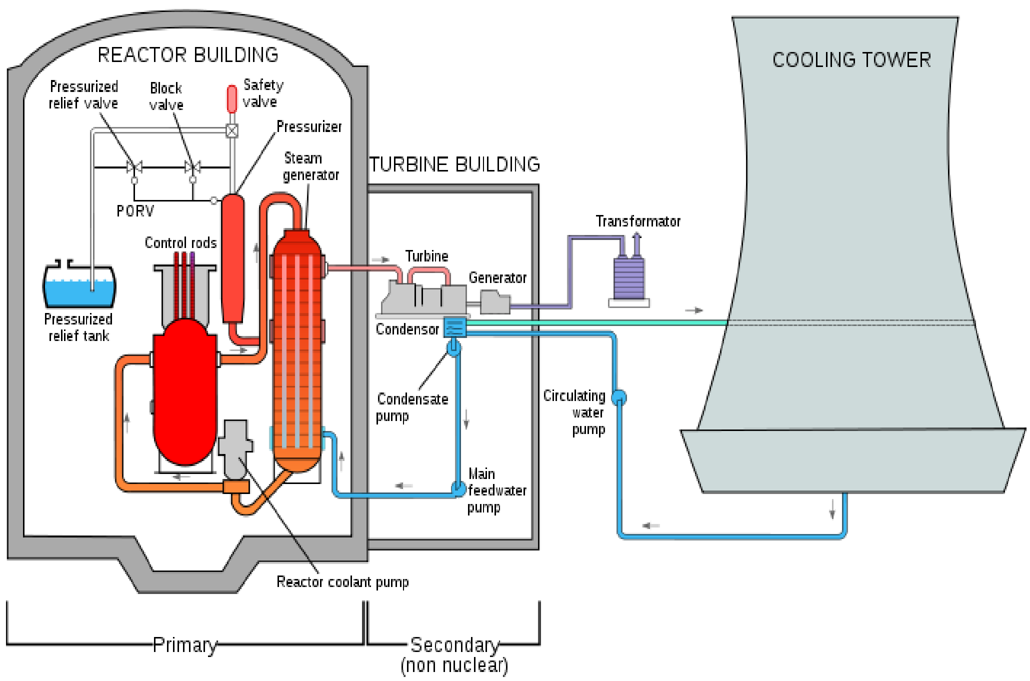
0.3. CURRENT NUCLEAR POWER SYSTEMS

The large majority of the nuclear power plants in the world today use light water as the coolant and are known generically as **light water reactors** (**LWR's**). They consist **PWR** and **BWR.** We will also be including a discussion of the **RBMK** because of the effect on the nuclear industry of the accident which occurred at Chernobyl. Finally we will also be including a detailed discussion on the **Pebble Bed Modular Reactor.**

SECTION ONE: DETAILS OF CURRENT POWER SYSTEMS

1.1. PRESSURIZED WATER REACTOR

SCHEMATIC OF THE PRESSURE WATER REACTOR AT THREE MILE ISLAND



1.1.1. INTRODUCTION

Pressurized water reactors (**PWR**s) comprise a majority of all western nuclear power plants. In a **PWR** the primary coolant (superheated water) is pumped under high pressure to the reactor core, then the heated water transfers thermal energy to a steam generator. The Nuclear Reactors at Three Mile Island are all **PWR,** types of reactors.

1.1.2. PRESSURIZED WATER REACTOR OPERATION

1. The reactor core transfers the fission energy, primarily kinetic energy created by recoil of the fission fragments in the fuel rods into thermal energy of the water which is both the moderator and the cooling agent in a Light Water Reactor
2. Pressurized-water in the primary coolant loop carries the heat to the steam generator.

3. Inside the steam generator heat from the primary coolant loop vaporizes the water in the secondary loop producing steam.
4. The steam line directs the steam to the main turbine causing it to turn the turbine which is connected to the generator to create electrical power.
5. The unused steam is condensed into water.
6. The resulting water is pumped out of the condenser with a series of pumps, reheated and pumped back to the steam generator.

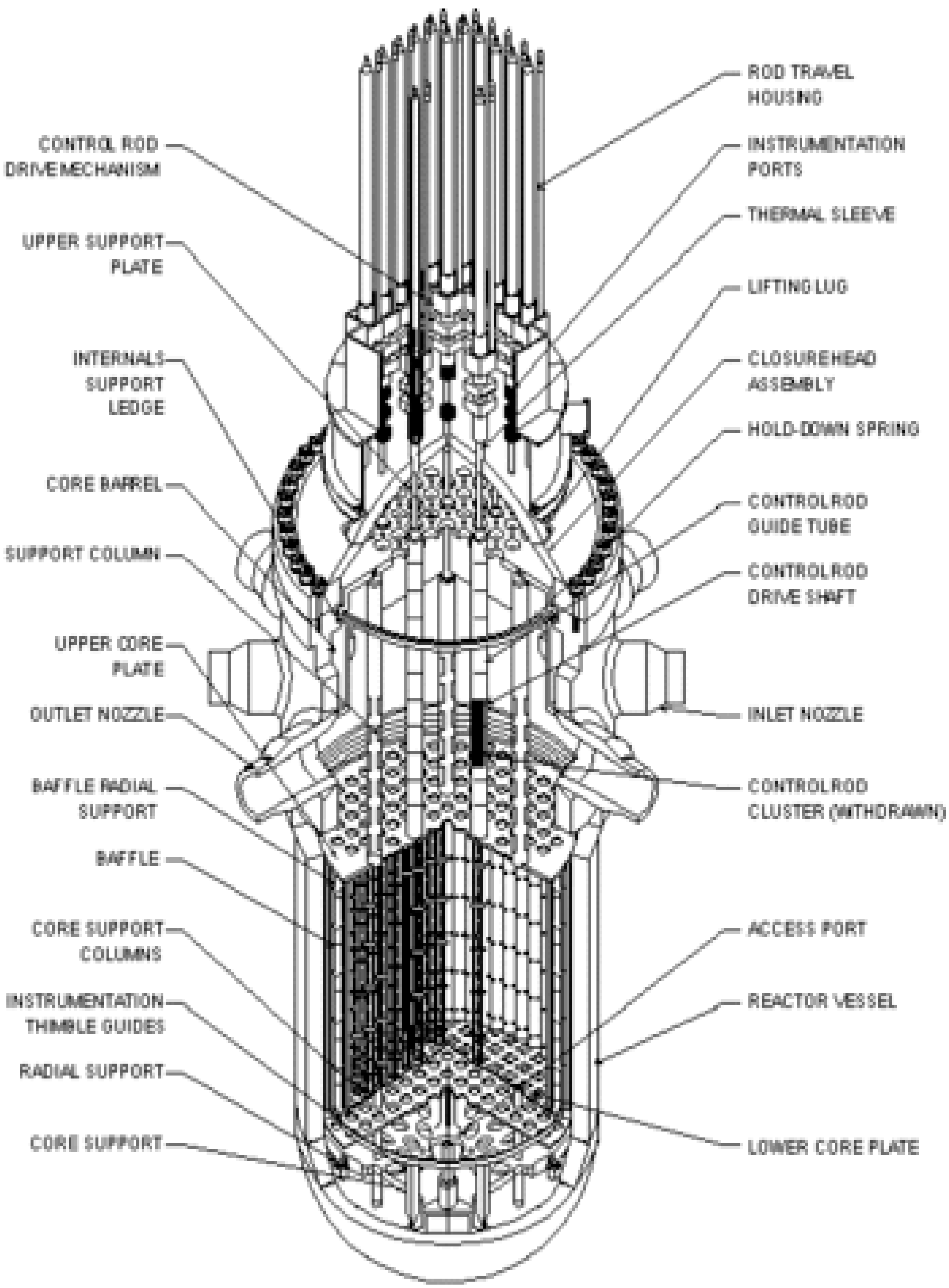
1.1.3. NUCLEAR STEAM SUPPLY SYSTEM:

Nuclear fuel in the reactor vessel is engaged in a fission chain reaction, which produces heat, heating the water in the primary coolant loop by thermal conduction through the fuel cladding. The hot primary coolant is pumped into a heat exchanger called steam generator, where heat is transferred across a set of tubes to the lower pressure secondary coolant, which evaporates to pressurized steam. The transfer of heat is accomplished without mixing the two fluids, which is desirable since the primary coolant might become radioactive.

Two things are characteristic for the **pressurized water reactor** (**PWR**) when compared with other reactor types: coolant loop separation from the steam system and pressure inside the primary coolant loop. In a **PWR**, there are two separate coolant loops (primary and secondary), which are both filled with demineralized/deionized water. The pressure in the primary coolant loop is typically 15–16 megapascals (153 atmospheres, 2,250 psig,150–160 bar), which is notably higher than in other nuclear reactors. As an effect of this, only localized boiling occurs and steam will recondense promptly in the bulk fluid.

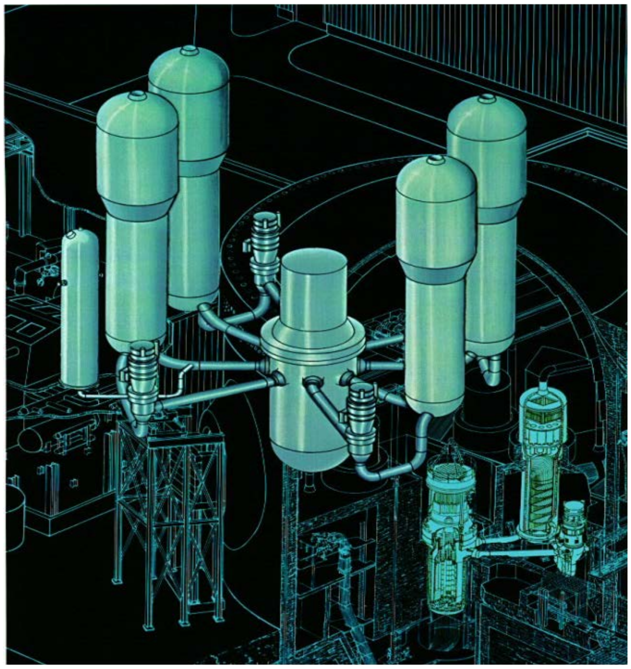
Pressure in the primary circuit is maintained by a Pressurizer, a separate vessel that is connected to the primary circuit and partially filled with water which is heated to the saturation temperature (boiling point) for the desired pressure by submerged electrical heaters. To achieve a pressure of 155 bar, the pressurizer temperature is maintained at 345 °C, which gives a sub-cooling margin (the difference between the pressurizer temperature and the highest temperature in the reactor core) of 30 °C. Thermal transients in the reactor coolant system result in large swings in pressurizer liquid volume, total pressurizer volume is designed around absorbing these transients without uncovering the heaters or emptying the pressurizer. Pressure transients in the primary coolant system manifest as temperature transients in the pressurizer and are controlled through the use of automatic heaters and water spray, which raise and lower pressurizer temperature, respectively. To achieve maximum heat transfer, the primary circuit temperature, pressure and flow rate are arranged such that subcooled nucleate boiling takes place as the coolant passes over the nuclear fuel rods.

PRESSURIZED WATER REACTOR: REACTOR PRESSURE VESSEL

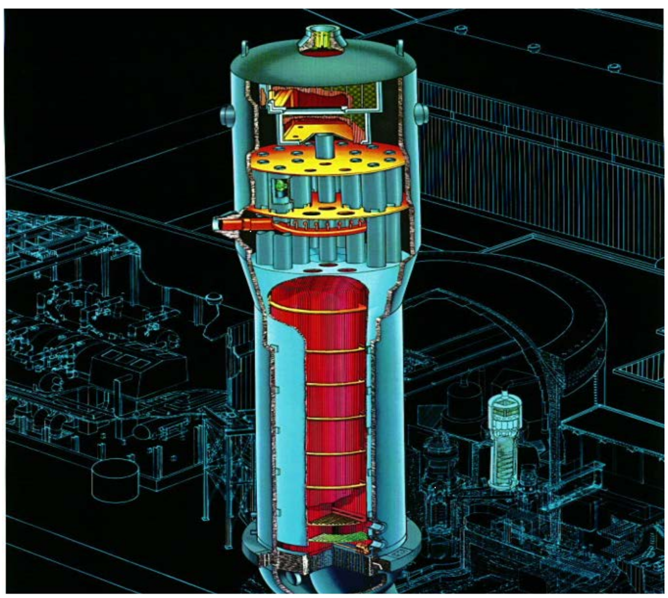


The POWER of ENGINEERING

PRESSURIZED WATER REACTOR: REACTOR PRESSURE VESSEL CONFIGURATION OF REACTOR AND STEAM GENERATORS IN PRESSURIZED WATER REACTOR



STEAM GENERTOR IN WESTINGHOUSE PRESURIZED WATER REACTOR



The coolant is pumped around the primary circuit by powerful pumps, which can consume up to 6 MW each. After picking up heat as it passes through the reactor core, the primary coolant transfers heat in a steam generator to water in a lower pressure secondary circuit, evaporating the secondary coolant to saturated steam — in most designs 6.2 MPa (60 atm, 900 psia), 275 °C (530 °F) — for use in the steam turbine. The cooled primary coolant is then returned to the reactor vessel to be heated again.

Pressurized water reactors, like all thermal reactor designs, require the fast fission neutrons to be slowed down (a process called moderation or thermalization) to interact with the nuclear fuel and sustain the chain reaction. In **PWR**s the coolant water is used as a moderator by letting the neutrons undergo multiple collisions with light hydrogen atoms in the water, losing speed in the process. This "moderating" of neutrons will happen more often when the water is denser (more collisions will occur). The use of water as a moderator is an important safety feature of PWRs, as any increase in temperature causes the water to expand and become less dense; thereby reducing the extent to which neutrons are slowed down and hence reducing the reactivity in the reactor. Therefore, if reactivity increases beyond normal, the reduced moderation of neutrons will cause the chain reaction to slow down, producing less heat. This property, known as the negative temperature coefficient of reactivity, makes PWR reactors very stable.

PWRs are designed to be maintained in an undermoderated state, meaning that there is room for increased water volume or density to further increase moderation, because if moderation were near saturation, then a reduction in density of the moderator/coolant could reduce neutron absorption significantly while reducing moderation only slightly, making the void coefficient positive. Also, light water is actually a somewhat stronger moderator of neutrons than heavy water, though heavy water's neutron absorption is much lower. Because of these two facts, light water reactors have a relatively small moderator volume and therefore have compact cores. One next generation design, the supercritical water reactor, is even less moderated. A less moderated neutron energy spectrum does worsen the capture/fission ratio for ^{235}U and especially ^{239}Pu, meaning that more fissile nuclei fail to fission on neutron absorption and instead capture the neutron to become a heavier non-fissile isotope, wasting one or more neutrons and increasing accumulation of heavy transuranic actinides, some of which have long half-lives.

In a nuclear power station, the pressurized steam is fed through a steam turbine which drives an electrical generator connected to the electric grid for distribution. After passing through the turbine the secondary coolant (water-steam mixture) is cooled down and condensed in a condenser. The condenser converts the steam to a liquid so that it can be pumped back into the steam generator, and maintains a vacuum at the turbine outlet so that the pressure drop across the turbine, and hence the energy extracted from the steam, is maximized. Before being fed into the steam generator, the condensed steam (referred to as feed-water) is sometimes preheated to minimize thermal shock.

1.1.4. CONTROL SYSTEM FOR PRESSURIZED WATER REACTOR

Reactor power is controlled via two methods: by inserting or withdrawing control rods and by adjusting the concentration of Boron (called a chemical shim) in the primary cooling circuit. Positioning (withdrawing or inserting) control rods is the normal method for controlling power when starting up a **PWR**. As control rods are withdrawn, neutron absorption decreases in the control material and increases in the fuel, so reactor power increases. As control rods are inserted, neutron absorption increases in the control material and decreases in the fuel, so reactor power decreases.

In **PWR**s reactor power can be viewed as following steam (turbine) demand due to the reactivity feedback of the temperature change caused by increased or decreased steam flow. Boron and control rods are used to maintain primary system temperature at the desired point. To decrease power, the operator throttles shut the turbine inlet valves. This results in less steam being drawn from the steam generators and causing an increase in temperature in the primary loop. Reactivity adjustment to maintain 100% power as the fuel is burned up in most commercial **PWR**s is normally achieved by varying the concentration of boric acid dissolved in the primary reactor coolant. Boron readily absorbs neutrons and increasing or decreasing its concentration in the reactor coolant will therefore affect the neutron activity correspondingly. An entire control system involving high pressure pumps (usually called the charging and letdown system) is required to remove water from the high pressure primary loop and re-inject the water back in with differing concentrations of boric acid. The reactor control rods, inserted through the reactor vessel head directly into the fuel bundles, are moved for the following reasons:

- To start up the reactor.
- To shut down the reactor.
- To accommodate short term transients such as changes to load on the turbine.

The control rods can also be used:

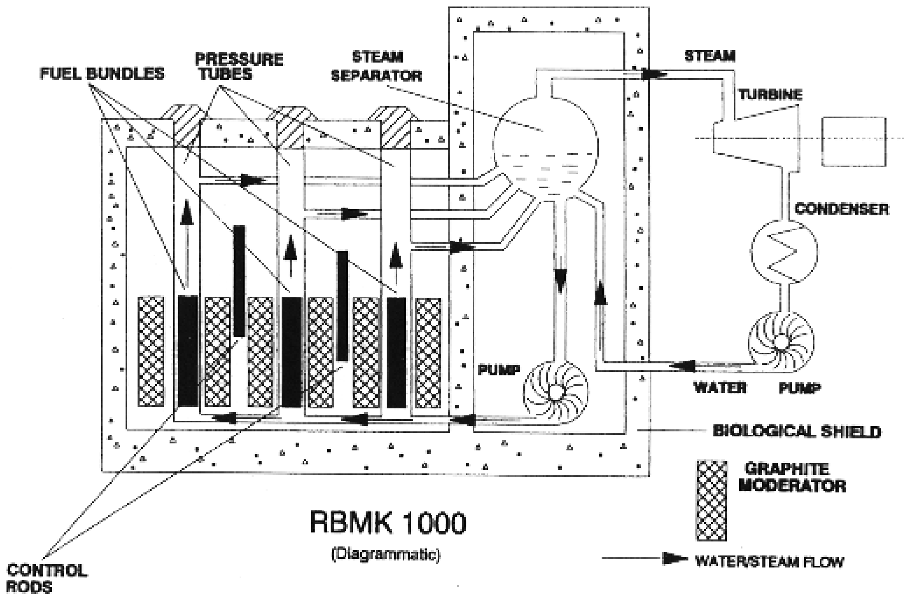
- To compensate for nuclear poison inventory.
- To compensate for nuclear fuel depletion.

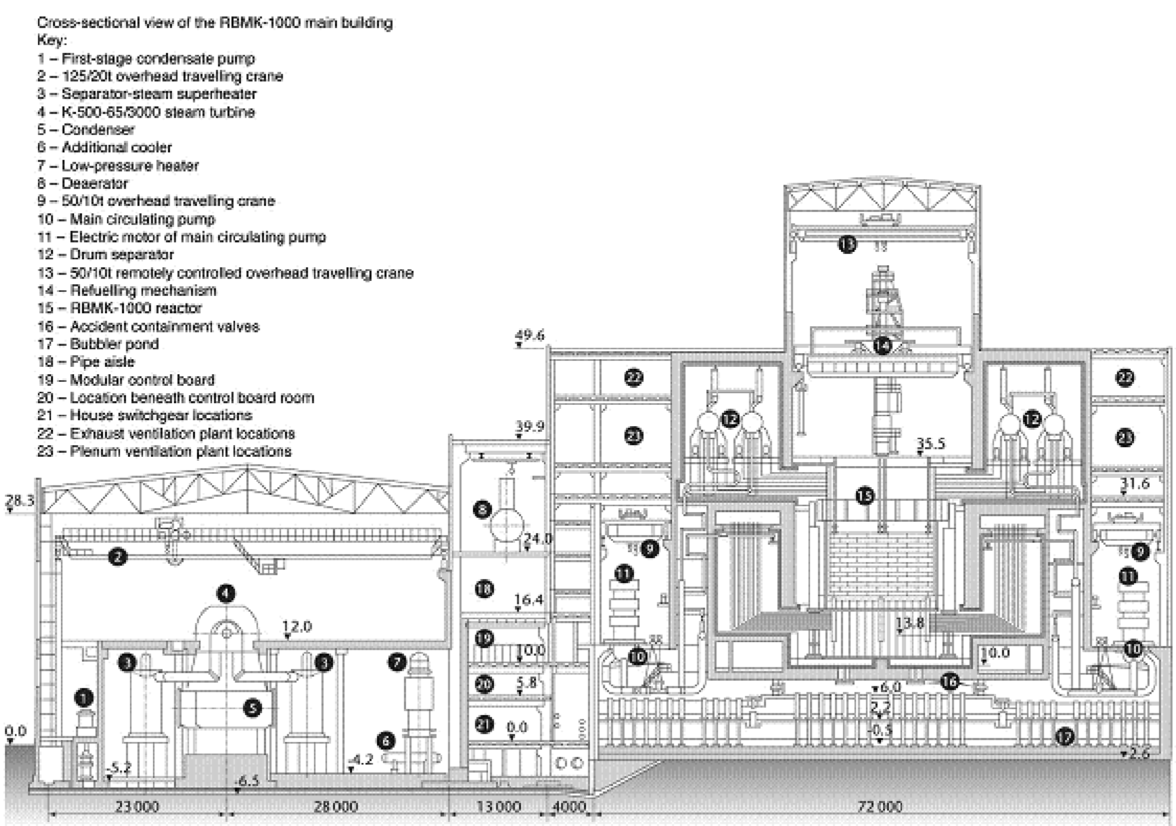
1.2. THE RBMK NUCLEAR REACTOR

The Soviet-designed RBMK (*reaktor bolshoy moshchnosty kanalny*, high-power channel reactor) is a pressurized water-cooled reactor with individual fuel channels and using graphite as its moderator. It is very different from most other power reactor designs as it derived from a design principally for plutonium production and was intended and used in Russia for both plutonium and power production.

The combination of graphite moderator and water coolant is found in no other power reactors in the world. As the Chernobyl accident showed, several of the RBMK's design characteristics – in particular, the control rod design and a positive void coefficient – were unsafe.

GRAPHIC REPRESENTATION OF THE RBMK





The RBMK is an unusual reactor design, one of two to emerge in the Soviet Union in the 1970s. The design had several shortcomings, and was the design involved in the 1986 Chernobyl disaster. Major modifications have been made to RBMK reactors still operating.

1.2.1. FEATURES OF THE RBMK

1. **Fuel:** Pellets of slightly-enriched uranium oxide are enclosed in a zircaloy tube 3.65m long, forming a fuel rod. A set of 18 fuel rods is arranged cylindrically in a carriage to form a fuel assembly. Two of these end on end occupy each pressure tube.
2. **Pressure tubes:** Within the reactor each fuel assembly is positioned in its own vertical pressure tube or channel about 7 m long. Each channel is individually cooled by pressurized water which is allowed to boil in the tube and emerges at about 290°C.
3. **Refueling**: When fuel channels are isolated, the fuel assemblies can be lifted into and out of the reactor, allowing fuel replenishment while the reactor is in operation.
4. **Graphite moderator:** A series of graphite blocks surround, and hence separate, the pressure tubes. They act as a moderator to slow down the neutrons released during fission so that a continuous fission chain reaction can be maintained. Heat conduction between the blocks is enhanced by a mixture of helium and nitrogen gas.
5. **Control rods:** Boron carbide control rods absorb neutrons to control the rate of fission. A few short rods, inserted upwards from the bottom of the core, even the distribution of power across the reactor. The main control rods are inserted from the top down and provide automatic, manual, or emergency control. The automatic rods are regulated by feedback from in-core detectors. If there is a deviation from normal operating parameters (*e.g.* increased reactor power level), the rods can be dropped into the core to reduce or stop reactor activity. A number of rods remain in the core during operation.
6. **Coolant:** Two separate water coolant loops each with four pumps circulate water through the pressure tubes to remove most of the heat from fission. There is also an emergency core cooling system designed to come into operation if either coolant circuit is interrupted.
7. **Steam separator:** Each of the two loops has two steam drums, or separators, where steam from the heated coolant is fed to the turbine to produce electricity in the generator (each loop has a turbo-generator associated with it). The steam is then condensed and fed back into the circulating coolant.
8. **Containment:** There is no secure containment in the sense accepted in the West. The reactor core is located in a reinforced concrete lined cavity that acts as a radiation shield. The core sits on a heavy steel plate, with a 1000 tonne steel cover plate on the top. The extensions of the fuel channels penetrate the lower plate and

the cover plate and are welded to each. The steam separators of the coolant systems are housed in their own concrete shields.

9. **Positive void coefficient:** The term 'positive void coefficient' is often associated with the RBMK reactors. Reactors cooled by boiling water will contain a certain amount of steam in the core. Because water is both a more efficient coolant and a more effective neutron absorber than steam, a change in the proportion of steam bubbles, or 'voids', in the coolant will result in a change in core reactivity. The ratio of these changes is termed the void coefficient of reactivity. When the void coefficient is negative, an increase in steam will lead to a decrease in reactivity. In those reactors where the same water circuit acts as both moderator and coolant, excess steam generation reduces the slowing of neutrons necessary to sustain the nuclear chain reaction. This leads to a reduction in power, and is a basic safety feature of most Western reactors. In reactor designs where the moderator and coolant are of different materials, excess steam reduces the cooling of the reactor, but as the moderator remains intact the nuclear chain reaction continues. In some of these reactors, most notably the RBMK, the neutron absorbing properties of the cooling water are a significant factor in the operating characteristics. In such cases, the reduction in neutron absorption as a result of steam production, and the consequent presence of extra free neutrons, enhances the chain reaction. This leads to an increase in the reactivity of the system. The void coefficient is only one contributor to the overall power coefficient of reactivity, but in RBMK reactors it is the dominant component, reflecting a high degree of dependence of reactivity on the steam content of the core.

   At the time of the accident at Chernobyl, the void coefficient of reactivity was so positive that it overwhelmed the other components of the power coefficient, and the power coefficient itself became positive. When the power began to increase, more steam was produced, which in turn led to an increase in power. The additional heat resulting from the increase in power raised the temperature in the cooling circuit and more steam was produced. More steam means less cooling and less neutron absorption, resulting in a rapid increase in power to around 100 times the reactor's rated capacity. The value of the void coefficient is largely determined by the configuration of the reactor core. In RBMK reactors, an important factor affecting this is the operating reactivity margin.

10. **Operating reactivity margin:** Although the definition is not precise, the operating reactivity margin (ORM) is essentially the number of 'equivalent' control rods of nominal worth remaining in the reactor core. The operators at Chernobyl seemed to believe that safety criteria would be met so long as the lower limit for the ORM of 15 equivalent rods was adhered to, regardless of the actual configuration of the core. The operators were not aware of the 'positive scram' effect where, following a scram signal, the initial entry of the control rods actually added reactivity to the lower region of the core (see section below on *Post accident changes to the RBMK*). The ORM could have an extreme effect on the void coefficient of reactivity,

as was the case for the core configuration of Chernobyl 4 in the run-up to the accident. Unacceptably large void coefficients were prevented for initial cores by increasing fuel enrichment levels, with the excess reactivity balanced by fixed absorbers. However, with increasing fuel burn-up, these absorbers could be removed to maintain the fuel irradiation levels - shifting the void coefficient in the positive direction and increasing the sensitivity of the coefficient to the extent of insertion of the control and protection rods.

1.2.2. POST ACCIDENT CHANGES TO THE RBMK

After the accident at Chernobyl, several measures were taken to improve the safety of RBMK plants. All operating RBMK reactors in the former Soviet Union had the following changes implemented to improve operating safety:

- Reduction of the void coefficient of reactivity.
- Improvement of the response efficiency of the emergency protection system.
- Introduction of calculation programs to provide an indication of the value of the **operating reactivity margin** (ORM, *i.e.* the effective number of control rods remaining in the core) in the control room.
- Prevention of the emergency safety systems from being bypassed while the reactor is operating.
- To ensure adequate sub-cooling at the core inlet, the avoidance of modes of operation that cause a reduction in the departure from nuclear boiling (DNB) ratio of the coolant at the reactor inlet.

Measures to reduce the void coefficient of reactivity were carried out by:

- The installation of 80-90 additional fixed absorbers in the core to inhibit operation at low power.
- Increasing the ORM from 26-30 rods (in steady state operational mode) to 43-48.
- An increase in fuel enrichment from 2% to 2.4%.

The increase in the number of fixed absorbers and the ORM reduced the value of the void coefficient of reactivity to +ß (where ß is the effective delayed neutron fraction). The additional absorbers require the use of higher fuel enrichment to compensate for the increased neutron absorption. The efficiency and speed of the emergency protection system was improved by implementing three independent retrofitting operations:

- Retrofitting of control rods with a design that does not give rise to water columns at the bottom of the channels.
- Scram (shut down) rod insertion time cut from 18 to 12 seconds.
- The installation of a fast-acting emergency protection (FAEP) system.

1.2.3. THE FAST-ACTING EMERGENCY PROTECTION (FAEP) SYSTEM

One of the most important post-accident changes to the RBMK was the retrofitting of the control rods. A graphite 'displacer' is attached to each end of the length of absorber of each rod (except for 12 rods used in automatic control). The lower displacer prevents coolant water from entering the space vacated as the rod is withdrawn, thus augmenting the reactivity worth of the rod. However, the dimensions of the rod and displacers were such that, with the rod fully withdrawn, the 4.5 m displacer sat centrally within the fuelled region of the core with 1.25 m of water at either end. On a scram signal, as the rod falls, the water at the lower part of the channel is replaced by the bottom of the graphite displacer, thus initially adding reactivity to the bottom part of the core. Following the Chernobyl accident, this 'positive scram' effect was mitigated by retrofitting the control rods so that, with the rods fully retracted, there would not be a region containing water at the bottom of the core.

The FAEP system was designed so that 24 emergency protection control rods would insert negative reactivity of at least 2ß in under 2.5 seconds. Tests in 1987-'88 at the Ignalina and Leningrad plants (the first RBMKs to be fitted with the new FAEP system) confirmed these characteristics.

In addition to the above changes, several further modifications have been implemented at RBMK plants. These measures consist of:

- Replacement of the fuel channels at all units (except Smolensk 3).
- Replacement of the group distribution headers and addition of check valves.
- Improvements to the emergency core cooling systems.
- Improvements of the reactor cavity over-pressure protection systems.
- Replacement of the SKALA process computer.

1.2.4. OPERATING RBMK PLANTS

There are currently 11 operating RBMKs in the world, all of which are in Russia. One more was under construction in Russia (Kursk 5), but it is unlikely to be completed. All operating RBMKs began operation between 1973 (Leningrad 1) and 1990 (Smolensk 3). There are currently three distinct generations of reactors having significant differences with respect to their safety design features:

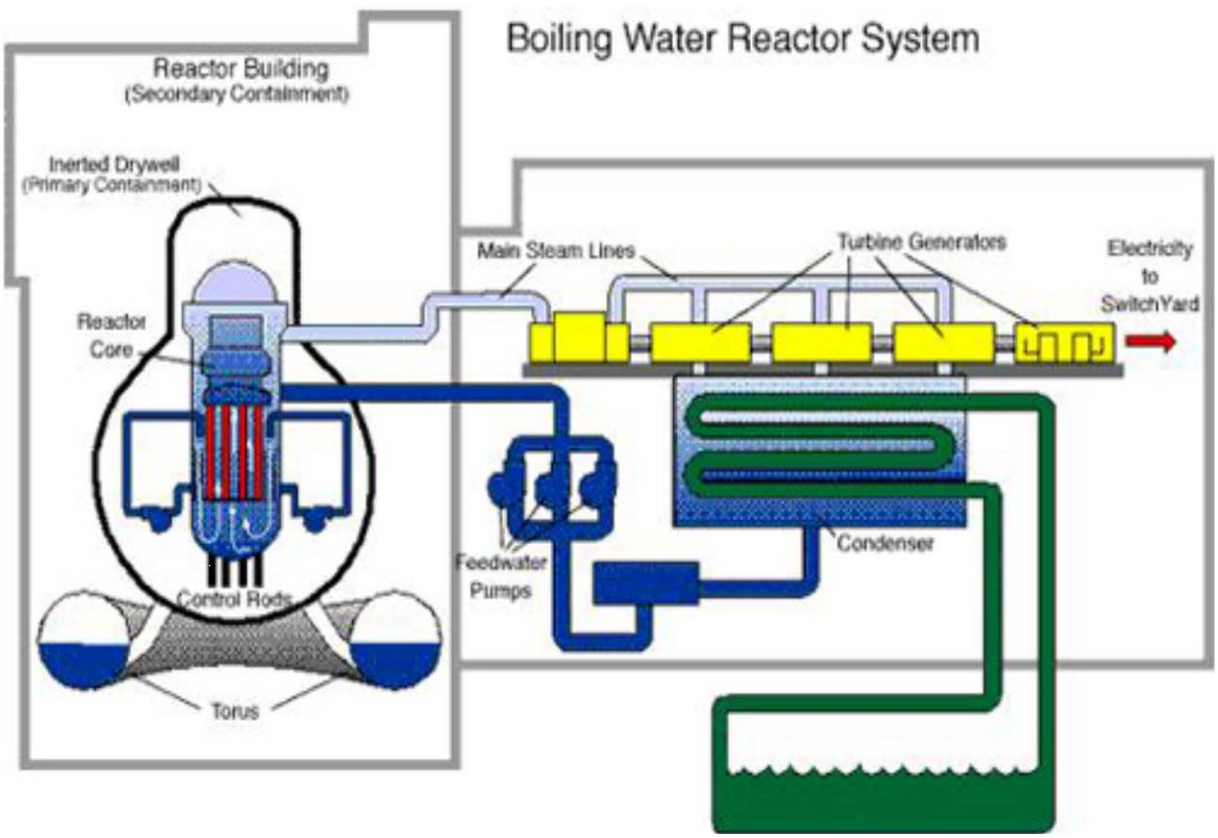
The four first-generation units are Leningrad 1 and 2, and Kursk 1 and 2. They were designed and brought on line in the early-to-mid 1970s, before new standards on the design and construction of nuclear power plants, the OPB-82 General Safety Provisions, were introduced in the Soviet Union in 1982.

Second-generation RBMKs, brought on line since the late 1970s and early 1980s include Leningrad 3 and 4; Kursk 3, and 4; Ignalina 1 (now closed); and Smolensk 1 and 2. Ignalina 2 (now closed) had safety features beyond those of other second generation units. These units conform to the OPB-82 standards.

1.3. BOILING WATER REACTOR

1.3.1. INTRODUCTION

The **Boiling Water Reactor (BWR)** uses demineralized water (light water) as a coolant and neutron moderator. Heat is produced by nuclear fission in the reactor core, and this causes the cooling water to boil, producing steam. The steam is directly used to drive a turbine, after which it is cooled in a condenser and converted back to liquid water. This water is then returned to the reactor core, completing the loop. The cooling water is maintained at about 75 atm (7.6 MPa, 1000-1100 psi) so that it boils in the core at about 285°C (550°F). In comparison, there is no significant boiling allowed in a **PWR** because of the high pressure maintained in its primary loop - approximately 158 atm (16 MPa, 2300 psi). The nuclear event in Fukushima, Japan occurred in a General Electric Mark I Nuclear Power Plant



BOILING WATER REACTOR SCHEMATIC

1.3.2. BOILING WATER REACTOR OPERATIONS

1. The reactor core transfers the fission energy, primarily kinetic energy created by recoil of the fission fragments in the fuel rods into thermal energy of the water which is both the moderator and the cooling agent in a Light Water Reactor.
2. A steam-water mixture is produced when very pure water (reactor coolant) move upward through the core absorbing heat.
3. The steam-water mixture leaves the top of the core and enters the two stages of water seperation where the water droplets are removed and the steam is dried before entering the steam lines.
4. The steam line directs the steam to the main turbine causing it to turn the turbine which is connected to the generator to create electrical power.
5. The unused steam is condensed into water.
6. The resulting water is pumped out of the condenser with a series of pumps, reheated and pumped back to the reactor vessel.
7. The reactor's core contains fuel assemblies which are cooled by water, which is force-circulated by electrically powered pumps.
8. Emergency cooling water is supplied by other water sources which can be powered by onsite diesel generators.

1.3.3. NUCLEAR STEAM SUPPLY SYSTEM

Steam exiting from the turbine flows into condensers located underneath the low pressure turbines where the steam is cooled and returned to the liquid state (condensate). The condensate is then pumped through feedwater heaters that raise its temperature using extraction steam from various turbine stages. Feedwater from the feedwater heaters enters the reactor pressure vessel (RPV) through nozzles high on the vessel, well above the top of the nuclear fuel assemblies (these nuclear fuel assemblies constitute the "core") but below the water level.

The feedwater enters into the downcomer region and combines with water exiting the water separators. The feedwater subcools the saturated water from the steam separators. This water now flows down the downcomer region, which is separated from the core by a tall shroud. The water then goes through either jet pumps or internal recirculation pumps that provide additional pumping power (hydraulic head). The water now makes a 180 degree turn and moves up through the lower core plate into the nuclear core where the fuel elements heat the water. Water exiting the fuel channels at the top guide is about 12 to 15% saturated steam (by mass), typical core flow may be 45,000,000 kg/hr (100,000,000 lb/hr) with 6,500,000 kg/hr (14,500,000 lb/hr) steam flow. However, core-average void fraction is a significantly higher fraction (~40%). These sort of values may be found in each plant's publicly available Technical Specifications, Final Safety Analysis Report, or Core Operating Limits Report.

The heating from the core creates a thermal head that assists the recirculation pumps in recirculating the water inside of the RPV. A BWR can be designed with no recirculation pumps and rely entirely on the thermal head to recirculate the water inside of the RPV.

The forced recirculation head from the recirculation pumps is very useful in controlling power, however. The thermal power level is easily varied by simply increasing or decreasing the forced recirculation flow through the recirculation pumps.

The two phase fluid (water and steam) above the core enters the riser area, which is the upper region contained inside of the shroud. At the top of the riser area is the water separator. By swirling the two phase flow in cyclone separators, the steam is separated and rises upwards towards the steam dryer while the water remains behind and flows horizontally out into the downcomer region. In the downcomer region, it combines with the feedwater flow and the cycle repeats. The saturated steam that rises above the separator is dried by a chevron dryer structure. The steam then exits the RPV through four main steam lines and goes to the turbine.

1.3.4. CONTROL SYSTEM

Reactor power is controlled via two methods: by inserting or withdrawing control rods and by changing the water flow through the reactor core. Positioning (withdrawing or inserting) control rods is the normal method for controlling power when starting up a BWR. As control rods are withdrawn, neutron absorption decreases in the control material and increases in the fuel, so reactor power increases. As control rods are inserted, neutron absorption increases in the control material and decreases in the fuel, so reactor power decreases. Some early BWRs and the proposed ESBWR (Economic Simplified BWR made by General Electric Hitachi) designs use only natural circulation with control rod positioning to control power from zero to 100% because they do not have reactor recirculation systems. Fine reactivity adjustment would be accomplished by modulating the recirculation flow of the reactor vessel.

Changing (increasing or decreasing) the flow of water through the core is the normal and convenient method for controlling power. When operating on the so-called "100% rod line," power may be varied from approximately 30% to 100% of rated power by changing the reactor recirculation system flow by varying the speed of the recirculation pumps. As flow of water through the core is increased, steam bubbles ("voids") are more quickly removed from the core, the amount of liquid water in the core increases, neutron moderation increases, more neutrons are slowed down to be absorbed by the fuel, and reactor power increases. As flow of water through the core is decreased, steam voids remain longer in the core, the amount of liquid water in the core decreases, neutron moderation decreases, fewer neutrons are slowed down to be absorbed by the fuel, and reactor power decreases.

1.3.5. POWER PRODUCTION CAPACITY

a. **Steam Turbines:** Steam produced in the reactor core passes through steam separators and dryer plates above the core and then directly to the turbine, which is part of the reactor circuit. Because the water around the core of a reactor is always contaminated with traces of radionuclides, the turbine must be shielded during normal operation, and radiological protection must be provided during maintenance. The increased cost related to operation and maintenance of a BWR tends to balance the savings due to the simpler design and greater thermal efficiency of a BWR when compared with a PWR. Most of the radioactivity in the water is very short-lived (mostly N-16, with a 7-second half-life), so the turbine hall can be entered soon after the reactor is shut down.

b. Size: A modern BWR fuel assembly comprises 74 to 100 fuel rods, and there are up to approximately 800 assemblies in a reactor core, holding up to approximately 140 tons of uranium.

1.3.6. PLANT AND REACTOR SAFETY SYSTEMS

a. Safety Systems: Like the pressurized water reactor, the BWR reactor core continues to produce heat from radioactive decay after the fission reactions have stopped, making a core damage incident possible in the event that all safety systems have failed and the core does not receive coolant. Also like the pressurized water reactor, a boiling water reactor has a negative void coefficient, that is, the neutron (and the thermal) output of the reactor decreases as the proportion of steam to liquid water increases inside the reactor. However, unlike a pressurized water reactor which contains no steam in the reactor core, a sudden increase in BWR steam pressure (caused, for example, by the actuation of the main steam isolation valve (MSIV) from the reactor) will result in a sudden decrease in the proportion of steam to liquid water inside the reactor. The increased ratio of water to steam will lead to increased neutron moderation, which in turn will cause an increase in the power output of the reactor. This type of event is referred to as a "pressure transient".

The BWR is specifically designed to respond to pressure transients, having a "pressure suppression" type of design which vents overpressure using safety relief valves to below the surface of a pool of liquid water within the containment, known as the "wetwell" or "torus". There are 11 safety overpressure relief valves on BWR/1-BWR/6 models (7 of which are part of the ADS) and 18 safety overpressure relief valves on ABWR models, only a few of which have to function to stop the pressure rise of a transient. In addition, the reactor will already have rapidly shut down before the transient affects the RPV.

Because of this effect in BWRs, operating components and safety systems are designed to ensure that no credible scenario can cause a pressure and power increase that exceeds the systems' capability to quickly shutdown the reactor before damage to the fuel or to components containing the reactor coolant can occur. In the limiting case of an ATWS derangement, high neutron power levels (~ 200%) can occur for less than a second, after which actuation of SRVs will cause the pressure to rapidly drop off. Neutronic power will fall to far below nominal power (the range of 30% with the cessation of circulation, and thus, void clearance) even before ARI or SLCS actuation occurs. Thermal power will be barely affected.

b. Reactor Core Isolation Cooling System (RCIC): The Reactor Core Isolation Cooling System is not a safety-related system proper, but is included because it can help cool the reactor in the event of a contingency, and it has additional functionality in advanced versions of the BWR. RCIC is designed to remove the residual heat of the fuel from the reactor once it has been shut down. It injects approximately 2,000 L/min (600 gpm) into the reactor core for this purpose, at high pressure. It also takes less time to start than the HPCI system, approximately 5 seconds from an initiating signal.

c. **Containment system:** The ultimate safety system inside and outside of every BWR are the numerous levels of physical shielding that both protect the reactor from the outside world and protect the outside world from the reactor. There are five levels of shielding:

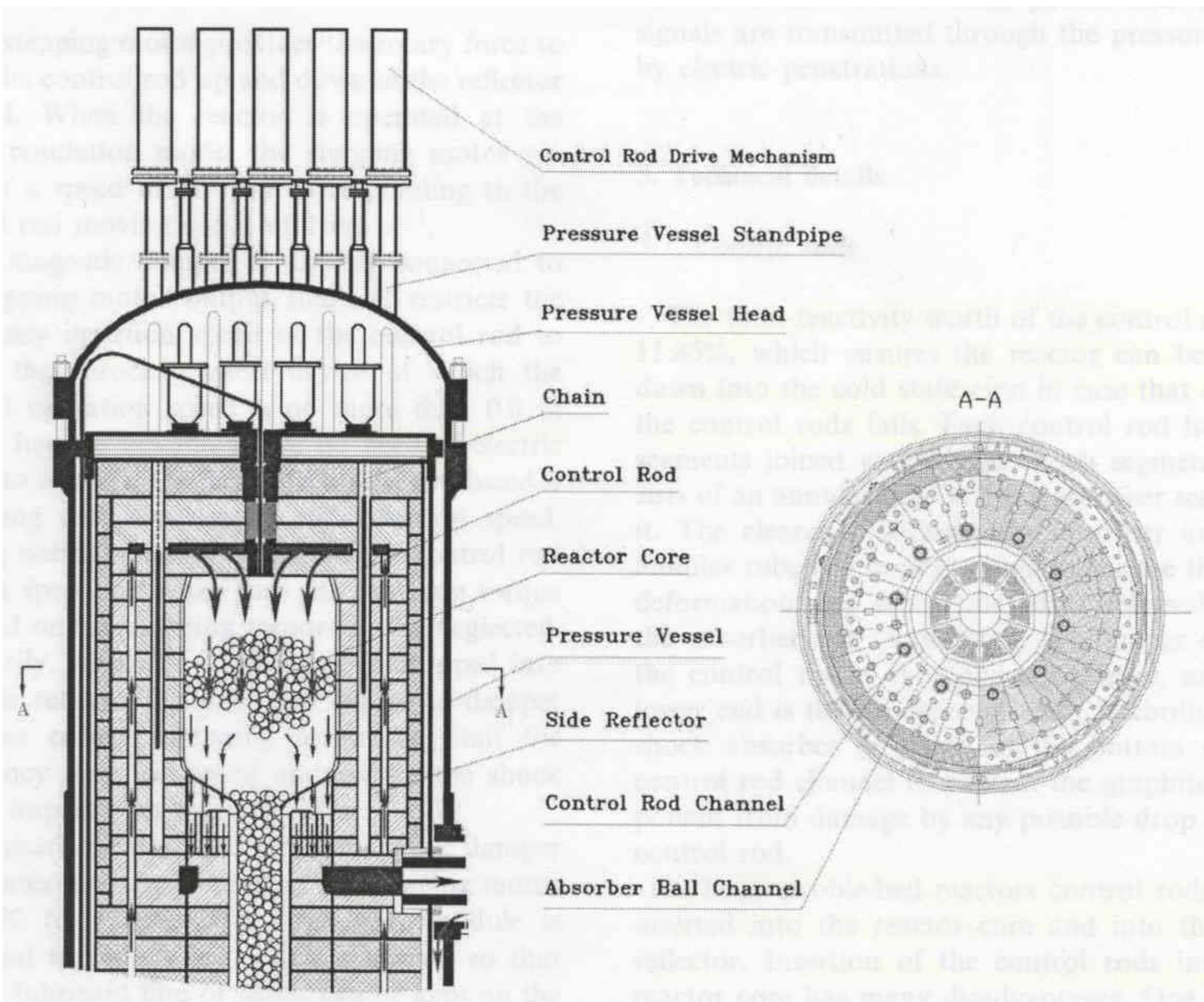
1. The fuel rods inside the reactor pressure vessel are coated in thick Zircalloy shielding;
2. The reactor pressure vessel itself is manufactured out of 6 inch thick steel, with extremely temperature, vibration, and corrosion resistant surgical stainless steel grade grade 316L plate on both the inside and outside;
3. The primary containment structure is made of steel 1 inch thick;
4. The secondary containment structure is made of steel-reinforced, pre-stressed concrete 1.2 - 2.4 meters (4 – 8 feet) thick.
5. The reactor building (the shield wall/missile shield) is also made of steel-reinforced, pre-stressed concrete .3 m to 1 m (1 – 3 feet) thick.

If every possible measure standing between safe operation and core damage fails, the containment can be sealed indefinitely, and it will prevent any substantial release of radiation to the environment from occurring in nearly any circumstance.

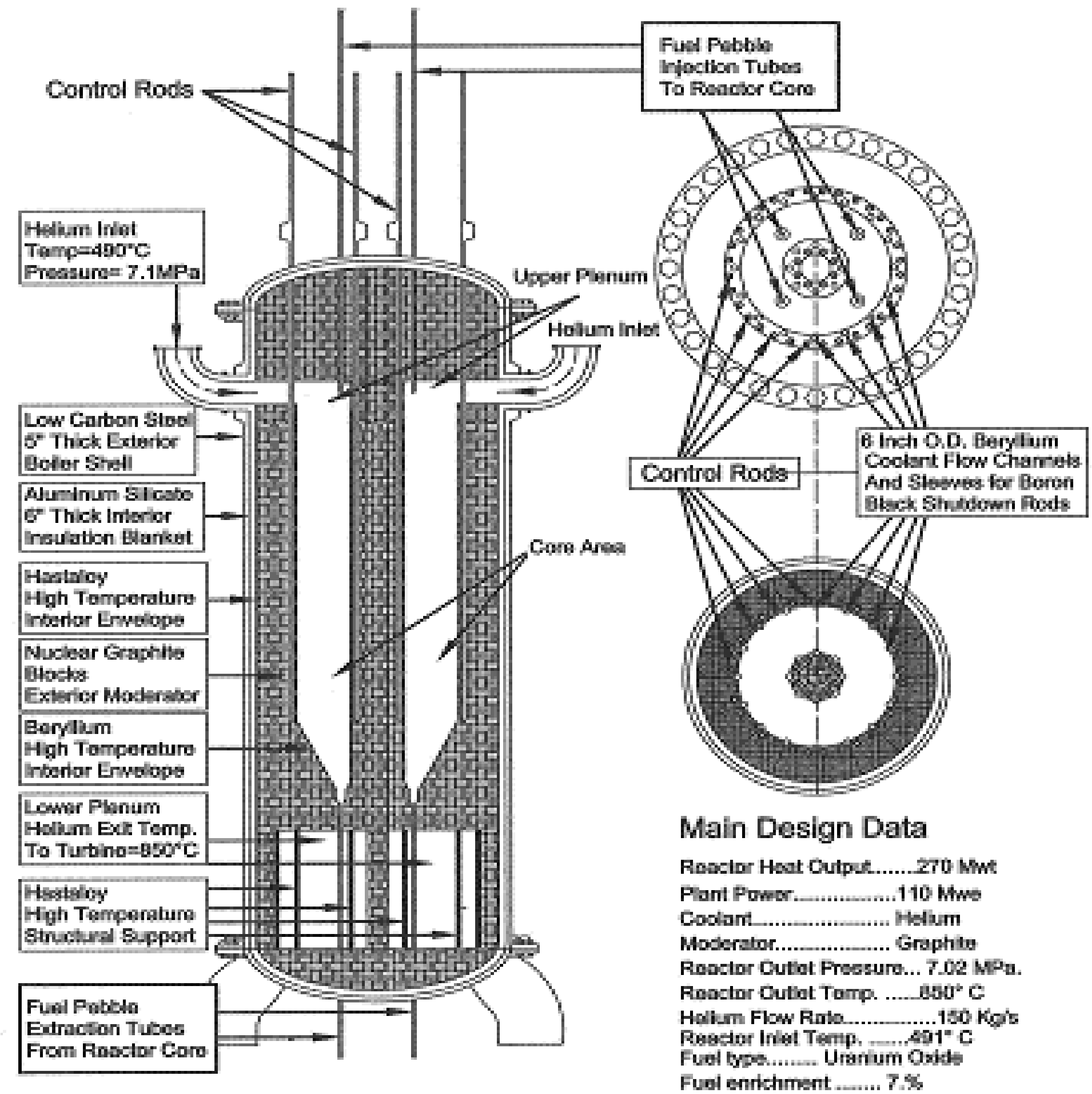
1.4. THE NUCLEAR TECHNOLOGY PEBBLE BED REACTOR

THE NTPBMR SOLUTION: The Nuclear Technology Pebble Bed Modular Reactor (**NTPBMR**) offers a future for the existing nuclear power plants. The **NTPBMR** is the only nuclear technology which can be used to replace the production capacity of an existing Nuclear Power Plant without increasing the diameter of its evacuation zone. They are gas-cooled, small, modular, inherently safe, flexible in design and operation, use a demonstrated nuclear technology and as the prices of natural gas increases, will become competitive with natural gas-fired turbine generators.

CROSS-SECTION OF CHINESE PEBBLE-BED REACTOR



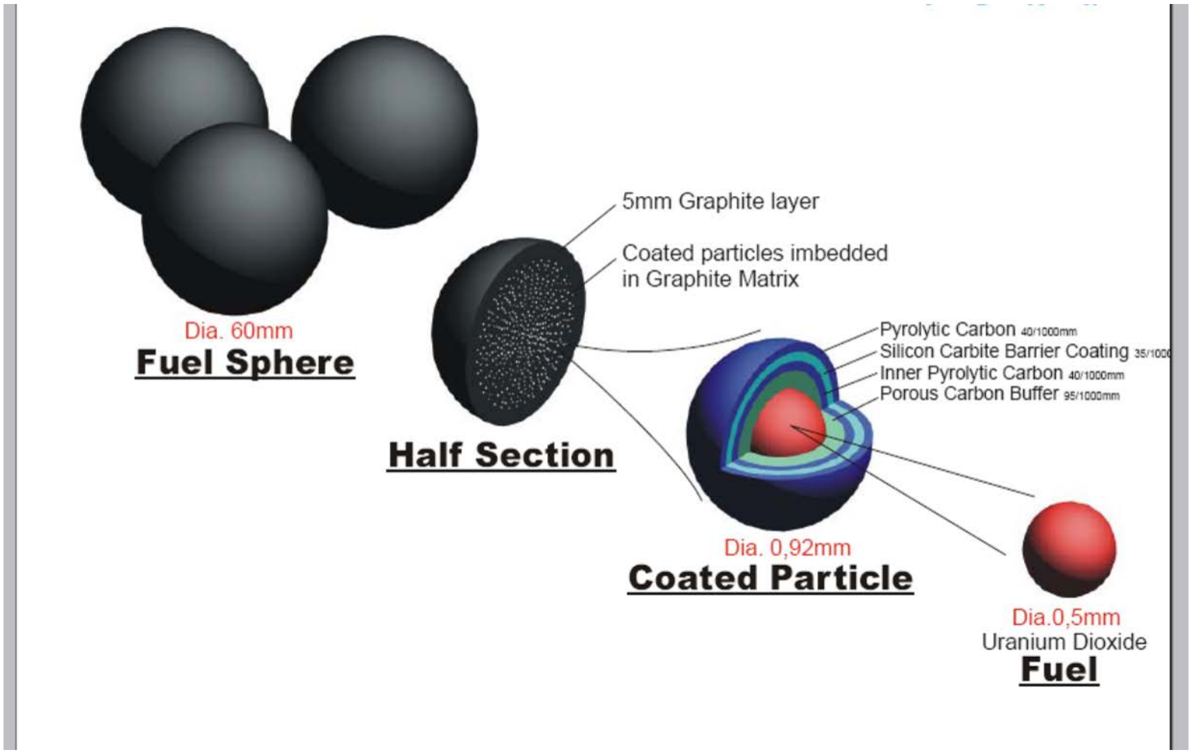
Nuclear Technology
Pebble Bed Modular Reactor
Preliminary Cross Section



The **NTPBMR** technology consists of extensions and refinements of very well documented and successfully operated, helium cooled reactors which were built by the Germans in the 1970's and 1980's.

1.4.1. THE FUEL ELEMENT

The fuel element is a completely ceramic pebble containing low enriched Uranium Oxide (**UO_2**) as fuel.



Each individual **NTPBMR** reactor modules will be engineered and licensed as a process with all the major systems and sub-systems of the power plant fabricated in an off-site manufacturing facility. In addition each process involving a system or a sub-system will be manufactured under a set of code standards registered with the **NRC,** International Standards Organization (**ISO)**, International Atomic Energy Agency (**IAEA**).

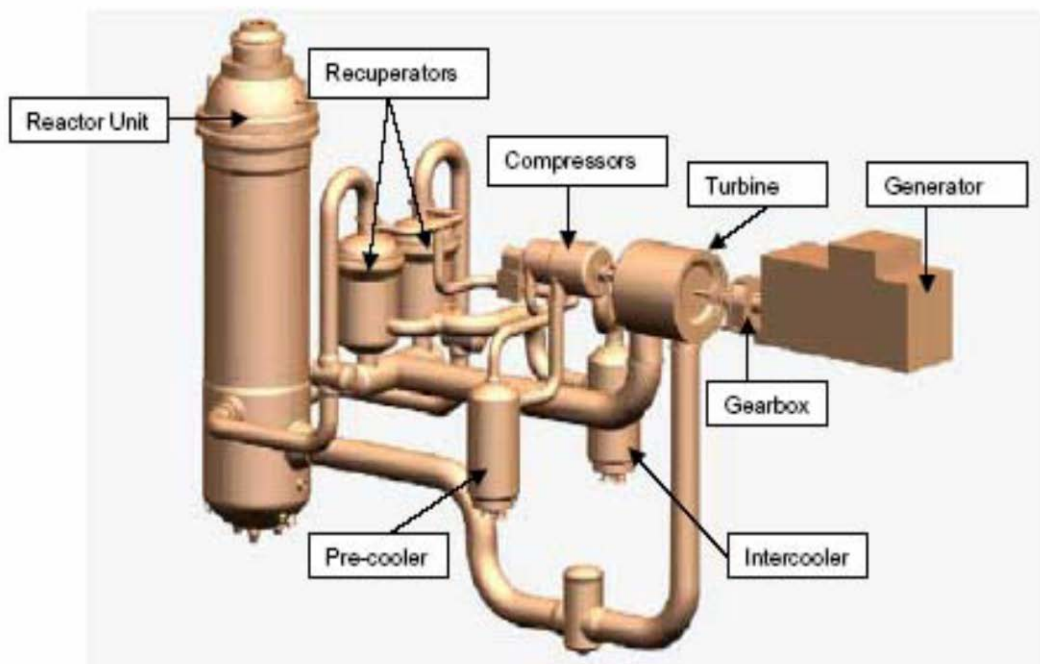
- A Nuclear reactor using gas as the core coolant will eliminate completely the types of problem which occurred at Three Mile Island and Chernobyl and Fukushima in their Water-cooled Nuclear Reactor.
- Advances in gas turbine technologies will allow us to use helium as the coolant. Helium is an ideal cooling agent for a Nuclear reactor since it is completely inert chemically and its neutron absorption cross-sections are quite low.
- The reactor core contains approximately 360,000 uranium fueled pebbles about the size of tennis balls. Each pebble contains about 9 grams of low enriched Uranium Oxide (**UO_2**) in 10,000 to 15,000 (depending on the design) tiny grains of sand-like micro-sphere coated particles each with its own hard silicon carbide shell.

- The particle fuel consists of a spherical kernel of fissile or fertile fuel material encapsulated in multiple coating layers. The multiple coating layers form a miniature, highly corrosion resistant pressure vessel and an essentially impermeable barrier to release of gaseous and metallic fission products. This capability has been demonstrated at temperatures in excess of those that are predicted to be achieved under worst-case accident conditions.
- The micro-spheres are tri-coated with coatings of pyrolytic carbon and silicon carbide. The pyrolytic carbon layer absorbs the fission fragments and the Silicon Carbide coating retains these fission fragments and radioactive gasses within the micro-sphere. These micro-spheres are embedded in a graphite matrix material.
- The Uranium Oxide (**UO_2**) fuel has a melting temperature of approximately 2800^{o}C while the ceramic coating does not have a melting point and begins to degrade approximately at 2100^{o}C, and the degradation of the ceramic shell in the 50 or so hours required to empty the reactor would require temperatures in excess of 4000^{o}C. The temperature buildup in the core of the reactor in the event of a **Loss of Coolant** is not expected to exceed 1600^{o}C
- Another unique feature of pebble bed reactors is the online refueling capability in which the pebbles are re-circulated with checks on integrity and consumption of uranium. This system allows new fuel to be inserted during operation and used or damaged fuel to be discharged and stored on site for the life of the plant.
- The online refueling capability allows for the extraction of all the nuclear fuel in the event of a **LOCA.** Extraction of all the nuclear elements in the core will mitigate the possibility of melting the fuel pebbles. The tubes into which the fuel spheres are extracted are part of the internal storage of spent fuel.
- The comparatively small size and the lack of complexity in the design of a pebble-bed reactor adds to their economic feasibility. Each power module will produce approximately 100-120 megawatts (electric).
- The simplicity of design of our power plant is dramatic. These units will have only two dozen major plant subsystems which we believe can all be plant manufactured, licensed separately and moved to the proposed nuclear site.

The **NTPBMR** modules are designed to produce 100-120MWe each. To place this in context a 100Mwe generator would produce the electricity consumed by 30,000 average homes. A single **NTPBMR** module would consist typically of a single main building, covering an area of approximately 13,000 square feet (130 x 100 feet). The height of the building would be approximately 120 feet. The majority of the structure will be below ground level. The part of the building that would be visible above ground is equivalent to a four story building. There would be a unit control room, a high voltage switch yard, and a cooling tower for inland facilities. More than one **NTPBMR** module can be located on an existing licensed site.

The Nuclear Helium Supply System: Helium gas is used as the core coolant. Helium has a very small cross-section for neutron absorption, is inert and operating in a closed-loop, brayton cycle, single phase thermodynamic cycle which can power a turbine with high cycle efficiency.

ISOMETRIC VIEW OF THE PEBBLE BED MODULAR REACTOR



1.4.2. THE THERMODYNAMIC CYCLE OF THE NTPBMR

1. Fission in the Triso-coated microspheres creates kinetic energy through the recoil of the Uranium atoms which are split by the injection of thermal neutrons.
2. The kinetic energy of recoil is transformed into thermal energy in the microspheres.
3. The thermal energy of the microsphere diffuses throughout the pebble and is transferred to the Helium Coolant by convective heat transfer.
4. The high pressure and high temperature helium is directed into the high pressure turbine. The high pressure turbine operates the compressors for the return of the helium to the reactor pressure vessel.
5. The helium is then directed to the low pressure turbine which operates the generator.

6. The helium is then cooled through a heat exchanger and the residual heat is exhausted to the atmosphere through an air powered radiator very much like an air conditioning unit on a house.

7. The cooled and compressed helium then re-enters the reactor pressure vessel.

1.4.3. UNIQUE CHARACTERISTICS OF THE NTPBMR TECHNOLOGY

A. On-line refueling capability: A unique feature of pebble bed reactors is the online refueling capability in which the pebbles are re-circulated with checks on integrity and consumption of uranium. This system allows new fuel to be inserted during operation and used or damaged fuel to be discharged and stored on site for the life of the plant.

The online refueling capability allows for the extraction of all the nuclear fuel in the event of a **LOCA.** Extraction of all the nuclear elements in the core will mitigate the melting of the fuel pebbles.

The online refueling capability allows for the insertion of graphite pebbles into the core as the extraction of all the nuclear fuel occurs in the event of a **LOCA.** The insertion of the graphite pebbles will increase the thermal mass of the core and thereby reduce the in-core temperature.

B. Graphite Moderator: The moderating environment of the **NTPBMR** is nuclear graphite. The **Reactor Pressure Vessel (RPV)** will house several hundred tons of Nuclear Graphite. The Nuclear graphite has high thermal mass and will allow for passive cooling of the reactor core in the loss of coolant event.

C. Solid Graphite Central Core: The moderating environment of the **NTPBMR** is will be greatly enhanced by the presence of a solid central core. The graphite central core will also be used to position the central control rod. This will greatly enhance the control ability of the **NTPBMR**.

D. Carbon Dioxide Emergency Core Fire Suppression System (ECFSS): The **ECFSS** is liquefied carbon dioxide. The carbon dioxide fire suppression system will mitigate the risk of a graphite fire of the type which occurred at Windscale, in England, in the early days of the English gas-cooled Magnox program. The carbon dioxide will also act as a passive emergency core cooling system to extract heat from the core.

D. Modular Design: The **NTPBMR** is modular in design and the comparatively small size and the lack of complexity in the design of the reactor adds to their economic feasibility. Each power module will produce approximately 110 megawatts (electric), with the use of two 55 MWe cooling loops.

The simplicity of design of our power plant is dramatic. These units will have only two dozen major plant subsystems which we believe can all be plant manufactured, licensed separately and moved to the proposed nuclear site. .

Each power module will produce approximately 110 megawatts electric, with the use of two 55 MWe cooling loops operating two closed loop brayton cycle gas turbines. The modules can easily be configured, in an energy park to produce up to 1.10 Gigawatts electrical power.

The technology can also be scaled down to 55 megawatts by employing only one leg of the Helium cooling system.

These reactor modules can be place in remote areas and connected to each other by the installation of smart, composite transmission lines to create a power grid or connect to an existing grid which need an increase in production capacity.

E. **Safety Characteristics:** The **NTPBMR** has the highest level of safety available in a Nuclear Power Plant. Its safety is a result of the design, the materials used and the physical processes rather than engineered safety systems. The peak temperature that can be reached in the reactor core (1,600 degrees Centigrade under the most severe conditions) is far below any sustained temperature (2,000 degrees Centigrade) that will damage the fuel elements.

F. **Economic Benefits:** The **NTPBMR** modules will all be built in a factory. This will allow the Company to capture the cost curve in the construction of Nuclear Power facilities, where the stakeholders have an equity position in the manufacturing of the components of the modules of the power plants. The Company's goal is to be able to design and build a Nuclear power Plant for less than $2000.00 per KW of electrical production.

SECTION TWO: NUCLEAR POWER AND RADIATION DOSES

2.1. PUBLIC CONCERN ABOUT NUCLEAR POWER:

The safety of nuclear power stations is a matter of considerable public concern. Past accidents such as the March 11, 2011 tsunami initiated nuclear event which occurred at the **Fukushima Daiichi Nuclear Power Facility,** the 1986 explosion of the reactor at Chernobyl in the Soviet Union and the 1979 accident at Three Mile Island (TMI) in the United States have contributed greatly to public fears (while also providing numerous lessons to the nuclear industry and its regulators that should lead to safety improvements at nuclear facilities). Public consciousness of the risk from nuclear power and associated activities appears to be much higher than for similar activities that pose comparable risks.

The reason for this is a subject of long-standing debate; one reason could be a mental association of nuclear power with nuclear weapons. (In this regard, it is important to note that a nuclear explosion such as that which occurs in an atomic bomb cannot occur in a nuclear power plant because, a nuclear power plant contains neither the necessary type nor configuration of nuclear materials.) Another reason could be fear of the invisible risk posed by radiation, and the involuntary nature of the risk.

Regardless of the specific reasons for public fears of nuclear power and for higher aversion of nuclear than other hazardous industrial activities, it is clear that continued use of nuclear power in developed and developing countries, and the prospects of its further development, requires not only firm assurance that technical and institutional measures will be effective in protecting public health and safety but also that public confidence and broad political support can be obtained. The technical complexity of nuclear power technology is one barrier to public understanding, making it difficult for many members of the public to evaluate safety questions for themselves.

This analysis does not address the question of public acceptance of Nuclear Power Production directly but rather seeks to characterize its health and safety risks, describe safety technology and regulations, and place the risk in perspective, so as to provide an adequate defense for the future use of Nuclear Power to produce electricity.

2.2. THE NATURE OF RADIATION:

To assist the reader in understanding portions of this analysis dealing with radiation exposure, risks and consequences, a comprehensive discussion of the nature of radiation and some of the units of radiation exposure and radioactivity is presented here. It is important to clarify the difference between "radioactive materials" and "radiation." In this context, radiation refers to the energy emitted from radioactive materials in the form of waves or particles as such materials decay due to instabilities within the atom.

Radioactive materials that are routinely emitted from nuclear power plants into air and water or that could be emitted in an accident may be ingested or inhaled by humans, after which they will continue to decay and thus cause a radiation dose to be delivered to the exposed person. Various pathways for such internal consumption of radioactive material are the principal concern with respect to limiting radiation doses from nuclear power plants.

The actual direct emanation of radiation from a nuclear power plant -- radiation "shine" - - is limited to the close proximity of the reactor itself and is of little concern to the general public living in the vicinity of the plant, although it is the principal concern with respect to personnel working at the plant (occupational exposure).

The radiation dose received by a nuclear power plant worker or a member of the public in the vicinity of a plant is measured in terms of the amount of energy deposited by the radiation in live tissue. The "rem" is one of the standard units for measuring radiation dose and is the unit used throughout this report.

Rem (Roentgen Equivalent Man): The acronym for roentgen equivalent man is a standard unit that measures the effects of ionizing radiation on humans. The dose equivalent in rems is equal to the absorbed dose in rads multiplied by the quality factor of the type of radiation (see 10 CFR 20.1004).

Röntgen or **roentgen (R):** Unit of exposure measuring the ionizing ability of g radiation; one röntgen produces one electric charge (1.6×10^{-19} Coulombs) per 10^6 m^3 of dry air at 0° C and atmospheric pressure. This corresponds to an energy loss of 0.0877 joule per kilogram in air. The röntgen is no longer accepted for use with the International System.

Another important measure of radiation dose is the collective dose, which expresses radiation dose integrated over the population.

Collective Dose: The sum of the individual doses received in a given period by a specified population from exposure to a specified source of radiation.

Collective dose may be expressed in units of person-rem. As an example of the relationship between individual dose and collective dose, an exposure which causes 10 individuals to receive a dose of 1 rem each would produce a collective dose of 10 person-rem.

Finally. radioactivity is measured in terms of the number of radioactive emissions (or disintegrations) from a given quantity of material per unit time. The standard unit for measuring quantities of radioactivity that is used in this report is the curie.

Curie (Ci): The basic unit used to describe the intensity of radioactivity in a sample of material. The curie is equal to 37 billion (3.7×10^{10}) disintegrations per second, which is approximately the activity of 1 gram of radium. A curie is also a quantity of any radionuclide that decays at a rate of 37 billion disintegrations per second. It is named for Marie and Pierre Curie, who discovered radium in 1898. This unit is no longer recognized as part of the International System of units. It has been replaced by the becquerel.

Becquerel (Bq): Unit of activity in the International System–one disintegration per second; 1 Bq = 27 pCi. The unit of radioactive decay equal to 1 disintegration per second. 37 billion (3.7×10^{10}) becquerels = 1 curie (Ci).

Each radioisotope has its own characteristic rate at which it "decays" as a result of these emissions. The time required for any given radioisotope to decrease to one half of its initial quantity is a measure of the speed with which the radioisotope undergoes radioactive transformation. This period of time is known as the half-life and is characteristic of that particular radioisotope. Materials which decay slowly -- i.e., that have a long half-life -- are thus less radioactive than materials that have a short half-life. Half-lives vary tremendously, from microseconds to billions of years. For example, krypton-90 has a half-life of 33 seconds, whereas the half-life of potassium-40 (which is naturally present in food, e.g. orange juice) is 1.3 billion years.

2.3. NATURAL BACKGROUND RADIATION

The most significant sources of radiation to which humans are routinely exposed exist naturally in the environment. These include cosmic rays; radiation emanating from the ground and building materials and from radon gas and its decay products; and radio-elements in food and in the body.

Radon (Rn): A radioactive element that is one of the heaviest gases known. Its atomic number is 86. It is a daughter of radium.

As a benchmark, the **United States National Council on Radiation Protection and Measurements** (**NCRP**) estimates that the average American receives from these natural background sources of radiation a dose of roughly 300 millirem/year (i.e., 0.3 rem/year), 200 millirem of which is the result of radon gas and its decay products.

Actual individual doses due to natural background sources of radiation vary over a wide range depending on each person's place of residence and activities, which determine the exposure to these sources. For example, a person living in Colorado might receive an additional 100 millirem/year mainly because of the high altitude and the resulting higher levels of natural cosmic radiation. Similarly, a person taking a coast-to-coast airplane flight in the US would receive a dose of about 5 millirem due to cosmic radiation. Natural background radiation levels depend not only on variations in cosmic radiation with altitude, but also on variations in terrestrial radiation levels from different rock types.

Medical and dental radiation exposure brings the average person's radiation dose up significantly. The **NCRP** estimates a US average annual exposure from these sources of 53 millirem. Consumer products contribute on average an additional 10 millirem per year.

As a result, the average total radiation dose to individuals in the US resulting from natural background, medical, dental and consumer product radiation is about 360 millirem. It should be noted that smokers are also exposed to the radionuclide polonium-210 which occurs naturally in tobacco, resulting in a radiation dose to the lungs of up to 20 rem, which is a very large dose compared to natural background radiation exposure.

2.4. HISTORICAL PERSPECTIVE AND BACKGROUND

Research on the effects of ionizing radiation on populations extends back to the end of the last century when medical scientists were beginning to realize that the use of radioactive materials (radium) and radiation (x-rays) in the diagnosis and treatment of patients might well lead to hitherto unknown side effects. Some side effects were already well known; for example, skin erythema and the loss of hair showed up rather promptly after exposure to the relatively large doses from therapeutic use of x-ray machines. However, the delayed effects of radiation, such as cancer, were unknown until they began to appear at a much later date in patients who had been treated with radiation or radioactive materials and in workers occupationally exposed.

One of the early examples of the effects of radio-nuclides taken into the body comes from the ingestion of radium by painters of fluorescent watch dials who consistently wetted and pointed their brush tips with their lips during the period 1915 to 1935 when the practice was stopped. High incidence of bone cancer- and head carcinomas were observed among these workers and also among patients who had been treated internally with radium for tuberculosis of the bone.

During the 1920's and early 1930's a significant increase in mortality from leukemia among radiologists also began to be noticed. The actual doses received by such persons are very uncertain since at that time it was not common practice to monitor for radiation dose. It is, however, significant that these cancer excesses have not been observed in radiologists who entered practice after the 1930's when greater protective measures were taken. One example of the latent effects of x rays in specific populations was the discovery later in life of an excessive likelihood of tumors in individuals who had been treated with x rays in their childhood for scalp ringworm or enlarged thymus glands.

These observations clearly demonstrated the delayed effects of internal and external radiation in fairly large doses and, together with other observations, led the medical scientists of the day to speculate on whether exposure to much lower doses of radiation might lead proportionally to similar latent effects particularly when exposure was prolonged over a period of time.

The most comprehensive information relating health effects to radiation exposure over a wide range of dose arose much later from the medical histories of the surviving populations who were exposed to the atomic bombing of Hiroshima and Nagasaki in 1945. The effect of high doses was immediately visible, but it was not until some time later that an excess of leukemias began to be observed among the survivors. In the ensuing years, medical follow-up of the survivors has revealed excesses of other cancers including cancers of the lung, stomach, thyroid, and breast.

There is little doubt that exposure to high doses of radiation increases the potential for cancer in humans as these experiences have demonstrated. However, extrapolating latent effects of radiation to demonstrate that an increased risk exists at lower radiation doses is quite another matter and much more problematic. Even in exposed populations such as those in Japan, the effects of exposure are not easy to quantify. For example, the medical records of the 80,000 atomic bomb survivors who were followed up from 1950 to 1978 showed that 23,500 persons had died, of which 4,750 had died of cancer. It has been estimated that only 250 of these were attributable to radiation exposure, i.e. in excess of the expected number of cancer deaths in a similar, but not exposed population. To obtain an estimate of the effects of low doses, such as those experienced in and around nuclear installations, requires extrapolations from high dose observations based on either:

1. empirical evidence at high doses, i.e. epidemiology, and then extrapolation to low doses;
2. laboratory data on the effects of low radiation doses on animals
3. theoretical formulations which seek to quantify the relationship between dose and effect. Significant uncertainties are associated with these techniques as explained below.

2.5. THE EFFECTS OF HIGH-LEVEL VERSUS LOW-LEVEL RADIATION DOSES

While doses in the range of a few rads are generally regarded by the scientific community as being low-level doses, and doses in excess of 100 rads are regarded as being high-level doses, the demarcation line between high and low level radiation is not a scientifically defined one. Nevertheless, the United Kingdom Radiological Board regard low doses as being less than 1 rad per year or low dose rates as less than 10 rad per day.

- **Rad (Radiation Absorbed Dose):** The special unit for radiation absorbed dose, which is the amount of energy from any type of ionizing radiation (e.g., alpha, beta, gamma, neutrons, etc.) deposited in any medium (e.g., water, tissue, air). A dose of one rad means the absorption of 100 ergs (a small but measurable amount of energy) per gram of absorbing tissue (100 rad = 1 gray).

Part of the reason for this is that health physics is concerned with two types of exposure:

1. a single accidental exposure to a high dose of radiation during a short period of time, which is commonly called acute exposure, and which may produce biological effects within a short time after exposure and a relatively higher probability of latent effects such as cancer and genetic damage;
2. Long-term, low-level exposure, commonly called continuous or chronic exposure, where the results of the exposure is of a much lower probability and will not become apparent for years. Any such exposures are the result of improper or inadequate protective measures. Exposure of the whole body to an extremely high dose of radiation (of the order of 1000 rads) is almost certain to result in death within a matter of weeks but if a limited area of the body is briefly exposed to a very high dose, this may not be fatal. In fact hundreds of rads are used in many therapy regimes. For example, an instantaneous whole body dose greater than 500 rads would probably be lethal, provided no treatment was given, as a result of damage to the bone marrow and gastrointestinal tract but if the same total dose is received over a period of weeks or months, there is more opportunity for cellular repair and there may be no early signs of injury although damage to tissues may have occurred and may be manifested later in life, or possibly in the irradiated person's descendants. However, if only a limited area of the body is briefly exposed to a high dose of this nature, it may not be lethal but early effects may occur such as reddening of the skin (erythema) in a week or so.

The most important long term effect of radiation is cancer but the fundamental processes by which it is induced are not fully understood and, moreover, there is no way at present of medically distinguishing cancers caused by radiation from those occurring naturally and those caused by other carcinogens.

The main source of information on the risk of cancer following whole-body exposure to radiation comes from studies on the survivors from the atomic bombings of the cities of Hiroshima and Nagasaki. The risks derived from studies of these populations are based largely on exposure to high doses delivered over a short period of time (tens of rads or more), whereas most people are only exposed to low levels of radiation over long periods of time.

Because of the relatively low probability of effects occurring due to exposure to low-level radiation over long periods of time, the risks of such exposure can only be calculated from the data available on exposure to high levels of radiation. It is generally assumed for radiation protection purposes that there is a simple proportional relationship between dose and risk and for radiations from alpha particles this appears to be the case. However, for beta and gamma radiations and x rays there is considerable evidence that the risk is less at low doses and low dose rates than at high doses given at high dose rates. In either case, there is no sound basis for assuming the existence of a threshold below which no cancers or other health effects are induced.

2.6. NATURE OF EPIDEMIOLOGICAL STUDIES

One of the major problems in conducting epidemiological studies to estimate the effects of low-level radiation is the difficulty of identifying the influences of the multiple factors which have to be taken into account in order to estimate the effects. These factors include:

- **A.** the quality of the exposure and medical data being used;
- **B.** the selection of appropriate controls;
- **C.** the methodology and scientific design of the analyses;
- **D.** occupational conditions and personal habits and,
- **E.** the validity of the statistics for a given population size as discussed in the following sections.

- **A. Quality of Data:** One of the more complicated problems is the quality of the data used as input into the study. Epidemiology studies usually employ mortality data (death rates from a disease) or incidence data (the occurrence rate of a disease). Mortality data is usually based on death certificate information where it is often not known for certain whether the primary cause of death is cancer and whether it has been accurately represented on the certificate. For example, the type of cancer reported on the certificate may be the result of metastasis and not the site of origin. A similar problem exists in incidence data where diagnoses are based on "registrations" of a disease occurring, and might not be accurate.

- **B. Availability of Realistic Exposure Measurements:** A second problem is the limited availability of realistic exposure data. In most cases involving the deaths from, or diagnosis of, cancer in persons who are not occupationally exposed to radiation, valid exposure data almost never exists.

C. **Validity and Significance:** Third, for an epidemiological study to have a high degree of statistical significance, it is necessary to have a large enough data base. Detecting a subtle rise in cancer incidence above the "normal" and correctly attributing such an increase to low levels of radiation exposure requires the study of very large populations.

D. **Age-Dependence:** Another complication is that cancer is well known to be an age-dependent disease which is rarer in young people and much more prevalent in older populations. Consequently any analysis of cancer rates needs to account for the age distribution in the area in question and age-adjusted corrections made.

E. **Other Factors:** Other factors which affect cancer mortality and need to be considered in the analyses are duration and age when exposure begins; sex ratios; racial and ethnic factors; exposure to other environmental agents (viruses, carcinogens, smoking); and even social structure.

2.7. ESTIMATION OF RISK OF CANCER FROM EXPOSURE TO RADIATION

The derivation of the estimates of the risk of induction of cancer from exposure to radiation are carried out by various national and international bodies composed of internationally renowned experts in the fields of radiobiology, radiation epidemiology, health physics, medical radiology, statistics, genetics, etc. These bodies conduct comprehensive reviews of the evidence relating to risk of cancer, hereditary effects and other diseases as a result of radiation exposure.

Such bodies include:

- The **International Commission on Radiological Protection (ICRP),**
- The **United Nations Scientific Committee on the Effects of Atomic Radiation** (**UNSCEAR**),
- The **National Academy of Sciences Committee** on the **Biological Effects of Ionizing Radiation** (**BEIR**)
- The **National Council on Radiation Protection** and Measurements (**NCRP**) in the United States
- The **National Radiological Protection Board** (**NRPB**) in the U.K.

In 1977 the **ICRP** published its basic recommendations on the effects of exposure to radiation in which it assumed that there is no threshold below which radiation effects are not harmful and took the position that the probability of harmful effects increases with dose. Also in 1977, **UNSCEAR** published a comprehensive review of animal and human exposure to radiation and the induction of cancers, from which it derived an estimate of the risk of the induction of leukemia as being in the range of 2 cases per million of population per 100 mrem for low doses. This value was used by **ICRP** in its 1977 report which calculated the risk factor for the induction of all fatal cancers as being in the range of 10 cases per million of population per 100 mrem, or 5 times the leukemia risk.

On this basis if a population of 50-million people receive a dose of 100 mrem above natural background radiation as a result of exposure to medical and other sources, 500 additional cancer deaths due to this "extra" radiation can be expected some time in the future, 100 of which might be a leukemia, out of an annual total of about 125,000 deaths normally expected from cancer. The **UNSCEAR** risk estimates can also be used to compare the risks from exposure to natural background radiation with the number that might be expected from the operation of a power station which, under normal circumstances and conservative assumptions, would deliver an increment of 4 mrem per year over natural background (see Section 3 for further discussion of typical doses received routinely by persons living near nuclear power plants). In this case, if the risk factor assessed by the ICRP in 1977 is used for the calculation of the number of deaths expected from the natural background radiation in a local population of 100,000 persons, the estimated number of deaths would be 0.2, and the additional number from the operation of the power plant would be 0.008 deaths (or 1 death in 125 years) which is virtually impossible to statistically detect even by a massive study covering the whole of the regional population for a very large number of years.

In 1990 the **BEIR** Committee published its fifth update of its report (BEIR V). This suggests that these earlier estimates are too low and that the risk factor should be increased by a factor of four, or even by a factor of 10 as some have suggested. Even if the higher figure was used, it would still require a very substantial period of follow-up or very large population groups to be able to state with any certainty that the additional deaths were due to the effects of radiation. Furthermore, it would still be extremely difficult to detect the additional number of deaths due to man-made radiation among those arising from natural background radiation.

2.8. BEIR VII

BEIR VII develops the most up-to-date and comprehensive risk estimates for cancer and other health effects from exposure to low-level ionizing radiation. It is among the first reports of its kind to include detailed estimates for cancer incidence in addition to cancer mortality. In general, **BEIR VII** supports previously reported risk estimates for cancer and leukemia, but the availability of new and more extensive data have strengthened confidence in these estimates. A comprehensive review of available biological and biophysical data supports a “**linear-no-threshold**” (**LNT**) risk model—that the risk of cancer proceeds in a linear fashion at lower doses without a threshold and that the smallest dose has the potential to cause a small increase in risk to humans.

This report is the seventh in a series of publications from the National Academies concerning radiation health effects called the **Biologic Effects of Ionizing Radiation** (**BEIR**) reports. **BEIR VII** focuses on the health effects of low levels of low **linear energy transfer** (low-**LET**) ionizing radiation such as x-rays and gamma rays. The most recent **BEIR** report to address low level low-LET radiation was the BEIR V report published in 1990. Humans are exposed to ionizing radiation from both natural and man-made sources (see Figure 1). Very high doses can produce damaging effects in tissues that can be evident within days after exposure. Late effects such as cancer, which can occur after more modest doses including the low dose exposures that are the subject of this report, may take many years to develop. Most radiation sources have a mixture of high- and low-LET radiation. Compared to high-LET radiation, low- LET radiation deposits less energy in the cell along the radiation path and is considered less destructive per radiation track. The BEIR VII report defines low doses as those in the range of near zero up to about 100 mSv (0.1 Sv) of low-LET radiation. People in the United States are exposed to average annual background radiation levels of about 3 mSv; exposure from a chest X-ray is about 0.1 mSv and exposure from a whole body computerized tomography (CT) scan is about 10 mSv.

There are many challenges associated with understanding the health effects of low doses of low-LET radiation, but current knowledge allows several conclusions. The BEIR VII report concludes that the current scientific evidence is consistent with the hypothesis that, at the low doses of interest in this report, there is a linear dose-response relationship between exposure to ionizing radiation and the development of solid cancers in humans. It is unlikely that there is a threshold below which cancers are not induced, but at low doses the number of radiation induced cancers will be small. Other health effects (such as heart disease and stroke) occur at higher radiation doses, but additional data must be gathered before an assessment of any possible dose response can be made between low doses of radiation and non-cancer health effects. The report also concludes that with low dose or chronic exposures to low-LET irradiation, the risk of adverse heritable health effects to children conceived after their parents have been exposed is very small compared to baseline frequencies of genetic diseases in the population.

Naturally-occurring genetic (i.e., hereditary) diseases arise as a result of alterations (mutations) occurring in the genetic material (DNA) contained in the germ cells (sperm and eggs) and are heritable (i.e., they can be transmitted to the offspring and subsequent generations). The concern over whether exposure to ionizing radiation would cause an increase in the frequencies of genetic diseases launched extensive research programs to examine the adverse genetic effects of radiation in the children of A-bomb survivors and other studies focusing on mammals that could be bred in the laboratory, primarily the mouse. Studies of 30,000 children of exposed A-bomb survivors show a lack of significant adverse genetic effects. During the past 10 years, major advances have occurred in our understanding of the molecular nature and mechanisms underlying naturally occurring genetic diseases and radiation-induced mutations in experimental organisms including the mouse. The risk estimates presented in this report have incorporated all these advances. They show that, at low or chronic doses of low-LET irradiation, the genetic risks are very small compared to the baseline frequencies of genetic diseases in the population.

Given BEIR VII estimates, one would not expect to see an excess in adverse hereditary effects in a sample of about 30,000 children (the number of children evaluated in Hiroshima and Nagasaki). One reason that genetic risks are low is that only those genetic changes compatible with embryonic development and viability will be recovered in live births.

2.9. STUDIES OF THE EFFECTS OF NATURAL BACKGROUND RADIATION

Since there are substantial variations in natural background radiation levels from one geographic region to another, as discussed in Section 1.0, it might be expected that some difference in the incremental health impact of this type of radiation exposure would be observable.

In an attempt to determine whether such difference exist, a number of studies have been carried out in the USA, the UK and several other countries to investigate cancer incidence in different regions where the population is exposed to different levels of natural background radiation. The results of these studies have been inconclusive. Since the level of radiation that is routinely emitted from nuclear power plants (see Section 3) is substantially less than the variations in natural background radiation levels from one geographic region to another, it is not surprising that the incremental health impact of this type of radiation exposure, if any, is also very difficult to detect.

2.10. LEUKEMIA CLUSTERS

There have been persistent reports of leukemia in young persons living near nuclear facilities which have been described as "leukemia clusters". This issue is briefly addressed in this section. In the context of a disease such as .leukemia, the word "cluster" is generally used to describe an observation of an unusually high incidence of the disease in a small geographical area within a relatively short time period. It has also been used to refer to the persistent increased occurrence of the disease in a small area, such as might occur if the population of that area was permanently exposed to risk from a causative agent in the environment. The actual rates arid number of cases which occur in the locality being studied may be higher or lower than the national average. If the number is higher, then it may be described by some people as a "cluster". The definition of a leukemia cluster is complex but most specialists agree that it involves an unusually high incidence of leukemia in a small area for a limited time period. For example, it has been reported that a number of people living on the same road or in a small town developed leukemia within a few years of each other.

Reports of clusters of leukemia, due to unknown causes, have appeared in the medical literature for many years, one of the earliest being in the British Journal of Childhood Disease in 1917. Since the 1960's systematic searches, most not associated with nuclear energy, have been carried out in many parts of the world in an effort to determine whether leukemia cases tend to occur more closely together than would be expected by chance.

The results of these searches revealed the occurrence of leukemia "clusters" in the following places:

- Leukemia San Francisco 1948-55
- Childhood leukemia Buffalo, N.Y. 1943-56
- Childhood cancer Buffalo, N.Y. 1943-56
- Childhood leukemia Northumberland 1951-60
- Childhood leukemia Liverpool, U.K. 1955-64
- Childhood leukemia Portland,Oregon 1950-61

- Childhood leukemia New Zealand 1953-64
- Childhood leukemia Atlanta, Georgia 1958-88
- Leukemia/lymphoma Bahrain 1966-76
- Hodgkin's disease King County, 1974-79 Washington, USA

The clusters listed in the table above have been ascribed to a variety of causes including radiation, association with the dairy industry, and a flood disaster in New York. It is still unclear whether leukemia occurs in clusters to a greater extent than would be expected by chance but it is clear that leukemia clusters can occur randomly without an apparent cause. This occurrence is consistent with statistical theory since a random distribution is not uniform and apparent clusters are the rule rather than the exception.'

2.11. GENETIC EFFECT

Ionizing Radiation: Any radiation capable of displacing electrons from atoms or molecules, thereby producing ions. Some examples are alpha, beta, gamma, x-rays, neutrons, and ultraviolet light. High doses of ionizing radiation may produce severe skin or tissue damage.

Ionizing radiation can result in damage to the genetic material (DNA) in reproductive cells leading to mutations which may be transmitted to subsequent generations. Such mutations are not seen in irradiated individuals, but only in their immediate or generational offspring. As the **BEIR VII** report points out, mutations in reproductive cells may occur spontaneously due to natural causes, including those which can be associated with exposure to natural background radiation. It is extremely difficult to estimate what small increments of mutations effects may be induced by man-made radiation above this spontaneous occurrence rate. Estimates of genetic effects in humans must rely more on results from experimental animal studies than on human epidemiology studies that are extremely sparse. Genetic effects of ionizing radiation are detected through the study of certain endpoints such as chromosome abnormalities, spontaneous abortions, congenital malformations, or premature death.

It must be emphasized that mutations caused by radiation do not lead to the grossly deformed offspring as portrayed by popular science fiction. As the **BEIR VII** report states: "Some mutations have drastic effects that are expressed immediately, and these are eliminated from the population quite rapidly."

Although it is generally believed by the scientific and medical community that there is a need to assess the genetic effects of radiation exposure, the perspective has changed since the 1950s. As the **BEIR** V report states: "...in regard to the induction of mutations, the greater current risk seems to result from exposure to chemical mutagens in the environment rather than from exposure of populations to radiation." It is now clear that the more significant risk of health consequences in persons exposed to radiation is that of cancer, with genetic effects of lesser concern than earlier considered. As a consequence, substantial efforts have been made to limit personal exposure to reduce the risk of cancer and this in turn has limited genetically significant exposures.

2.12. CONCLUSIONS

Recent studies from the United States and the United Kingdom have reported increases in mortality from leukemia in young children, especially under the age of 10, living near certain nuclear installations. The reasons for these increases are not clear and there is no convincing evidence that they are connected with exposure to low-level radiation. Nevertheless, because of the concerns raised by these observations, epidemiologic studies have been, and are continuing to be, carried out in the United Kingdom and a number of other countries with nuclear facilities in an attempt to determine whether there are any health effects on workers and populations living in the vicinity of those nuclear facilities which are explainable as a consequence of radioactive emissions from those facilities.

The most exhaustive of these studies that has been completed so far has been that carried out by the **National Cancer Institute** (**NC**I) in the United States. This survey encompassed all 62 nuclear facilities that went into service in the United States prior to 1982 and evaluated over 900,000 cancer deaths occurring between 1950 and 1984 in 107 counties.

The results of this survey were evaluated by the Ad-Hoc Advisory Committee of medical and epidemiological experts set up by the NCI who concluded that the survey had:

"produced no evidence that an excess occurrence of cancer has resulted from living near nuclear facilities. Further, measurements of radioactive releases from nuclear facilities indicate that the dose from routine operations is generally much below natural background radiation, and hence may be unlikely to produce observable effects on the health of surrounding populations."

The type of study undertaken by the NCI should help to provide the public with the reassurance that the normal operation of nuclear facilities does not pose undue public health risks.

SECTION THREE: ROUTINE RADIOACTIVE EMISSIONS

3.1. INTRODUCTION

Routine emissions of radioactive material in solid, liquid and gaseous forms result from the operation of nuclear power plants. These releases increase the amount of radioactivity in the biosphere; hence their impact on public health must be considered. Such emissions are an inevitable result of normal plant operations and must be clearly distinguished from non-routine, accidental releases from power plants. This section discusses the origins and quantities of such emissions, the doses involved, and their health impact. Furthermore, routine exposure of nuclear power plant employees to radiation must be taken into account and is reviewed in this section.

In addition to nuclear power plants, nuclear fuel cycle facilities such as uranium mines and fuel reprocessing plants also routinely release small amounts of radioactivity to the environment which might be larger than the emissions from nuclear power plants. Such facilities also cause occupational radiation exposure.

3.2. SOURCES OF ROUTINE EMISSIONS

- **Fission:** The splitting of a heavy nucleus into two roughly equal parts (which are nuclei of lower-mass elements), accompanied by the release of a relatively large amount of energy in the form of kinetic energy of the two parts and in the form of emission of neutrons and gamma rays.
- **Fission products:** Nuclei formed by the fission of higher mass elements. They are of medium atomic mass and almost all are radioactive. Examples: ^{90}Sr, ^{137}Ce.

There are three principal categories of radioactive materials produced as a result of the nuclear fission process in light water reactors: fission products, neutron activation products and tritium. Fission products are produced when the uranium atoms in the nuclear fuel fission into two smaller atoms. They are produced in both solid and gaseous forms. Neutron activation products, in contrast with fission products, are produced outside of the fuel material in either the fuel cladding material, fuel assembly structural materials or the reactor structure itself. Neutron activation products result when neutrons emitted in a fission reaction are absorbed by these materials, thereby making them radioactive. Finally, tritium, which is the radioactive isotope of hydrogen, is produced in a variety of ways, including by neutron capture in the reactor's coolant water. These radioactive materials find their way into nuclear power plant effluents in the following manner.

A. During reactor operation, almost all fission products are retained within the uranium fuel material and the metal cladding within which fuel elements are encased. (This fuel material is eventually removed from the reactor and either reprocessed into new fuel or disposed of in solid form as high-level nuclear waste.) However, a small percentage of the fission products may escape from the fuel rods through hairline cracks that may develop in the cladding material. Such cracks result either from welding defects or localized corrosion that occurs during reactor operation. As a result, the reactor's internal coolant water may become contaminated with gaseous and, to a lesser extent, solid fission products;

B. similarly, small quantities of neutron activation products and tritium -- which are formed not in the fuel rods but in the coolant water or in structural materials that come into contact with the coolant water -- also contaminate the coolant water.

3.3. RADWASTE CONTROL SYSTEMS

Regulations require the application of "rad-waste" systems (described below) whose purpose is to reduce radioactivity levels in plant effluents to what are believed to be safe levels, based on the current understanding of the effects of radiation, as discussed in Section 2.0. **NRC** regulations place numerical limits on such effluents, and require radioactive emissions to be reduced to levels that are "as low as reasonably achievable" (**ALARA**). The radiation doses to the general public that result from nuclear power plant operation after such reductions are made are discussed in this Section and are compared to natural background levels of radiation.

Radwaste systems consist of liquid and gaseous waste processing systems. Radioactive liquids are decontaminated in two ways: evaporation and demineralization. Both are methods of filtering the liquid effluents so as to separate the radio-nuclides from the water that will be discharged to the environment. Similarly, gaseous emissions are passed through a particulate filter to remove solid radioactive particles. Gaseous radioactivity is reduced by storing gaseous wastes in holdup tanks before discharge to air, thus allowing radioactivity levels to reduce by natural radioactive decay. As a result of these decontamination procedures, the vast majority of the radioactivity that reaches the reactor coolant water is removed from that water, solidified by cementation or other methods, and shipped off-site for disposal as low-level radioactive waste. Effluents discharged from the plant into air and water contain only very small amounts of radioactivity that was not removed by these processes. 'The discharges must not exceed levels allowed under regulation. Tritium is particularly difficult to remove because it has chemical properties identical to hydrogen, and thus becomes an integral part of the reactor water.

The **United Nations Scientific Committee on the Effects of Atomic Radiation** (**UNSCEAR**) has compiled data on the quantities of various radioactive materials that are discharged from reactors worldwide, which vary depending on the reactor type.

The principal categories of effluents are:

- Fission product noble gases (such as krypton and xenon), which have short half-lives and high radioactivity levels but produce low radiation doses because they are chemically inert;
- Activation gases produced in gas-cooled reactor operation, especially argon- 41 and sulfur-35, which also have high activity levels but cause low doses
- Tritium, which, as mentioned above, has chemical properties identical to hydrogen;
- Carbon-14, which has a long half life (5730 years) and therefore is of concern in terms of long-term dose commitment. It is produced mainly from reactions with nitrogen and oxygen in the fuel and moderator.
- heavy water reactors (HWRs) produce relatively high levels of C-14 due to presence of oxygen in the moderator;
- Iodine-131, which has a half-life of 8 days, is mobile in the environment, and selectively migrates to and irradiates the thyroid;
- Particulates, which either arise directly, as decay products of fission product noble gases, or from corrosion of materials in the primary coolant circuit; and Other liquid effluents.

3.4. DOSE LEVELS TO THE GENERAL PUBLIC AND HEALTH IMPACT

The principal pathways for human exposure to radioactive effluents are:

- Inhalation;
- Ingestion of food crops and animal products
- Ingestion of drinking water
- Ingestion of fish and invertebrates
- Air submersion
- Ground irradiation.

Other pathways which have been found to cause generally much smaller doses include:

- Direct exposure from waterborne activities (swimming, boating, shoreline recreation)
- Ingestion of crops that were irrigated with contaminated water.

Based on known airborne releases from nuclear power plants in the United States, estimates of the doses received by persons residing near those plants have been calculated by the US **Nuclear Regulatory Commission (**NRCQ). The average distribution of doses among the estimated population of 140-million living within 2 to 80 km around each site for 70 nuclear power plants in the US are as follows:

- About 84% of the population at risk from airborne releases has been estimated as receiving a dose commitment of between 0.000003 and 0.001 mrem.
- About 0.4% of the population at risk received a dose of between 0.003 and 0.01 mrem.

The study did not estimate the maximum dose received by an individual, but licensee calculations at sites with the highest emissions indicated values of up to approximately 100 times the average individual doses, i.e., of the order of a few millirem per year.

Similarly, using international effluent data, the **United Nations Scientific Committee on the Effects of Atomic Radiation** (**UNSCEAR**) calculated doses to populations living near nuclear power plants resulting from each category of emissions and for each type of reactor. It should be noted that whereas the **NRC** figures given above are stated in terms of dose to the average individual, the **UNSCEAR** figures are given in terms of total population dose, which is equal to the average individual dose multiplied by the size of the exposed population. **UNSCEAR** also estimates that when these figures for nuclear power plants are combined with comparable figures for other nuclear fuel cycle facilities, the total population dose is 400 person-rem per gigawatt-year, so that with current nuclear power generation at about 190 gigawatt-years per year, the annual dose to the world's population resulting from nuclear power plants and nuclear fuel cycle facilities is about 76,000 person-rem. For comparison purposes, it should also be noted that **UNSCEAR** has estimated that radioactive material emitted to the atmosphere from the burning of coal in coal-fired electricity generating plants results in a population dose of about 400 person-rem per gigawatt-year also.

For purposes of comparison with the individual and population doses due to nuclear power given above, it should be noted that the average person receives a dose due to natural background radiation of roughly 300 mrem/year, including the dose from cosmic rays, naturally occurring radioactive materials in the ground and building materials (including radon gas), and radio elements in the body. As also noted, medical and dental radiation exposure, plus exposure to radiation from consumer products, bring a person's radiation dose up significantly; the average total radiation dose to individuals in the US resulting from natural background radiation and these other sources is about 360 millirem. (In addition, smokers are also exposed to the radionuclide polonium-210 which occurs naturally in tobacco, resulting in a radiation dose to the lungs of up to 20 rem.)

Furthermore, by multiplying the average individual background dose figure of 300 millirem/year by the world population of approximately 5 billion, the total worldwide population dose due to natural background radiation can be determined to be about *1.5* billion person-rem/year, which can be compared with the figure of 76,000 person-rem/year for world population dose due to nuclear power and nuclear fuel cycle facilities.

This comparison of the radiation doses routinely received by the population as a result of nuclear power and those received from natural and medical sources strongly suggests that routine emissions from nuclear power plants should have little or no impact on public health. To corroborate this assumption, a number of studies have been done to assess whether or not the incidence of cancer is greater in populations living near nuclear power plants than populations living in other locations. A report published in 1987 by the British Office of Population Censuses and Surveys on cancer risk in the vicinity of nuclear facilities in England and Wales found that, overall, there was no evidence to conclude that cancer mortality near UK nuclear installations was higher than elsewhere in the U.K.. It did, however, note an increase in deaths from leukemia in young persons under age ten in the vicinity of the Sellafield fuel reprocessing plant but the reasons for this were not clear.

Subsequently, the **National Cancer Institute** in the US initiated a large-scale survey of the incidence of cancer in persons living near nuclear facilities in the United States, published in July 1990. The authors conclude that the survey produced no evidence that an excess occurrence of cancer has resulted from living near nuclear facilities. They also conclude that measurements of radioactive releases from such facilities indicate that doses due to routine emissions are generally much lower than doses from natural background radiation and therefore may be unlikely to produce observable effects on the health of surrounding populations.

3.5. OCCUPATIONAL EXPOSURE

While the doses to the general public from nuclear power plants have been generally quite low and the health impact thus far undetectable, the doses to workers are naturally higher and often exceed natural background radiation dose levels. **UNSCEAR** has tabulated data on worldwide occupational radiation exposure at nuclear power plants during the period 1980 to 1984. For the same period, **UNSCEAR** also determined the following average collective occupational dose levels on a per-gigawatt-year basis, grouped by reactor type: Collective Dose Per Unit Energy Generated (person-rem per gigawatt-year):

- Light Water Reactor (LWR) 1300
- Heavy Water Reactor (HWR) 400
- Gas-Cooled Reactor (GCR) 500
- High Temperature Gas-Cooled Reactors (HTGR) 10

Among light water reactors, it was found that the collective dose in **BWR'**s can be up to a factor of two higher than in **PWR'**s, possibly because more maintenance work in radiation areas is necessary in **BWR'**s. The occupational exposure to radiation for the **NTPBMR (**A

High Temperature Helium-Cooled Gas Reactor**)** is significantly lower than both types of Light Water Reactors.

According to figures recently published by the US Nuclear Regulatory Commission, in 1989 nuclear power plant workers in the US received an average dose of 340 mrem that year (somewhat higher than the average natural background radiation dose level)." The average collective dose per reactor was 344 person-rems. These figures are based on exposure data at 108 **PWR**s and **BWR**s, and represent a 14% decline from 1988 level-. Broken down further, the average PWR work force received a collective dose of 296 person-rems and the average BWR work force received a collective dose of 439 person-rems.

SECTION FOUR: THE SAFETY OF NUCLEAR POWER REACTORS

4.1. INTRODUCTION

The energy produced in the core of a nuclear reactor comes about as a result of the fissioning of the nuclei of uranium' atoms in the nuclear fuel. To convert the heat released through nuclear fission into electricity, a coolant flows through the reactor core to absorb the heat and make steam, which spins turbines that power electrical generators. The materials produced from the fissioning of uranium (the "fission products") are highly radioactive and have to be strictly contained to prevent them from being released to the environment, as do other categories of radioactive materials produced in a nuclear power plant.

As discussed in Section 3.0, small quantities of fission products and other radioactive materials contaminate reactor coolant water under normal operating conditions. This contamination is largely removed using specially designed systems which ensure that routine releases of contaminated water to the environment remain strictly within regulatory limits. More importantly, accidental releases of radioactive material to the environment must be prevented. There are many possible events which could lead to accidental releases; for example, in a **pressurized water reactor** (**PWR**), the rupture of one of the many tubes in the heat exchangers would allow radioactive water to escape from the primary coolant into the secondary coolant. The large pipes of the secondarv cooling circuit penetrate the containment structure of a **PWR.** Consequently, once outside the containment, radioactive material leaked from the primary system through the ruptured tube could then potentially escape into the environment.

However, the principal event which could lead to large quantities of radioactive material being released to the environment is the **loss of coolant accid**ent (**LOCA**).

A **LOCA** could be initiated by a number of means:

- steam line breaks
- sudden expulsion of control rods
- loss of offsite power
- severe natural phenomena such as earthquakes, tornadoes and hurricanes.

The most serious event which has been postulated would be a break of a major pipe in the circuit that provides coolant to the reactor core, which could lead to the loss of substantial quantities of coolant. It is essential that the core be kept completely covered with coolant at all times. Otherwise the core, or parts of it, could overheat and the fuel elements could degrade and possibly melt, resulting in the release of large quantities of radioactive materials into the reactor vessel.

It is primarily to the prevention of such **LOCA'**s and their potential consequences that nuclear reactor safety is addressed. To prevent **LOCA'**s from evolving into serious accidents with offsite releases of radioactive material, reactors must be designed to shut down quickly and reliably when necessary, and redundant cooling systems must be available to remove the heat that remains in the reactor core after the nuclear chain reaction has been shut down. In the event that such systems fail and fuel melting does occur, possibly allowing radioactive materials to breach the reactor vessel, most nuclear power plant designs include a large concrete containment building that would limit the release of radioactive materials to the environment.

This Section reviews the general principles behind nuclear power plant safety and describes the basic systems in a nuclear power plant designed to prevent or mitigate nuclear accidents. Subsequently, a discussion of the range of possible accidents that could occur is provided, the methodology for estimating the risk of severe nuclear power plant accidents is explained, and current estimates of such risk are given. Finally, the effectiveness of regulatory systems and management on safety, including the impact of human factors, are addressed. Most of this discussion focuses **on light water reactors** (**LWRs**) – comprising **Pressure Water Reactors** (**PWR**) and **boiling water reactors (BWR**) -- which account for about 78% of the nuclear power plants in operation worldwide today (or 86% in terms of net MWe). The other major reactor types currently in use are gas-cooled reactors (9%), heavy water reactors (7%), graphite moderated light water reactors (5%) and liquid metal fast breeder reactors (1%).2 Safety aspects of new, advanced reactor designs are discussed in Section 6.0.

4.2. THERMAL POWER AFTER REACTOR SHUTDOWN

After the nuclear chain reaction ceases, radioactivity remaining in the fuel will generate heat as a result of radioactive decay. Assuming that the reactor had been operating for a substantial period, the power generated immediately after shutdown will be approximate 7% of the level before shutdown. For a 3000 MWth reactor, with 1000 MWe capacity, this implies and initial decay power level of about 200 MWth. Due to the rapid decay of short-lived species, this decay heat level decreases rapidly, but it is this heat that imposes the requirement that, in a light-water reactor, cooling water remain available to prevent damage to the fuel.

4.3. SAFETY PHILOSOPHY: DEFENSE IN DEPTH

The concept of "defense in depth" is the most fundamental principle underlying the safety of today's nuclear reactors. As stated in the International Nuclear Safety Advisory Group's basic safety principles, published in 1988, it centers on having "several levels of protection including successive barriers preventing the release of radioactive material to the environment." Defense in depth includes:

1. avoiding accident "precursors" that could lead to physical damage to the plant and to the various barriers to the release of radioactive material (accident prevention)
2. measures to:
   a. prevent accident precursors from evolving into accidents
   b. protect the public and the environment from harm in the event that accidents do occur and barriers to the release of radioactive material are not completely effective (accident mitigation).

There are five levels of protection under the defense in depth philosophy:

1. Conservative design, quality assurance, surveillance activities and a general safety culture. This combination is intended to ensure that the reactor and various plant components will operate with a high degree of reliability with only a small chance of malfunctioning.
2. Control of operations, including the ability to respond to abnormal, un-anticipated events or to any indication of system failure. Redundant instruments monitor the various operational process variables (such as the temperature of water as it leaves the reactor) and trigger automatic responses, such as shutting down the reactor, when necessary. An example of an abnormal event would be the loss of off-site power to operate critical safety systems that could be needed in an emergency, which is compensated by having several backup electricity generators at the plant.
3. **Engineered safety features (ESF'**s) that halt the progress of accidents that are considered in the design and, when necessary, mitigate their consequences. The most extreme among the range of accidents considered in the design are termed **design basis accidents,** such as a major break in the primary coolant system that leads to **a LOCA. Severe accidents** that are beyond the design basis have a low probability of occurrence, but backup safety systems offer protection even if an accident progresses beyond the design basis assumptions.

   ESF's work in parallel or as backup to normal operating systems to safeguard essential safety functions: controlling reactor power, cooling the fuel, and confining the radioactivity within the reactor. An example of this is a system which automatically moves the control rods into the core to shut down the reactor in the event of an equipment malfunction in the core. Since the coolant water must still continue to circulate so as to prevent a heat buildup and possible fuel melting, another **ESF** provides emergency core cooling in the event that the primary coolant circuit has also been damaged. The containment structure around the reactor is another **ESF**, serving to prevent or limit the release of any radioactivity that is released from the reactor in an accident situation.

4. **Accident management strategies** to help operators decide quickly on appropriate actions. The aim of these measures is to prevent or limit damage to the core, preserve the integrity of the containment, and maintain the functions of design features such as vents and filters installed in the containment intended to preserve containment integrity in the event of a serious accident.

5. **Emergency planning**, which is intended to mitigate the radiological health consequences should an accidental release of radioactive material occur. Emergency planning includes early notification of an accident, radiation monitoring, decontamination, sheltering and/or evacuation of nearby residents within a specified radius of the plant, and possibly the administration of protective measures. (One such protective measure is distribution of potassium iodide tablets, which would block radioactive iodine that could be emitted in a nuclear accident from accumulating in the thyroid and increasing the risk of thyroid cancer.)

Another way of looking at defense-in-depth is in terms of the various physical barriers present in a nuclear power plant that serve to prevent the release of radioactive material. These physical barriers include the fuel pellets themselves; the fuel cladding, which seals the fuel pellets into the fuel rods; the boundary of the primary coolant system; and, in most reactor designs, the containment structure, which is a hermetically-sealed building designed to confine radioactivity that might otherwise escape because of the failure of other safety barriers.

The 1979 accident at Three Mile Island (TMI), in the United States, which is discussed in detail in Section 5.0, is an example of a major accident in a reactor leading to the breach of several barriers in which a serious release of radioactive material to the environment was prevented because the containment structure maintained its integrity.

4.4. ENGINEERED SAFETY FEATURES

Current light water reactors and most other kinds of nuclear power plants are designed to withstand rare but potentially very serious events. This includes the rupture of a major coolant pipe (which could, under circumstances in which additional safety systems fail, result in the complete loss of coolant from the reactor core) as well as other initiating events such as those identified above.

Protection against such events is provided by engineered safety features. The principal **Engineered Safety Feature (ESF**'s) in **PWR'**s are:

A. the emergency core cooling system

B. the containment building; systems that spray, clean and cool the containment atmosphere;

C. auxiliary feedwater systems which ensure continuous heat removal in the plant's steam generators; and emergency electric power sources.

Similar **ESF**'s are used for **BWR'**s. The function of the emergency core cooling system and the containment building are reviewed in this section. For the sake of brevity, descriptions of these **ESF**'s are provided for only the case of **PWR**'s, which is illustrative of the basic safety principles that also apply to **BWR's** as well as other designs. It should be noted that in **LWR'**s, water serves as both the moderator and the coolant.

In **BWR**'s, the heat generated in the reactor core turns the coolant water directly to steam. In contrast, in **PWR'**s the coolant water that passes through the core is under such high pressure that it cannot boil, but rather transfers its heat in a "steam generator" to a secondary coolant circuit that is maintained at a lower pressure, thus allowing the secondary coolant water to boil into steam.

A. **Emergency Core Cooling System:** Although early designs of **LWR**'s included systems for core cooling, they did not include the type of emergency cooling systems that could be shown to prevent fuel melting in the event of a loss of coolant accident. This was raised as a major concern in the 1960s by nuclear safety researchers in the US, who felt that such systems must be included in reactor designs to prevent what was labeled "The China Syndrome." This expression takes its name from a concept, initially spoken of in jest, which assumed that if the fuel in a reactor melted down it could burn its way through the bottom of the pressure vessel and concrete substrate and continue burning "all the way to China".

   Extensive hearings were held on this subject by the Atomic Energy Commission and its successor agency the **Nuclear Regulatory Commission** (**NRC**). The critics of nuclear power participated in these hearings (and challenged the adequacy of the requirements for emergency core cooling that were imposed as a result of these hearings). Today the **Emergency Core Cooling System** (**ECCS**) is seen as being critical to preventing the reactor core from overheating in the event of a **LOCA.**

   However, **ECCS** adequacy continues to be questioned by certain nuclear power critics. If substantial melting were to take place in the core, large amounts of fuel would be deposited at the bottom of the reactor vessel, and, in the absence of restored cooling, could eventually melt through the reactor vessel. Even if such an extreme state is not reached, high temperatures and breach of the fuel cladding could drive off volatile fission products such as iodine, cesium and noble gases, which could then escape into the environment if there was also a breach of containment.

   PWR's usually have three independent **ECCS** subsystems that operate at different system pressures. Each subsystem has multiple backups in terms of both equipment and flow path. If a small break in a **PWR'**s primary coolant circuit occurred, causing a moderate pressure drop, the **ECCS**'s high-pressure injections system would be activated to replenish the primary coolant lost through the break. A larger break in the coolant circuit would cause a rapid large pressure drop and would actuate the **accumulator injection system**. This subsystem ensures that large tanks of water containing boron are available to flood the reactor core. (The element boron is a neutron absorber and would ensure the cessation of fission reactions in the reactor core.) Finally, **the low-pressure injection system** would be actuated if pressure continues to drop below a preset level. This subsystem would continue to pump borated water from a large storage tank into the reactor long after the accumulators are empty, after which the subsystem automatically would switch to pumping borated water from the containment sump (into which excess water would have over-flown). The accumulator injection system is a passive system; it does not require the operation of pumps and valves, which are dependent on a power supply. The high- and low-pressure injection systems, on the other hand, require active operation, i.e. the presence of a power supply.

B. Containment Systems: Containment systems are intended to hold essentially all the steam and radioactivity that might be released from the reactor vessel in a **LOCA**, and are provided for all **LWR'**s as well as most other reactor types. The exception is a number of earlier design reactors in the Soviet Union, discussed later in this chapter, which have a less effective containment system. A typical **PWR** containment structure is made of reinforced concrete, over one meter in thickness, with an internal steel liner. The entire primary coolant circuit, including the reactor vessel, is enclosed in the containment structure. The containment structure is capable of withstanding the maximum temperature and pressure that could be expected if all the water in the primary coolant circuit was expelled into the containment building as steam. Various systems inside the containment building would be available to cool and clean up the containment atmosphere.

One of these involves spraying water on to the steam, or passing the steam over ice beds, to cause it to condense. In addition, sodium hydroxide may be introduced to the containment atmosphere through the containment spray system in order to remove radioactive iodine; similarly, the ice inventory may include chemical substances that would remove fission products from the containment atmosphere. Filters are also used to remove iodine and particulate matter. Radioactive noble gases, krypton and xenon, cannot be removed, but holding them in the containment building for a certain period allows them to decay substantially into non-radioactive species before they are released to the environment.

Unfortunately, when a serious accident occurred at the Chernobyl-4 reactor in the Soviet Union in 1986, the containment provided at the plant was incapable of containing the accident that occurred. A graphite-moderated light water reactor of the Soviet **RBMK** design, Chernobyl-4 was equipped with a concrete structure capable only of partial confinement of radioactive gases. Thus, the structure was unable to effectively contain the accident and massive graphite fire at the reactor. There are approximately 20 **RBMK** units currently operating in the Soviet Union. Details of the **RBMK** reactor and the Chernobyl-4 accident are described in Section 5.0. A number of the Soviet **PWR**s (**WER'**s) do not have containment either. These Soviet PWRs do not comply with the guidelines established by the **International Atomic Energy Agency** (**IAEA)** and the regulatory agencies in

Western countries and would not be licensed in most countries in the world. There are, moreover, several such reactors outside the Soviet Union: four in former East Germany (which have been shut down due to safety concerns), four in Bulgaria and two in Czechoslovakia

4.5. TYPE AND SEVERITY OF NUCLEAR ACCIDENTS

A wide range of incidents and accidents can be postulated in nuclear power plants, from minor incidents, such as when a specific operating procedure is not followed or a non-safety related piece of equipment malfunctions, to a variety of serious accident scenarios that are conceivably possible. The **Nuclear Regulatory Commission (NRC)** as well as the **IAEA** and the **Nuclear Energy Agency** of the **Organization for Economic Cooperation and Development** (**OECD/NEA**) have, within the past few years, developed accident severity scales in order to facilitate communications and understanding among nuclear personnel, the media and the general public through the use of a simple classification system.

The French adopted an accident severity scale in April 1988 which includes six progressive categories, with the least important incidents designated level 1 and the most serious accidents being designated level 6. The levels are distinguished by the risk of radioactive discharge outside the installation where an accident has occurred. Lesser incidents are those in which radioactive discharges are below the allowed annual limits, or in which operating difficulties have occurred that do not impose directly a radiation risk but which may reveal weaknesses that need to be remedied.

An accident severity scale has also been developed and used in Japan. It is graduated into nine levels, from 0 to 8, and assesses event severity in terms of three criteria: effect on the public; effect on personnel; and effect on reactor safety (impact on integrity of "defense in depth," etc.). All reactor events that are reportable to the regulatory authority can be evaluated on this scale, including minor events having no effect on plant safety.

Drawing from the experience in using severity scales in France and Japan and proposals to use such scales in other countries, the **IAEA** and the **NEA** convened a series of meetings of experts and developed the **International Nuclear Event Scale** (**INES**).

The **International Nuclear Event Scale** (**INES**) is a tool to promptly and consistently communicate to the public the safety significance of reported events at nuclear installations. By putting events into proper perspective, the Scale can ease common understanding among the nuclear community, the media and the public. The group was guided in its work by the findings of a series of international meetings held to discuss general principles underlying such a scale. Initially applied for a trial period to classify events at nuclear power plants, 32 countries participated in the trial and international agencies, and user countries monitored progress. The Scale operated successfully and now has been made available for formal adoption by each country.

The **Scale** also has been extended and adapted to enable it to be applied to all nuclear installations associated with the civil nuclear industry and to any events occurring during the transport of radioactive materials to and from those facilities. Events are classified on the Scale at seven levels. Their descriptors and criteria are shown below with examples of the classification of nuclear events which have occurred in the past at nuclear installations. The lower levels (1-3) are termed **incidents**, and the upper levels (4-7) **accidents**. Events which have no safety significance are classified as level 0 / below scale and are termed deviations. Events which have no safety relevance are termed out of scale.

Although the same scale is used for all installations, it is physically impossible for events to occur which involve the release to the environment of considerable quantities of radioactive material at some types of installation. For these installations, the upper levels of the scale would not be applicable. These include research reactors, unirradiated nuclear fuel treatment facilities and waste storage sites. Industrial accidents or other events which are not related to nuclear or radiological operations are not classified and are termed "out of scale". For example, although events associated with a turbine or generator can affect safety-related equipment, faults affecting only the availability of a turbine or generator would be classified as out of scale. Similarly, events such as fires are to be considered out of scale when they do not involve any possible radiological hazard and do not affect the safety layers.

The Scale is not appropriate as the basis for selecting events for feedback of operational experience, as important lessons can often be learnt from events of relatively minor significance. It is not appropriate to use the Scale to compare safety performance among countries. Each country has different arrangements for reporting minor events to the public, and it is difficult to ensure precise international consistency in rating events at the boundary between level 0 and level 1. The statistically small number of such events, with variability from year to year, makes it difficult to provide meaningful international comparisons. Although broadly comparable, nuclear and radiological safety criteria and the terminology used to describe them vary from country to country. The INES has been designed to take account of this fact.

The scale is intended to be more or less logarithmic, so that each successively higher level on the scale should correspond to about a tenfold drop in the number of events. As examples of how past events have been classified in INES, the 1986 Chernobyl accident, which had widespread environmental and health effects, has been classified as Level 7. The 1979 TMI accident severely damaged the reactor core but had very limited offsite consequences and it was classified as Level 5. The Windscale accident, in which there was a significant external release of fission products, has been classified as Level 5.

4.6. PROBABILISTIC RISK ASSESSMENT

Whether consciously or unconsciously, individuals and institutions use probability and risk assessment in everyday decision making. Financial institutions, for example, use probability in decision making to determine whether a borrower will be able to repay a loan. In mathematical terms this can be written as p(R\H) where p is "the probability of' and R is "the loan will be repaid" and H is "the borrower's past financial history, assets, liabilities etc". The symbol \ denotes "given." Risk is a commonly used word that conveys a variety of meanings to different people but is defined in the dictionary as "the possibility of loss or injury." In the example quoted above, risk is also an element in the decision process and for a bank represents the probability of a given loan not being repaid.

Risk is defined mathematically as the product of the probability of an outcome times the consequences of this outcome. Thus by combining probability (or likelihood) assessments with risk analysis, a financial institution can minimize the adverse outcomes from loan non-repayment. The same principles of risk analysis (probability and consequence) can be used to evaluate an individual's estimated lifespan, airline accidents, nuclear and chemical plant accidents, etc. Regardless of the evaluation being performed, the mathematical laws of probability and the utility assessment of risk are the sample.

In recent years, scientists and engineers working on the development and construction of new nuclear reactors have turned increasingly to the use of **probabilistic risk assessment** (**PRA**) as a tool to help estimate the likelihood and consequence of accidents in the facility that could lead to financial losses and personal injury on- and off-site. The first major application of **PRA** to nuclear reactor safety was made by Professor Norman Rasmussen of the Massachusetts Institute of Technology (MIT) and colleagues who performed the well known Reactor Safety Study. The study pointed out that a major element in the characterization of the radioactive releases associated with potential nuclear power plant accidents is the identification of the accident sequences that can potentially lead to risks to the public.

Current **PRA** analyses of nuclear power plants utilize what is called "event tree methodology." An event tree is a logic method for identifying the various possible outcomes of a given event called the initiating event. (This technique, which is known in business circles as the application of decision trees, is widely used in many business applications where the initiating event is a particular business decision and the various outcomes depend on subsequent decisions.) In nuclear reactor safety the initiating event is generally a system failure and the subsequent events are determined by the characteristics of the reactor system and the engineering.

Use of PRA enables nuclear engineers to identify and, as a consequence, rectify prior to construction any weaknesses in a system which could lead to system failure and possible release of radioactive materials into the biosphere. It also facilitates prioritizing possible safety improvements that could be made in terms of their degree of safety significance. **PRA** also enables an estimate to be made of the probability of a serious accident occurring when a number of reactors are operating over a long period of time. **PRA** also helps demonstrate whether a plant meets "safety goals" which the **NRC** and other national regulatory bodies have developed in recent years, as discussed in the next section.

4.7. SAFETY GOALS

After the **TMI** accident in 1979, the **NRC** decided to develop an explicit policy statement on safety philosophy and the consideration of costs in **NRC** safety decisions. The agency proceeded to develop a policy statement on safety goals for nuclear power plants, issuing interim safety goals in 1983 and final goals in 1986. The final goals provided both qualitative and quantitative goals:

1. Nuclear power plant operation should not impose significant additional risk to an individual's life and health;
2. Societal risks should be comparable to or less than the risks of generating electricity by viable competing technologies;
3. The risk of prompt fatalities to the average individual in the vicinity of a power plant should not exceed 0.1% of all prompt fatality risks from other accidents in the US; and
4. The societal risk of cancer fatalities to the population near a power plant should not exceed 0.1% of all cancer fatality risks from other causes. In addition, **NRC** stated that, as a guideline for implementing these goals, the overall mean frequency of a large release of radioactive materials to the environment from a reactor accident should be less than 10i per reactor-year of operation.8 Subsequently NRC decided that a core damage probability of less than 104 per reactor-year as a subsidiary goal could be useful in evaluating regulations related to accident prevention.

Other countries have since developed safety goals comparable to the **NRC**'s, and the **AIEA** is now developing international guidance on the establishment of national safety goals.

4.8. REGULATION OF NUCLEAR POWER AND ITS EFFECTIVENESS

Regulatory authorities serve on behalf of the government to license, regulate and oversee the safe operation of nuclear facilities and the safe use of nuclear materials. Such organizations are responsible for developing safety standards and regulations; conducting reviews of license applications against those standards and regulations and taking licensing actions; monitoring the operations of licensed facilities to ensure their continued safety; taking necessary enforcement measures where safety levels are not met; conducting safety research programs and providing safety and licensing-related information to the public. Regulatory organizations need to have sufficient resources and technical expertise to carry out their responsibilities, as well as the necessary legal authority and free access to facilities and information.

The approach to fulfilling this regulatory responsibility varies substantially among countries who have licensed nuclear power plants. Some countries -- most notably the United States - - follow a highly prescriptive approach, under which detailed technical regulations have been developed as well as detailed guidance on complying with these regulations. Demonstration of compliance with the regulations is accepted as a demonstration that overall standards of safety will be achieved. Other countries are less prescriptive and require the licensee to demonstrate only that broad safety requirements will be met. In either case, the regulatory authority ultimately requires plants to comply with detailed operating specifications -- or "technical specifications" -- limiting the plant's conditions of operation. Also, in either case, the burden of proof that a proposed facility will not have an adverse impact on public health, safety and the environment falls on the licensee. While regulators should maintain an arm's length from the industry they regulate, experience suggests that regulatory organizations should also work cooperatively with industry rather than in an adversarial manner. The **NRC** has been accused in the past of taking too adversarial an approach towards license applicants and unnecessarily causing cost increases.

At the same time, the **NRC** has been accused of not maintaining sufficient independence from industry. For example, the Union of Concerned Scientists, a leading nuclear power critic in the US, wrote in 1987 that "nuclear power is an inherently dangerous technology requiring the highest standards of care and performance." They fault the NRC for "indifference and shortsightedness [which] have allowed so many generic technical problems to persist for so long," and state that "NRC's primary and instinctive allegiance is still to the industry it regulates... Congress must assume a more assertive oversight role to see that the **NRC** lives up to its safety-first mandate.""

The organizational relationships between nuclear power proponents and regulators differ from country to country. In the United States, the Atomic Energy Commission was responsible for both promotion of nuclear power and regulation thereof until 1974, when the regulatory functions were separated out and given to the new **Nuclear Regulatory Commission. NRC** is organizationally completely separate from its licensees. In contrast, the French **Service Central de Surety des Installations Nucleaires** (**SCSIN**) and its sole reactor licensee **Electricite de France** (**EdF)** are both part of the Ministry of Industry. **SCSIN** is now moving in the direction of independence from **EdF**. However, there is some perception that this move is intended primarily to please the general public and was not necessary to ensure regulatory independence, as well as apprehension that this could lead to power struggles and adversarial relations as in the US. Another example is the UK, where the Nuclear Installations Inspectorate (NII) is part of a larger agency which regulates industry in general, the Health and Safety Executive (HSE), but is completely separate from the industries it regulates (including utilities).

The **International Nuclear Safety Advisory Group's** (**INSAG**) basic safety principles recommend a clear separation between the responsibilities of the regulatory authority and other organizations, so that the regulators retain independence as a safety authority and are protected from undue pressure. **INSAG** also believes this will ensure that safety is the only mission of the regulatory personnel.

With respect to future applications to construct power plants of advanced designs, there is increasing support in the **US** and elsewhere for modifications in the nuclear plant licensing procedure to introduce greater licensing efficiency as well as preserve or possibly improve safety levels. In the US, one of the key proposals is to streamline the licensing process by issuing a combined construction and operating license in a single step rather than the approach followed in the past in which these licenses were issued separately and as the result of separate licensing proceedings.

Standardized designs for certain advanced reactors are now being reviewed by the **NRC**, which will decide whether to certify that these designs are acceptable for referencing in subsequent utility license applications. This pre-approval of designs could make the licensing process more predictable by removing most design questions from the process. Pre-approval of possible power plant sites is also gaining support as it would expedite the licensing schedule.

Regulatory considerations are very relevant to the question of building nuclear power plants in developing countries. Government authorities in developing countries would require adequate resources and capabilities to review and evaluate nuclear power plant license applications and to oversee safety during plant operations. As noted above, there are no hard and fast rules regarding the organization of national regulatory authorities, except that the authority should be organizationally independent of the regulated industry and competent.

4.9. EFFECT OF MANAGEMENT ON SAFETY

A study undertaken by the MIT's Nuclear Engineering Department compared nuclear operating experience in the major nuclear power countries to understand why **US** plants have been consistently outperformed (i.e., in terms of plant availability) by their foreign counterparts.' The study found that managerial reforms are the key to improving US plant performance, rather than changes in the environment within which these plants are operated including US regulatory zeal, diverse plant ownership patterns, and financial regulation by the states, factors which have been widely blamed for the poor performance of US plants.

Industry wide cooperation between utilities, suppliers and regulators has started late in the US and there is still deep distrust between utilities and regulators as well as competition among suppliers, the authors found. They also suggest that utilities that show consistently good results operate with a large degree of managerial involvement in day-to-day activities. Investing in a plant's intellectual resources through training programs and staff exchanges with other organizations can foster an "esprit de corps" that benefits plant operations. Good management can be expected to benefit plant safety as much as plant performance. **INSAG'**s basic safety principles include guidelines with respect to safety culture and responsibility of the operating organization. With respect to safety culture, they state that:

The starting point for the necessary full attention to safety matters is with the senior management of all organizations concerned. Policies are established and implemented which ensure correct practices, with the recognition that their importance lies not just in the practices themselves but also in the environment of safety consciousness which they create...

These matters are especially important for operating organizations and the staff directly engaged in plant operation. For the latter, at all levels, training emphasizes the significance of their individual tasks from the standpoint of basic understanding and knowledge of the plant and the equipment at their command, with special emphasis on the reasons underlying safety limits and the safety consequences of violations.

With respect to responsibility of the operating organization, the **INSAG** principles state that: Once the operating organization accepts possession, it is in complete charge of the plant, with full responsibility and commensurate authority for approved activities in the production of electric power. Since these activities also affect the safety of the plant, the operating organization establishes policy for adherence to safety requirements, establishes procedures for safe control of the plant under all conditions, including maintenance and surveillance, and retains a competent, fit and fully trained staff.

4.10. HUMAN FACTORS

One factor believed to contribute to anxiety about the safety of nuclear power plants is the possibility that accidents might be caused or aggravated by human error. Human error can occur at many stages in the design, manufacture or construction of a nuclear power plant. It can also be crucial in the operation and maintenance of power plants. Human error has contributed to many past events and was chiefly responsible for the accident at TMI, in which an operator shut down the **ECCS** even though the reactor core was being uncovered, because he had faulty information (design flaws also contributed to the accident). Human error combined with the application of inappropriate operating procedures caused a chain of uncontrollable events which led to the disaster at the Chernobyl Power Station.

Judgments involved in the subject known as "human factors" are extremely complex. For example, the role of the operators of a nuclear power plant is far more than a mechanical one. Plant operators must have knowledge and understanding of the plant which they will be required to apply, in conjunction with the plant's automatic control system, to ensure that the plant operates reliably and safely.

Human factors has attracted a great deal of attention in the nuclear industry since the TMI accident. Improvement in control room designs is one major benefit that has resulted from application of this science to nuclear power plants. However, it is clear that in addition to human factors, good management is a key element of accident prevention. To the extent that accidents caused by human error reflect the shortcomings of the management system, efforts to correct defects in organization, training, or procedures will lead to commensurate gains in plant safety level. It is clearly essential that utility managers at the highest level make a high priority of nuclear safety and allocate sufficient funds for safety-related activities, including human factors.

SECTION FIVE: MAJOR NUCLEAR ACCIDENTS

Although there have been many minor incidents at commercial nuclear energy facilities, there have in fact been only three major accidents to nuclear power plants since the development of nuclear energy began in the late 1940's. The three accidents, which occurred at Windscale in England, Three Mile Island in the USA and Chernobyl in the Soviet Union, were so fundamentally different in kind from each other that a description of each is considered to be worthwhile.

5.1. THE WINDSCALE ACCIDENT

In the early 1950's, the United Kingdom decided to go ahead with the development of nuclear weapons for defense purposes. In order to proceed on this route the UK required a supply of weapons-grade plutonium which it decided to manufacture in a number of weapons-material production "piles" (the original name for nuclear reactors) which it built at Windscale on the Northwest coast of England.

The Windscale Pile (as it is known) was one of the first reactors ever to be built and was, by today's standards, a very primitive type of system. The fuel utilized was natural uranium in the form of metal rods clad in a special alloy made from magnesium and aluminum, chosen because of its low neutron absorption characteristics. The moderator was high purity graphite and the whole system was cooled by air. The reactor ran at a relatively low temperature.

5.1.1. WIGNER STORED ENERGY

At the time these reactors were built very little was known about the effects of bombardment of graphite at low temperatures resulting in the production of so-called "defects" in the internal structure of the graphite due to the carbon atoms being knocked out of their normal positions in the graphite lattice. These displaced atoms are capable of returning to their normal positions again at which time their stored energy (known as Wigner stored energy after the name of Eugene Wigner who discovered it) is released in the form of heat.

Although the phenomenon of Wigner stored energy had been known for some time when the reactors were built, there was very little knowledge about how such stored energy might be released. It was known that stored energy builds up progressively with irradiation and the rate at which it accumulates is temperature dependent, virtually no energy being stored above 400°C, and that a spontaneous release of stored energy could occur as happened in the Windscale No. 1 Pile in 1952, while the pile was shut down, but without any harmful effects.

As a result of this experience procedures were instituted for the controlled release of this stored energy by allowing the chain reaction in the reactor core to commence without coolant airflow thus raising the graphite and uranium temperatures and starting the so-called Wigner energy release in the graphite. Under these conditions the release becomes self-sustaining. Eight such releases of stored energy had taken place by the end of 1956 but it had been found difficult to release energy in all the graphite in the pile and on three occasions a second heating was found necessary.

5.1.2. THE WINDSCALE FIRE

In October 1957 the No. 1 pile was shut down and a Wigner energy release was started. After some hours the nuclear heating was stopped as planned but the temperature of the graphite appeared to the plant operator to be dropping rather than increasing.

Consequently the pile operator decided to boost the release with a second nuclear heating. During this second heating a rapid rise in temperature of the uranium cartridges was observed at which time the control rods were again inserted to reduce the power. As a result of this second heating the graphite temperatures rose rapidly, leading to oxidation of the uranium which had been exposed by the overheating.

This gradually led to the failure and combustion of other uranium cartridges and subsequently to combustion of the graphite itself, all of which was exacerbated by the introduction of air into the pile in attempts to cool it. Over the next day a number attempts were made to cool the pile but without effect and eventually it became necessary to couple water hoses to the top of the pile and to flood the affected channels. This technique proved successful and after 24 hours the pile was cold.

5.1.3. HEALTH CONSEQUENCES OF THE ACCIDENT

Examination of the workers revealed that fourteen had received exposures higher than normal during the accident but even the highest exposure was only *50%* above the **ICRP** safe continuous level. Moreover, the highest level of Iodine-131 measured in the thyroid gland was very small and well below the level at which harm could be done.

The exhaust cooling gases from the Windscale piles were normally fed to the atmosphere through tall stacks equipped with filters to trap radioactive particulate matter. During the fire these filters worked adequately and it was subsequently found that no harmful amounts of plutonium or any other elements had been released with the exception of Iodine-131, a radioactive isotope of iodine. The risk from inhalation of radioactive materials was found to be as insignificant outside the factory as it was inside and no restrictions were placed on the consumption of vegetables, eggs, meat and water in the area as a consequence.

However a problem arose due to the deposition of the radioactive iodine on the grass under the area over which the plume from the chimney passed and which was eaten by the cows from the local farms. Since iodine tends to concentrate in the milk, the potential danger to young children and others drinking milk from cows which had eaten the grass on which the radioactive iodine had deposited becomes apparent. As a precaution, therefore, milk deliveries from twelve milk producers within a two-mile radius of Windscale were stopped for a time until the levels of radioactive iodine had reduced to an acceptably low level. The special Committee from the Medical Research Council which was set up after the fire to investigate the health consequences of the accident concluded: "After examining the various possibilities, we are satisfied that it is in the highest degree unlikely that any harm has been done to the health of anybody, whether a worker in the Windscale plant or a member of the general public".

5.1.4. CAUSE OF THE ACCIDENT

Following the report by the Committee of Inquiry, the Chairman of the Atomic Energy Authority (then Sir Edwin Plowden) wrote in a Memorandum that the cause of the accident was attributable to inadequacies in the instrumentation provided for the operation of the

Wigner energy release and to faults of judgement by the operating staff, which themselves were attributable to weakness of organization (the Atomic Energy Authority).

5.1.5. COMMENTARY

This particular accident occurred in a type of reactor which no longer exists since the Windscale piles which were used exclusively for the production of military materials were, in fact, never restarted after the 1957 fire. The gas-cooled, graphite moderated power reactors (Magnox and AGR) in operation in the United Kingdom today run at much higher temperatures than the Windscale piles and do not require the periodic release of Wigner stored energy. Moreover, they utilize carbon dioxide as a coolant, which is inert and would not lead to increased combustion in the event of an overheating incident. The accident itself led to a number of organizational changes in reactor management and in particular to the realization of the need for close liaison between the management of the reactor site and the local interests. These changes have led to the tight controls which are in place today in the United Kingdom.

5.2 . THREE MILE ISLAND ACCIDENT

In March 1979, the No. 2 unit at the Three Mile Island (TMI) nuclear power station in Pennsylvania, USA, suffered a severe core degradation accident, the only one of its kind to happen to any **pressurized water power reactor** (**PWR**) in the world to date. In order to understand what happened during the accident, a brief description of the plant is necessary.

TMI-2 is a pressurized water reactor with three interrelated cooling circuits. Heat generated by the reactor core is transferred to water circulating in the primary circuit which is under high pressure (about 2200 psi) to keep it from boiling. The heat from the primary circuit is transferred to a secondary circuit by means of two steam generators which produce the steam for the steam turbine which drives the electricity generator. After passing through the turbine the steam is condensed back to water by a third circuit which circulates water between the condenser and the cooling towers.

Under normal operating conditions, essentially all radioactivity is contained within the uranium oxide fuel pellets, and the fuel cladding tubes which are made from zirconium alloy that resists corrosion and high temperatures. In the event that fission products escape through the fuel cladding, such as through defects, these are trapped in the primary coolant from which they can be removed in the reactor purification system. However, krypton and xenon do not readily dissolve in water, particularly at high temperatures and collect as a gas above the coolant when the system is depressurized. The core of the reactor is encased in a pressure vessel which is a 36-foot high tank with steel walls about nine inches thick. The reactor pressure vessel and the remainder of the primary coolant system, which includes the pressurizer, steam generators and associated piping, are contained in the reactor (or containment) building. The containment building has steel-lined thick concrete walls and is the final barrier to the outside environment. The auxiliary building is located close to, but external to, the containment building. During the

TMI-2 accident, radioactivity was released to the environment when radioactive liquids were pumped from the reactor building to this auxiliary building.

5.2.1. EVENTS CONTRIBUTING TO THE ACCIDENT

On the day of the accident, a malfunction occurred to components that maintain the flow of coolant water to the steam generators in the secondary loop. This resulted in a loss of ability to remove heat from the primary loop with the result that most of the heat generated by the reactor remained in the reactor vessel and primary loop. This caused the coolant water temperature and pressure to increase rapidly which, in turn, caused a relief valve on the pressurizer to open allowing steam and water to discharge to the reactor coolant drain tank located in the basement in accordance with design procedures.

The drain tank is equipped with a pressure-limiting rupture disc. As there was no valve position indicator for the pressure relief valve clearly visible in the control room, the fact that the pressure relief valve was open was not deduced by the operators for more than two hours during which time water continued to be discharged through the valve into the drain tank. As the reactor pressure continued to fall due to the open pressure relief valve and resultant loss of primary coolant, the high pressure safety injection system (which is part of the emergency core cooling system) began automatic operation as intended.

This system was twice cut off or reduced in flow manually by operators who interpreted instrument readings to indicate that water level in the reactor was adequate. As coolant inventory declined due to continued loss of coolant through the open relief valve and the cutback of the high pressure injection system, a number of flow anomalies developed to which the operators responded in varying ways. During this period, significant fractions of the core became uncovered for extended periods and core damage resulted. Voids were created in the system, preventing natural circulation cooling and interfering with forced circulation, which was finally reestablished in one of the two loops of the system.

So much water and steam were discharged through the relief valve that the storage capacity of the drain tank was quickly exceeded, causing the rupture disc to burst, allowing some 250,000 gallons of radioactive coolant to be discharged into the reactor building sump and basement. Radioactive coolant water in the reactor building sump was then automatically pumped into the sump tank in the auxiliary building which was already about half full. Consequently, much of the water spilled into the auxiliary building, which was not designed to contain radioactive material. This liquid did not contain significant amounts of radioactivity, however, because major fuel damage did not occur until about two hours later.

After fuel damage occurred, radioactive materials were transported through the primary coolant system via the letdown line to the makeup and purification system in the auxiliary building. Because this liquid was a stream of primary coolant directly from the reactor, it contained significant amounts of radioactivity. As a result of liquid leaks in the makeup and purification system, large amounts of radioactive material were released into the auxiliary building. No longer held under pressure, krypton, xenon and other volatile radio-nuclides evolved from the water into the auxiliary building atmosphere.

In one of the least expected and most highly publicized facets of the incident, the upper section of the reactor pressure vessel became occupied by hydrogen formed by reaction of primary coolant water with overheated zircaloy cladding when the core was partially exposed. A portion of this hydrogen escaped into the reactor containment building with the water vented through the pressure relief valve, and this hydrogen ignited at 10 hours after initiation of the incident, resulting in a containment pressure spike of 28 psi. This hydrogen ignition or explosion was unreported for some time to both the **NRC** and the press, but for several days, wide and sensational publicity was given to the presence of the hydrogen "bubble" in the reactor, and to the possibility of its explosion, the risk of which was nonexistent, since no free oxygen could be present in the gas under the conditions in the reactor. Removal of the hydrogen from the system became, in press reporting, one of the most dramatic and risky aspects of the incident, with attention focused on the possibility of explosion in the containment building as hydrogen released -o the containment atmosphere built up. 'This was avoided by activation of a catalytic recombination which kept the hydrogen concentration below combustible limits.

5.2.2. RADIOACTIVITY RELEASE TO THE ENVIRONMENT

During the accident, approximately 50 percent of the noble gases and particulate cesium, 30 percent of the iodine and small quantities of other fission products normally present in irradiated fuel were released from the damaged fuel into the primary coolant water. Before being released into the environment, the small amount of the airborne radioactivity released to the reactor building was filtered and monitored.

The highly efficient filtration system in the auxiliary and fuel handling buildings was designed to remove more than 99 percent of radioactive cesium, strontium and alpha-emitting radio-nuclides, In addition to mechanical filtration, ventilated air in these buildings was also passed through multiple charcoal filters, which chemically removed 90 to 95 percent of the radioactive iodine.

While offsite radiation levels never exceeded about 35 mrem/hr, and total exposure to any individual in the areas of highest activity are estimated not to have exceeded 80 mrem, compared to a typical background exposure of around 300 mrem/yr per person, the presence of offsite radioactivity and the exaggerated threat of its massive release from a possible breach of the containment due to possible hydrogen explosion, coupled with sensational media reporting, generated intense nationwide concern for over a week.

The prospect of a large-scale evacuation of the surrounding population and the planning for that contingency further aroused public concern. On the third day, evacuation of pregnant women and children under six years of age residing within five miles of the plant site was officially recommended by the governor of Pennsylvania. General evacuation was never ordered (although the possibility of such evacuation was openly discussed by the press and officials at every level, including President Carter) but an estimated 80,000-200,000 residents of the area voluntarily left their homes. Most returned shortly after Governor Thornburgh advised some days later that it was safe to do so.

5.2.3. POTENTIAL HEALTH EFFECTS FROM THE ACCIDENT

It was the release of radioactivity from the plant and the appearance of detectable amounts of radiation beyond the plant boundaries which led to the most serious public and media reactions even though radiation exposure and contamination never reached significant levels from the standpoint of health. Traces of radioactive iodine were detected authorities in some milk samples, but at levels so low that none was ever removed from the market. It has since been estimated that cumulative exposure from the incident could result in one additional cancer death, one added nonfatal cancer, and one additional birth defect over the next 25 years among the two million people within 50 miles of the facility. These two million people are statistically expected to suffer 325,000 cancer deaths from natural causes other than the T'MI accident.

Although there have been many allegations of increased leukemia and other cancers in people living in the area, particularly young people, studies by the Pennsylvania Department of Health have not revealed incidences greater than normal. These findings have, moreover, been confirmed by a team of independent epidemiologists who have been studying the allegations for the TMI Health Fund and whose results were published in September 1990.

Nevertheless, one of the major concerns emerging during the period of the accident was the psycho-behavioral impact on local residents. The Pennsylvania Department of Health has reported that for some months after the accident many local residents suffered from severe distress.

5.2.4. COMMENTARY

The Three Mile Island accident was caused by a combination of human error and system malfunction. It resulted in the degradation and partial melting of the reactor core and the total loss of the reactor which is still being decontaminated. Nevertheless, in spite of the enormous media attention given to it at the time, the safety features engineered into the system prevented the release of all but trivial amounts of radioactivity into the biosphere.

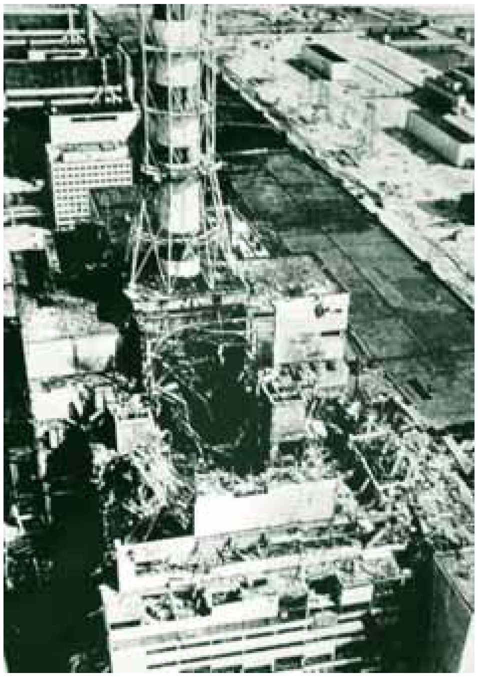
The accident had a big effect on the industry and also on the regulators since it clearly pointed up the defects in operator training and in some of the engineered safety features of the reactor system which had hitherto been considered adequate. As a result, the industry set up it own "watchdog", the **Institute for Nuclear Power Operations** (**INPO**), which is independent of the **Nuclear Regulatory Commission. INPO** oversees the operations of the industry and will take action as and when required to ensure industry compliance with good practice.

For its part, the **NRC** required a number of back-fits to be carried out on existing reactors to ensure that future incidents of this kind have a very low probability of happening. The **NRC** also instituted a program for reactor operator training which is designed to improve the quality of performance of future operators. Most of these improvement have since been implemented by overseas operators of light water reactors as part of the overall safety improvements of reactors all over the world.

5.3. THE CHERNOBYL ACCIDENT

PHOTOGRAPH OF FOUR REACTORS AT CHERNOBYL

CLOSE-UP PHOTOGRAPH OF REACTOR #4 AT CHERNOBYL



On April 26, 1986, the worst accident in the history of commercial nuclear power generation occurred at the Chernobyl Nuclear Power Station some 60 miles north of Kiev in the Ukraine. The accident caused extensive damage to the reactor and the building which housed it; some 31 people died as a result of the fire and explosion, or as a result of receiving lethal radiation doses.

A significant release of fission products occurred, contaminating the land around the station and requiring the evacuation of around 135,000 people from their homes. The radioactive cloud generated by the accident over many days was carried by winds all over Europe and led to restrictions on the consumption of meat and vegetables which became contaminated from it. Although the latent health effects may not be statistically significant when viewed against the normal mortality rate over the next 40 years, nevertheless the accident has had a big impact on public concern about nuclear safety. It is, therefore, desirable to provide a brief description of the reactor and the events which contributed to the accident.

The accident destroyed the Chernobyl 4 reactor, killing 30 operators and firemen within three months and several further deaths later. One person was killed immediately and a second died in hospital soon after as a result of injuries received. Another person is reported to have died at the time from a coronary thrombosis. 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 within a few weeks of the accident. Nineteen more subsequently died between 1987 and 2004 but their deaths cannot necessarily be attributed to radiation exposure. Nobody off-site suffered from acute radiation effects although a large proportion of childhood thyroid cancers diagnosed since the accident is likely to be due to intake of radioactive iodine fallout. Furthermore, large areas of Belarus, Ukraine, Russia and beyond were contaminated in varying degrees.

The Chernobyl disaster was a unique event and the only accident in the history of commercial nuclear power where radiation-related fatalities occurred. However, the design of the reactor is unique and the accident is thus of little relevance to the rest of the nuclear industry outside the then Eastern Bloc.

The Chernobyl Power Complex, consisted of four nuclear reactors of the RBMK-1000 design, units 1 and 2 being constructed between 1970 and 1977, while units 3 and 4 of the same design were completed in 1983. Two more RBMK reactors were under construction at the site at the time of the accident. To the southeast of the plant, an artificial lake of some 22 square kilometres, situated beside the river Pripyat, a tributary of the Dniepr, was constructed to provide cooling water for the reactors.

This area of Ukraine is described as Belarussian-type woodland with a low population density. About 3 km away from the reactor, in the new city, Pripyat, there were 49,000 inhabitants. The old town of Chernobyl, which had a population of 12,500, is about 15 km to the southeast of the complex. Within a 30 km radius of the power plant, the total population was between 115,000 and 135,000.

5.3.1. EVENTS LEADING TO THE ACCIDENT

Ironically the immediate cause of the accident was an experiment designed to improve the safety of the plant. The objective of the experiment was to test the turbo-generator's ability to provide in-house power after shutting off its steam supply for the short time needed for the emergency diesels to start and come online, nominally 40 to 50 seconds, and required the reactor to be at about 25% full power.

This test had been attempted twice before in 1982 and 1984, on which occasion it was found that the voltage output decreased faster than desired and the purpose of the test was to verify proper operation of a new voltage regulator design for the generator. In the subsequent inquiry into the causes of the accident, it became clear that the experimental test had been badly planned, that the safety case had been inadequate, and that the operators had departed from laid down operating procedures and had violated several operating rules.

The test procedure itself called for turning off the emergency core cooling system. Operator actions included disconnecting the signal that automatically shuts down the reactor when two turbo-generators. are disconnected, operating the main coolant pumps in a regime where cavitation might occur, turning off various protection system signals, and operating with less than the minimum required number of inserted control rods. Power reduction to the test power level of 700-1000 MWt began but was halted while the operators disconnected one of the two turbo-generators from the reactor. Four main cooling pumps, and two feed-water pumps were connected to the turbo-generator to be run down. The operators also disabled the signal which results in automatic reactor shutdown when both turbo-generators are disconnected. This action was intended to permit rerunning the test if needed - but the test procedure did not call for disabling this emergency system.

In addition, the operators disabled the emergency core cooling system, but this was done in accordance with test procedure. Before power reduction could continue, the grid controller requested the operators to hold power and not continue with the test. In complying with this request a further violation of normal plant operating procedures occurred since continuous operation at power with the emergency core cooling system disabled is a violation.

Following the delay, the operators continued the power descent and disengaged the local automatic power regulation system. A further operator error was made at this point when the operators failed to set the backup automatic controller to its proper "hold power" set-point. This resulted in the operators being unable to control the reactor power which began a rapid unplanned power reduction, falling to as low as 30 MWt before they were able to stabilize power at about 200 MWt.

This unplanned power reduction allowed the build-up of xenon (which is a strong neutron absorber) to a sufficiently high level that it reduced core reactivity which had to be compensated by withdrawal of control rods. Attempts were then made to increase power to the required level of 700-1000 MWt but were unsuccessful due to low core reactivity.

This was made more difficult by the fact that the control rods had been mostly withdrawn to compensate for the buildup of xenon.

Consequently, with the reactor only at 200 MWt, the decision was made to proceed with the test and two of the eight main circulation pumps, which up to then had not been in operation were started up and the flow rate of the water to the core was thereby increased. The result was a reduction in steam formation and a fall in water level in the steam drums which the operators tried to increase by using feed-water pumps. The immediate effect was to reduce core reactivity because of the reduction in steam voids and the operators responded by removing manual control rods from the core.

Conditions were thus produced with a potential for a large increase in steam voids and core reactivity. Nevertheless the experiment was started at which time events were only about one minute away from disaster. At a lower operating regime the **RBMK** reactor is fundamentally unstable due to its design. The reason for this involves the concepts of the positive void coefficient and the positive power coefficient.

At the time of the accident the Chernobyl reactor was being operated at less than 20% full power and thus in the unstable region. Immediately the experiment commenced, steam supply to one of the operating turbo-generators was shut off, which should have automatically caused a shutdown of the reactor. However, the operators had deliberately disabled the protection system to keep the reactor running so that the experiment could be repeated if the first attempt was unsuccessful. The turbo-generator rapidly decelerated and the four main circulating pumps connected to it started to run down. The water in the core started to boil increasing the volume of steam and creating voids in the core.

As a result of the positive void coefficient the power of the reactor started to rise and a positive feedback ensued (i.e. the power increased by itself). Although the operators tried to stop the reactor from "running away" by inserting the control rods as rapidly as possible, it was far too late. The rate of increase of power was such that the power rose in an uncontrolled manner to some 100 times full power in a matter of a few seconds causing severe fuel damage and fuel channel disruption.

A violent steam explosion occurred due to the interaction of water with the molten fuel, and blew off the 1000 tonne reactor cap and ejected burning material into the air, some of which landed on the roof of the joint turbine hall and put the adjacent undamaged reactor at risk. The term "void coefficient" means that if the power from the fuel increases, or the flow of coolant water decreases, or a combination of both, the amount of steam in the fuel channel increases.

This causes the density of the coolant to decrease because of the steam voids which have been created in the water. In most reactor designs, such as the **LWR,** the production of voids causes the number of neutrons to decrease and thus reduce the power. In this case the void coefficient is said to be "negative". In the case of the **RBMK** however, the design of the core is such that it has a "positive void coefficient" so that when the coolant density decreases the number of neutrons increases and thus the reactor power increases. Although the initial fires were started by the burning debris ejected from the reactor, the main fire was due to the graphite also catching fire. This raging fire acted as a chimney to loft particulates of the fuel and fission products very high into the air.

5.3.2. IMMEDIATE IMPACT OF THE CHERNOBYL ACCIDENT

It is estimated that all of the xenon gas, about half of the iodine and cesium, and at least 5% of the remaining radioactive material in the Chernobyl 4 reactor core (which had 192 tonnes of fuel) was released in the accident. Most of the released 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. The casualties included firefighters who attended the initial fires on the roof of the turbine building. All these were put out in a few hours, but radiation doses on the first day were estimated to range up to 20,000 millisieverts (mSv), causing 28 deaths – six of which were firemen – by the end of July 1986. The next task was cleaning up the radioactivity at the site so that the remaining three reactors could be restarted, and the damaged reactor shielded more permanently. About 200,000 people ('liquidators') from all over the Soviet Union were involved in the recovery and clean-up during 1986 and 1987. They received high doses of radiation, averaging around 100 millisieverts. Some 20,000 of them received about 250 mSv and a few received 500 mSv. Later, the number of liquidators swelled to over 600,000 but most of these received only low radiation doses. The highest doses were received by about 1000 emergency workers and on-site personnel during the first day of the accident.

Initial radiation exposure in contaminated areas was due to short-lived iodine-131; later caesium-137 was the main hazard. (Both are fission products dispersed from the reactor core, with half lives of eight days and 30 years, respectively. 1.8 EBq of I-131 and 0.085 EBq of Cs-137 were released.) about five million people lived in areas contaminated (above 37 kBq/m^2 Cs-137) and about 400,000 lived in more contaminated areas of strict control by authorities (above 555 kBq/m^2 Cs-137).

The plant operators' town of Pripyat was evacuated on 27 April (45,000 residents). By 14 May, some 116,000 people that had been living within a 30 kilometers radius had been evacuated and later relocated. About 1000 of these returned unofficially to live within the contaminated zone. Most of those evacuated received radiation doses of less than 50 mSv, although a few received 100 mSv or more. In the years following the accident, a further 220,000 people were resettled into less contaminated areas, and the initial 30 km radius exclusion zone (2800 km^2) was modified and extended to cover 4300 square kilometers. This resettlement was due to application of a criterion of 350 mSv projected lifetime radiation dose, though in fact radiation in most of the affected area (apart from half a square kilometers) fell rapidly so that average doses were less than 50% above normal background of 2.5 mSv/yr.

5.3.3. ENVIRONMENTAL AND HEALTH EFFECTS OF THE ACCIDENT

Several organizations have reported on the impacts of the Chernobyl accident, but all have had problems assessing the significance of their observations because of the lack of reliable public health information before 1986. In 1989, the World Health Organization (WHO) first raised concerns that local medical scientists had incorrectly attributed various biological and health effects to radiation exposure. Following this, the Government of the USSR requested the International Atomic Energy Agency (IAEA) to coordinate an international experts' assessment of accident's radiological, environmental and health consequences in selected towns of the most heavily contaminated areas in Belarus, Russia, and Ukraine. Between March 1990 and June 1991, a total of 50 field missions were conducted by 200 experts from 25 countries (including the USSR), seven organizations, and 11 laboratories. In the absence of pre-1986 data, it compared a control population with those exposed to radiation. Significant health disorders were evident in both control and exposed groups, but, at that stage, Subsequent studies in the Ukraine, Russia and Belarus were based on national registers of over one million people possibly affected by radiation. By 2000, about 4000 cases of thyroid cancer had been diagnosed in exposed children. However, the rapid increase in thyroid cancers detected suggests that some of it at least is an artefact of the screening process. Thyroid cancer is usually not fatal if diagnosed and treated early. In February 2003, the IAEA established the Chernobyl Forum, in cooperation with seven other UN organizations as well as the competent authorities of Belarus, the Russian Federation and Ukraine. In April 2005, the reports prepared by two expert groups – "Environment", coordinated by the IAEA, and "Health", coordinated by WHO – were intensively discussed by the Forum and eventually approved by consensus. The conclusions of this 2005 Chernobyl Forum study (revised version published 2006[i]) are in line with earlier expert studies, notably the UNSCEAR 2000 report which said that "apart from this [thyroid cancer] increase, there is no evidence of a major public health impact attributable to radiation exposure 14 years after the accident. There is no scientific evidence of increases in overall cancer incidence or mortality or in non-malignant disorders that could be related to radiation exposure." As yet there is little evidence of any increase in leukemia, even among clean-up workers where it might be most expected. However, these workers – where high doses may have been received – remain at increased risk of cancer in the long term.

The Chernobyl Forum report says that people in the area have suffered a paralyzing fatalism due to myths and misperceptions about the threat of radiation, which has contributed to a culture of chronic dependency. Some "took on the role of invalids." Mental health coupled with smoking and alcohol abuse is a very much greater problem than radiation, but worst of all at the time was the underlying level of health and nutrition. Apart from the initial 116,000, relocations of people were very traumatic and did little to reduce radiation exposure, which was low anyway. Psycho-social effects among those affected by the accident are similar to those arising from other major disasters such as earthquakes, floods and fires.

According to the most up-to-date estimate of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the average radiation dose due to the accident received by inhabitants of 'strict radiation control' areas (population 216,000) in the years 1986 to 2005 was 61 mSv (over the 20-year period), and in the 'contaminated' areas (population 6.4 million) it averaged 9 mSv, a minor increase over the dose due to background radiation over the same period (50 mSv).

The numbers of deaths resulting from the accident are covered in the *Report of the Chernobyl Forum Expert Group "Health"*, and are summarized in Chernobyl Accident Appendix 2: Health Impacts. Some exaggerated figures have been published regarding the death toll attributable to the Chernobyl disaster. A publication by the UN Office for the Coordination of Humanitarian Affairs (OCHA) lent support to these. However, the Chairman of UNSCEAR made it clear that "this report is full of unsubstantiated statements that have no support in scientific assessments, and the Chernobyl Forum report also repudiates them

5.3.4. PROGRESSIVE CLOSURE OF THE CHERNOBYL PLANT

In the early 1990s, some US$400 million was spent on improvements to the remaining reactors at Chernobyl, considerably enhancing their safety. Energy shortages necessitated the continued operation of one of them (unit 3) until December 2000. (Unit 2 was shut down after a turbine hall fire in 1991, and unit 1 at the end of 1997.) Almost 6000 people worked at the plant every day, and their radiation dose has been within internationally accepted limits. A small team of scientists works within the wrecked reactor building itself, inside the shelter. Workers and their families now live in a new town, Slavutich, 30 km from the plant. This was built following the evacuation of Pripyat, which was just 3 km away. Ukraine depends upon, and is deeply in debt to, Russia for energy supplies, particularly oil and gas, but also nuclear fuel. Although this dependence is gradually being reduced, continued operation of nuclear power stations, which supply half of total electricity, is now even more important than in 1986.

When it was announced in 1995 that the two operating reactors at Chernobyl would be closed by 2000, a memorandum of understanding was signed by Ukraine and G7 nations to progress this, but its implementation was conspicuously delayed. Alternative generating capacity was needed, either gas-fired, which has ongoing fuel cost and supply implications, or nuclear, by completing gas-fired, which has ongoing fuel cost and supply implications, or nuclear, by completing Khmelnitski unit 2 and Rovno unit 4 ('K2R4') in Ukraine. Construction of these was halted in 1989 but then resumed, and both reactors came on line late in 2004, financed by Ukraine rather than international grants as expected on the basis of Chernobyl's closure.

5.3.5. CHERNOBYL TODAY

Chernobyl unit 4 is now enclosed in a large concrete shelter which was erected quickly to allow continuing operation of the other reactors at the plant. However, the structure is neither strong nor durable. The international Shelter Implementation Plan in the 1990s involved raising money for remedial work including removal of the fuel-containing materials. Some major work on the shelter was carried out in 1998 and 1999. Some 200 tonnes of highly radioactive material remains deep within it, and this poses an environmental hazard until it is better contained. A New Safe Confinement structure will be built by the end of 2011, and then will be moved into place on rails. It is to be an 18,000 tonne metal arch 105 metres high, 200 metres long and spanning 257 metres, to cover both unit 4 and the hastily-built 1986 structure. The Chernobyl Shelter Fund, set up in 1997, had received €810 million from international donors and projects towards this project and previous work. It and the Nuclear Safety Account, also applied to Chernobyl decommissioning, are managed by the European Bank for Reconstruction and Development (EBRD), which announced a €135 million contribution to the fund in May 2008. The total cost of the new shelter is estimated to be €1.2 billion. Used fuel from units 1 to 3 is stored in each unit's cooling pond, in a small interim spent fuel storage facility pond (ISF-1), and in the reactor of unit 3.

In 1999, a contract was signed for construction of a radioactive waste management facility to store 25,000 used fuel assemblies from units 1-3 and other operational wastes, as well as material from decommissioning units 1-3 (which will be the first RBMK units decommissioned anywhere). The contract included a processing facility, able to cut the RBMK fuel assemblies and to put the material in canisters, which will be filled with inert gas and welded shut. They will then be transported to the dry storage vaults in which the fuel containers would be enclosed for up to 100 years. This facility, treating 2500 fuel assemblies per year, would be the first of its kind for RBMK fuel. However, after significant parts of the storage structures had been built, technical deficiencies in the concept emerged, and the contract was terminated in 2007. The interim spent fuel storage facility (ISF-2) is now planned to be completed by others by mid-2013. In April 2009, Nukem handed over a turnkey waste treatment center for solid radioactive waste (ICSRM, Industrial Complex for Radwaste Management). In May 2010, the State Nuclear Regulatory Committee licensed the commissioning of this facility, where solid low- and intermediate-level wastes accumulated from the power plant operations and the decommissioning of reactor blocks 1 to 3 is conditioned. The wastes are processed in three steps. First, the solid radioactive wastes temporarily stored in bunkers is removed for treatment. In the next step, these wastes, as well as those from decommissioning reactor blocks 1-3, are processed into a form suitable for permanent safe disposal. Low- and intermediate-level wastes are separated into combustible, compactable, and non-compactable categories. These are then subject to incineration, high-force compaction, and cementation respectively. In addition, highly radioactive and long-lived solid waste is sorted out for temporary separate storage. In the third step, the conditioned solid waste materials are transferred to containers suitable for permanent safe storage.

As part of this project, at the end of 2007, Nukem handed over an Engineered Near Surface Disposal Facility for storage of short-lived radioactive waste after prior conditioning. It is 17 km away from the power plant at the Vektor complex within the 30-km zone. The storage area is designed to hold 55,000 m^3 of treated waste which will be subject to radiological monitoring for 300 years, by then the radioactivity will have decayed to such an extent that monitoring is no longer required.

Another contract has been let for a Liquid Radioactive Waste Treatment Plant, to handle some 35,000 cubic meters of low- and intermediate-level liquid wastes at the site. This will need to be solidified and eventually buried along with solid wastes on site. In January 2008, the Ukraine government announced a four-stage decommissioning plan which incorporates the above waste activities and progresses towards a cleared site.

5.3.6. RESETTLEMENT OF CONTAMINATED AREAS

In the last two decades there has been some resettlement of the areas evacuated in 1986 and subsequently. Recently the main resettlement project has been in Belarus. In July 2010, the Belarus government announced that it had decided to settle back thousands of people in the 'contaminated areas' covered by the Chernobyl fallout, from which 24 years ago they and their forbears were hastily relocated. Compared with the list of contaminated areas in 2005, some 211 villages and hamlets had been reclassified with fewer restrictions on resettlement. The decision by the Belarus Council of Ministers resulted in a new national program over 2011-15 and up to 2020 to alleviate the Chernobyl impact and return the areas to normal use with minimal restrictions. The focus of the project is on the development of economic and industrial potential of the Gomel and Mogilev regions from which 137,000 people were relocated.

The main priority is agriculture and forestry, together with attracting qualified people and housing them. Initial infrastructure requirements will mean the refurbishment of gas, potable water and power supplies, while the use of local wood will be banned. Schools and housing will be provided for specialist workers and their families ahead of wider socio-economic development. Overall, some 21,484 dwellings are slated for connection to gas networks in the period 2011-2015, while about 5600 contaminated or broken down buildings are demolished. Over 1300 kilometers of road will be laid, and ten new sewerage works and 15 pumping stations are planned. The cost of the work was put at BYR 6.6 trillion ($2.2 billion), split fairly evenly across the years 2011 to 2015 inclusive.

The feasibility of agriculture will be examined in areas where the presence of caesium-137 and strontium-90 is low, "to acquire new knowledge in the fields of radiobiology and radioecology in order to clarify the principles of safe life in the contaminated territories." Land found to have too high a concentration of radionuclides will be reforested and managed. A suite of protective measures is to be set up to allow a new forestry industry whose products would meet national and international safety standards. In April 2009, specialists in Belarus stressed that it is safe to eat all foods cultivated in the contaminated territories, though intake of some wild food was restricted.

Protective measures will be put in place for 498 settlements in the contaminated areas where average radiation dose may exceed 1 mSv per year. There are also 1904 villages with annual average effective doses from the pollution between 0.1 mSv and 1 mSv. The goal for these areas is to allow their re-use with minimal restrictions, although already radiation doses there from the caesium are lower than background levels anywhere in the world. The most affected settlements are to be tackled first, around 2011- 2013, with the rest coming back in around 2014-2015.

5.3.7. LESSONS LEARNED FROM CHERNOBYL

Leaving aside the verdict of history on its role in melting the Soviet 'Iron Curtain', some very tangible practical benefits have resulted from the Chernobyl accident. The main ones concern reactor safety, notably in Eastern Europe. (The US Three Mile Island accident in 1979 had a significant effect on Western reactor design and operating procedures. While that reactor was destroyed, all radioactivity was contained – as designed – and there were no deaths or injuries.) While no-one in the West was under any illusion about the safety of early Soviet reactor designs, some lessons learned have also been applicable to Western plants. Certainly the safety of all Soviet-designed reactors has improved vastly. This is due largely to the development of a culture of safety encouraged by increased collaboration between East and West, and substantial investment in improving the reactors.

Modifications have been made to overcome deficiencies in all the RBMK reactors still operating. In these, originally the nuclear chain reaction and power output could increase if cooling water were lost or turned to steam, in contrast to most Western designs. It was this effect which led to the uncontrolled power surge that led to the destruction of Chernobyl 4 All of the RBMK reactors have now been modified by changes in the control rods, adding neutron absorbers and consequently increasing the fuel enrichment from 1.8 to 2.4% U-235, making them very much more stable at low power. Automatic shut-down mechanisms now operate faster, and other safety mechanisms have been improved. Automated inspection equipment has also been installed. A repetition of the 1986 Chernobyl accident is now virtually impossible, according to a German nuclear safety agency report.

Since 1989, over 1000 nuclear engineers from the former Soviet Union have visited Western nuclear power plants and there have been many reciprocal visits. Over 50 twinning arrangements between East and West nuclear plants have been put in place. Most of this has been under the auspices of the World Association of Nuclear Operators (WANO), a body formed in 1989 which links 130 operators of nuclear power plants in more than 30 countries. Many other international programs were initiated following Chernobyl. The International Atomic Energy Agency (IAEA) safety review projects for each particular type of Soviet reactor are noteworthy, bringing together operators and Western engineers to focus on safety improvements. The Convention on Nuclear Safety adopted in Vienna in June 1994 is another outcome. The Chernobyl Forum report said that some seven million people are now receiving or eligible for benefits as 'Chernobyl victims', which means that resources are not targeting the needy few percent of them. Remedying this presents daunting political problems however.

5.3.8. HEALTH EFFECTS OF THE ACCIDENT

The Soviets have calculated that about 10% of the graphite (about 250 tons) was burned and some 3-4% of the fuel was expelled from the core. The release of radioactive material from the core did not occur in a single massive event. Only 25% of the materials released escaped during the first day of the accident as a result of the explosion. The rest escaped over a nine-day period as a result of the fire before it was contained. It has been estimated that the proportions of the core inventory deposited at various distance from Chernobyl was as follows:

- On-site 0.3-0.5%
- 0-20 km 1.5-2%
- Beyond 20 km 1.0-1.5%

The immediate health impact was, of course, on the plant personnel and rescue workers, a number of whom received massive doses of radiation from which they died. Others had to be hospitalized for treatment of radiation burns. Outside the immediate area of the reactor accident the doses were too small to cause "acute" radiation effects.

Initially the local population was instructed to remain indoors and to close their windows, but as the levels of radiation began to increase, evacuation commenced and arrangements were made for decontamination of the skin and clothing where necessary. Outside the Soviet Union the doses received from the fallout were large enough, particularly in Western Europe, to cause an appreciable increase above the average natural radiation exposure.

In the first year the estimated increase over natural background was about 20% in the countries of the European Community. Nevertheless, an International Panel of Experts, convened by the Commission of the European Communities to advise on the feasibility of studies on health effects in western Europe from the Chernobyl accident, concluded that the levels of exposure were so low as to preclude any effects being detected in the exposed populations of the EEC.

Although there was no immediate health impact on the local population from the fallout from the accident, the doses received might be expected to result in an increased incidence of radiation-induced cancers in later years. At the present time, however, adverse health effects due to radiation exposure have not been observed. A study carried out by the International Chernobyl Project has pointed out that many of the local clinical investigations of health effects were poorly done and produced confusing , and often contradictory results.

Nevertheless, the International Project stated in its report that "....adverse health effects have not been substantiated by those local studies which were adequately performed or by the studies under the Project". The Project report points out, however, that there were significant non-radiation health disorders in the populations of both survey contaminated and surveyed control settlements studies by the Project, but no health disorders that could be attributed directly to radiation exposure.

However, as the Soviet Union has a population around 275-million and over the next 40 years the number of deaths can be expected to be approximately 30-million, of which some 7.6-million will be from cancer. Consequently, deaths due to Chernobyl, which appear to lie in the range 4,000/38,000, may be impossible to detect with any certainty. In fact, the International Chernobyl Project states in its recent report that "On the basis of the doses estimated by the Project and currently accepted radiation risk estimates, future increases over the natural incidence of cancers or hereditary effects would be difficult to discern, even with large and well- designed long term epidemiological studies".

5.3.9. COMMENTARY

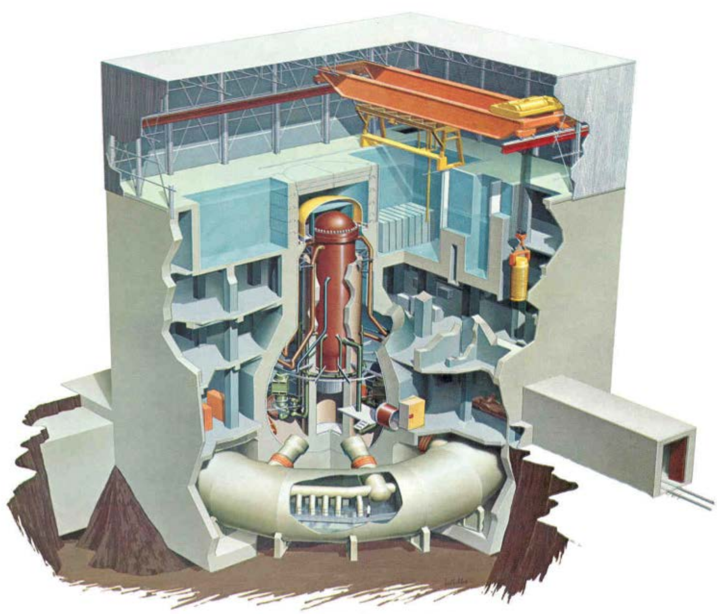
A number of factors combined together to bring about this accident. It could not have occurred had the **RBMK** not had certain design features, notably its positive void coefficient at low power operation, or if the design had included safety systems to cope with such a characteristic. Equally the accident could not have occurred had there not been the application of inappropriate operating rules by the operators.

From the standpoint of the developing countries the lessons from the Chernobyl accident are of great importance. In the first instance it stresses the need for ensuring that the reactors being built have adequate safety features, particularly those which prevent an accident from happening in the event of operator error. Such systems will, presumably, be purchased from exporting countries and will have been certified by the regulatory bodies in those countries. More importantly, however, the Chernobyl accident stresses the importance of good operator training and supervision.

It is quite clear from the Soviet report on the accident that the operators did not understand their plant and were not sufficiently aware of its special technological features. It is also clear from the same report that the operators had become complacent (as they had at TMI) to the extent that they had slipped into the dangerous attitude that an accident could never happen.

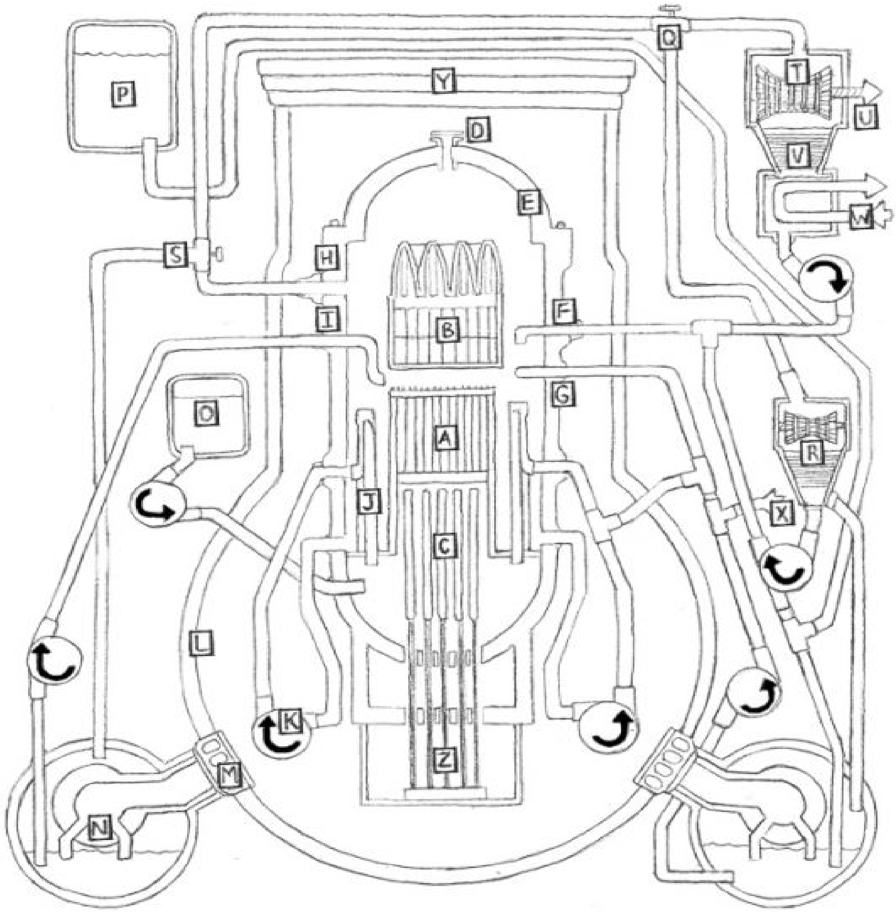
5.4. THE EVENT IN THE GE-MARK I REACTOR AT FUKUSHIMA, JAPAN

ISOMETRIC VIEW OF GE-MARK I NUCLEAR POWER PLANT



DRYWELL TORUS

SCHEMATIC OF GE-MARK I REACTOR AT FUKUSHIMA, JAPAN



Mark I Reactor Components

- **A.** Uranium fuel rods
- **B.** Steam Separator and dryer assemblies
- **C.** Graphite control rods
- **D.** Vent and head spray
- **E.** Reactor Vessel
- **F.** Feedwater inlet
- **G.** Low pressure coolant injection inlet
- **H.** Steam Outlet
- **I.** Core spray inlet
- **J.** Jet pump
- **K.** Recirculation pump
- **L.** Concrete Shell “Drywell”
- **M.** Venting System
- **N.** Suppression pool
- **O.** Boron tank
- **P.** Condensate storage tank

5.4.1. THE NUCLEAR EVENT AT FUKUSHIMA, JAPAN

The earthquake that hit Japan was 5 times more powerful than the worst earthquake the nuclear power plant was designed and built for (the Richter scale works logarithmically; the difference between the 8.2 that the plants were built for and the 8.9 that happened is 5 times, not 0.7). So the first hooray for Japanese engineering, everything held up.

When the earthquake hit with 8.9, the nuclear reactors all went into automatic shutdown. Within seconds after the earthquake started, the control rods had been inserted into the core and nuclear chain reaction of the uranium stopped. When the rods are inserted into the reactor core the turbines are automatically taken off-line. Now, the auxiliary diesel generators need to start and activate the cooling system which has to carry away the residual heat. The residual heat load is about 3% of the heat load under normal operating conditions.

The earthquake destroyed the external power supply of the nuclear reactor. That is one of the most serious accidents for a nuclear power plant, and accordingly, a “plant black out” receives a lot of attention when designing backup systems. The power is needed to keep the coolant pumps working. Since the power plant had been shut down, it cannot produce any electricity by itself any more.

Things were going well for an hour. One set of multiple sets of emergency Diesel power generators kicked in and provided the electricity that was needed. Then the Tsunami came, much bigger than people had expected when building the power plant. The tsunami took out all multiple sets of backup Diesel generators.

When designing a nuclear power plant, engineers follow a philosophy called “Defense of Depth”. That means that you first build everything to withstand the worst catastrophe you can imagine, and then design the plant in such a way that it can still handle one system failure (that you thought could never happen) after the other. A tsunami taking out all backup power in one swift strike is such a scenario. The last line of defense is putting everything into the third containment, that will keep everything, whatever the mess, control rods in our out, core molten or not, inside the reactor.

When the diesel generators were gone, the reactor operators switched to emergency battery power. The batteries were designed as one of the backups to the backups, to provide power for cooling the core for 8 hours. And they did.

Within the 8 hours, another power source had to be found and connected to the power plant. The power grid was down due to the earthquake. The diesel generators were destroyed by the tsunami. So mobile diesel generators were trucked in.

This is where things started to go seriously wrong. The external power generators could not be connected to the power plant (the plugs did not fit). So after the batteries ran out, the residual heat could not be carried away any more.

At this point the plant operators begin to follow emergency procedures that are in place for a “loss of cooling event”. It is again a step along the “Depth of Defense” lines. The power to the cooling systems should never have failed completely, but it did, so they “retreat” to the next line of defense. All of this, however shocking it seems to us, is part of the day-to-day training the operators go through as part of operator training, right through to managing a core meltdown.

It was at this stage that people started to talk about core meltdown. Because at the end of the day, if cooling cannot be restored, the core will eventually melt (after hours or days), and the last line of defense, the core catcher and third containment, would come into play.

But the goal at this stage was to manage the core while it was heating up, and ensure that the first containment (the Zircaloy tubes that contains the nuclear fuel), as well as the second containment remain intact and operational for as long as possible, to give the engineers time to fix the cooling systems.

Because cooling the core is such a big deal, the reactor has a number of cooling systems, each in multiple versions (the reactor water cleanup system, the decay heat removal, the reactor core isolating cooling, the standby liquid cooling system, and the emergency core cooling system). Which one failed when or did not fail is not clear at this point in time.

So imagine a pressure cooker on the stove, heat on low, but on. The operators use whatever cooling system capacity they have to get rid of as much heat as possible, but the pressure starts building up. The priority now is to maintain integrity of the first containment (keep temperature of the fuel rods below 2200°C), as well as the second containment, the pressure cooker. In order to maintain integrity of the pressure cooker (the second containment), the pressure has to be released from time to time. Because the ability to do that in an emergency is so important, the reactor has 11 pressure release valves. The operators now started venting steam from time to time to control the pressure. The temperature at this stage was about 550°C.

This is when the reports about "radiation leakage" starting coming in. The Senior Engineer explained above why venting the steam is theoretically the same as releasing radiation into the environment, but why it was and is not dangerous. The radioactive nitrogen as well as the noble gases do not pose a threat to human health. At some stage during this venting, the explosion occurred. The explosion took place outside of the third containment (our "last line of defense"), and the reactor building. Remember that the reactor building has no function in keeping the radioactivity contained.

It is not entirely clear yet what has happened, but this is the likely scenario: The operators decided to vent the steam from the pressure vessel not directly into the environment, but into the space between the third containment and the reactor building (to give the radioactivity in the steam more time to subside). The problem is that at the high temperatures that the core had reached at this stage, water molecules can "disassociate" into oxygen and hydrogen – an explosive mixture. And it did explode, outside the third containment, damaging the reactor building around.

It was that sort of explosion, but inside the pressure vessel (because it was badly designed and not managed properly by the operators) that lead to the explosion of Chernobyl. This was never a risk at Fukushima. The problem of hydrogen-oxygen formation is one of the most important in the design of a power plant (if you are not Soviet, that is), so the reactor is built and operated in a way it cannot happen inside the containment. It happened outside, which was not intended but a possible scenario and OK, because it did not pose a risk for the containment.

So the pressure was under control, as steam was vented. Now, if you keep boiling your pot, the problem is that the water level will keep falling and falling. The core is covered by several meters of water in order to allow for some time to pass (hours, days) before it gets exposed. Once the rods start to be exposed at the top, the exposed parts will reach the critical temperature of 2200 °C after about 45 minutes. This is when the first containment, the Zircaloy tube, would fail.

And this started to happen. The cooling could not be restored before there was some (very limited, but still) damage to the casing of some of the fuel. The nuclear material itself was still intact, but the surrounding Zircaloy shell had started melting. What happened now is that some of the byproducts of the uranium decay – radioactive Cesium and Iodine – started to mix with the steam. The big problem, uranium, was still under control, because the uranium oxide rods were good until 3000 °C. It is confirmed that a very small amount of Cesium and Iodine was measured in the steam that was released into the atmosphere.

It seems this was the “go signal” for a major plan B. The small amounts of Cesium that were measured told the operators that the first containment on one of the rods somewhere was about to give. The Plan A had been to restore one of the regular cooling systems to the core. Why that failed is unclear. One plausible explanation is that the tsunami also took away / polluted all the clean water needed for the regular cooling systems.

The water used in the cooling system is very clean, demineralized (like distilled) water. The reason to use pure water is the above mentioned activation by the neutrons from the Uranium: Pure water does not get activated much, so stays practically radioactive-free. Dirt or salt in the water will absorb the neutrons quicker, becoming more radioactive. This has no effect whatsoever on the core – it does not care what it is cooled by. But it makes life more difficult for the operators and mechanics when they have to deal with activated (i.e. slightly radioactive) water.

But Plan A had failed – cooling systems down or additional clean water unavailable – so Plan B came into effect. This is what it looks like happened:

In order to prevent a core meltdown, the operators started to use sea water to cool the core. I am not quite sure if they flooded our pressure cooker with it (the second containment), or if they flooded the third containment, immersing the pressure cooker.

The point is that the nuclear fuel has now been cooled down. Because the chain reaction has been stopped a long time ago, there is only very little residual heat being produced now. The large amount of cooling water that has been used is sufficient to take up that heat. Because it is a lot of water, the core does not produce sufficient heat any more to produce any significant pressure. Also, boric acid has been added to the seawater. Boric acid is “liquid control rod”. Whatever decay is still going on, the Boron will capture the neutrons and further speed up the cooling down of the core.

The plant came close to a core meltdown. Here is the worst-case scenario that was avoided: If the seawater could not have been used for treatment, the operators would have continued to vent the water steam to avoid pressure buildup. The third containment would then have been completely sealed to allow the core meltdown to happen without releasing radioactive material. After the meltdown, there would have been a waiting period for the intermediate radioactive materials to decay inside the reactor, and all radioactive particles to settle on a surface inside the containment. The cooling system would have been restored eventually, and the molten core cooled to a manageable temperature. The containment would have been cleaned up on the inside. Then a messy job of removing the molten core from the containment would have begun, packing the (now solid again) fuel bit by bit into transportation containers to be shipped to processing plants. Depending on the damage, the block of the plant would then either be repaired or dismantled.

5.4.2. COMMENTARY FROM THE PRINCIPAL ENGINEER

- The plant is safe now and will stay safe.
- Japan is looking at an **INES** Level 4 Accident: Nuclear accident with local consequences. That is bad for the company that owns the plant, but not for anyone else.
- Some radiation was released when the pressure vessel was vented. All radioactive isotopes from the activated steam have gone (decayed). A very small amount of Cesium was released, as well as Iodine. If you were sitting on top of the plants' chimney when they were venting, you should probably give up smoking to return to your former life expectancy. The Cesium and Iodine isotopes were carried out to the sea and will never be seen again.
- There was some limited damage to the first containment. That means that some amounts of radioactive Cesium and Iodine will also be released into the cooling water, but no Uranium or other nasty stuff (the Uranium oxide does not "dissolve" in the water). There are facilities for treating the cooling water inside the third containment. The radioactive Cesium and Iodine will be removed there and eventually stored as radioactive waste in terminal storage.
- The seawater used as cooling water will be activated to some degree. Because the control rods are fully inserted, the Uranium chain reaction is not happening. That means the "main" nuclear reaction is not happening, thus not contributing to the activation. The intermediate radioactive materials (Cesium and Iodine) are also almost gone at this stage, because the Uranium decay was stopped a long time ago. This further reduces the activation. The bottom line is that there will be some low level of activation of the seawater, which will also be removed by the treatment facilities.
- The seawater will then be replaced over time with the "normal" cooling water
- The reactor core will then be dismantled and transported to a processing facility, just like during a regular fuel change.
- Fuel rods and the entire plant will be checked for potential damage. This will take about 4-5 years.
- The safety systems on all Japanese plants will be upgraded to withstand a 9.0 earthquake and tsunami (or worse)
- As the Senior Engineer of the **NTPBMR Prototype Project,** I believe the most significant problem will be a prolonged power shortage. 11 of Japan's 55 nuclear reactors in different plants were shut down and will have to be inspected, directly reducing the nation's nuclear power generating capacity by 20%, with nuclear power accounting for about 30% of the national total power generation capacity. I have not looked into possible consequences for other nuclear plants not directly affected. This will probably be covered by running gas power plants that are usually only used for peak loads to cover some of the base load as well. I am not familiar with Japan 's

energy supply chain for oil, gas and coal, and what damage the harbors, refinery, storage and transportation networks have suffered, as well as damage to the national distribution grid. All of these items will increase the cost of energy and lead to higher electricity bill, as well as lead to power shortages during peak demand and reconstruction efforts.

- This all is only part of a much bigger picture. Emergency response has to deal with shelter, drinking water, food and medical care, transportation and communication infrastructure, as well as electricity supply. In a world of lean supply chains, we are looking at some major challenges in all of these areas.

APPENDIX A: LIST OF ABBREVIATIONS

ACNW	Advisory Committee on Nuclear Waste
ACRS	Advisory Committee for Reactor Safeguards
ALARA	As low as reasonably achievable
ASME	American Society of Mechanical Engineers
ATWS	Anticipated transient without SCRAM
BWR	Boiling-water reactor
BWROG	Boiling Water Reactor Owners Group
CANDU	Canadian Deuterium-Natural Uranium Reactor
CCF	Common-cause failure
CCWS	Closed cooling water system
CDBA	Containment design-basis accident
CDC	Center for Disease Control
	Computer design code
CDF	Core damage frequency
CDM	Central data management
.	Certified design material
CDN	Corporate data network
CDP	Core damage probability
CDR	Conceptual design requirement
CD-ROM	Compact disk/read-only' memory
CFR	*U.S. Code of Federal Regulations*
CFR 10-50	*U.S. Code of Federal Regulations for Construction Permit and Operator's License*
CFR 10-52	*U.S. Code of Federal Regulations for Combined Construction Permit and Operator's License*
DOE	Department of Energy
ECCS	emergency core cooling system
EDO	Executive Director of Operations
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ESBWR	economic and simplified boiling water reactor
ET	Executive Team
FAVOR	a probabilistic fracture mechanics code
FCSS	Division of Fuel Cycle Safety and Safeguards (NMSS/FCSS)
FSAR	final safety analysis report
FTE	full-time employees

GAO	General Accounting Office (now Government Accountability Office)
GDC	general design criterion/criteria
GEM	graphical evaluation module
GSI	generic safety issue
HERA	Human Event Repository and Analysis
HRA	human reliability analysis
HLW	high-level waste
IDCCS	Integrated Data Collection and Coding System
IMNS	Division of Industrial and Medical Nuclear Safety (NMSS/IMNS)
INPO	Institute of Nuclear Power Operations
IPEEE	individual plant examination for external events
IPE	individual plant examination
ISFSI	independent spent fuel storage installation
ISA	integrated safety analysis
LCO	limiting conditions for operation
LER	licensee event report
LERF	large early release frequency
LOCA	loss-of-coolant accident
LOOP	loss of offsite power
LP/SD	low-power/shutdown
MSLB	main steam line break
MSPI	Mitigating Systems Performance Index
NEI	Nuclear Energy Institute
NFPA	National Fire Protection Association
NMSS	NRC Office of Nuclear Material Safety and Safeguards
NRC	Nuclear Regulatory Commission
OCFO	NRC Office of the Chief Financial Officer
OEDO	NRC Office of the Executive Director for Operations
OM	operation and maintenance
PBMR	Pebble Bed Modular Reactor
PBPM	planning, budgeting, and performance management
PRA	probabilistic risk assessment
PRASC	PRA steering committee
PTS	pressurized thermal shock
PWR	pressurized-water reactor
QA	quality assurance

RADS	Reliability and Availability Data System
RASP	Risk Assessment Standardization Project
RBI	risk-based performance indicators
RCS	reactor coolant system
RES	NRC Office of Nuclear Regulatory Research
RG	regulatory guide
RI	risk-informed
RIE	risk-informed environment
RILP	risk-informed licensing panel
RIPB	risk-informed, performance-based
RIRIP	Risk-Informed Regulation Implementation Plan
RPV	reactor pressure vessel
RTG	Risk Task Group (NMSS)
SCRAM	super critical reactor axe man
SG	steam generator
SGTAP	Steam Generator Task Action Plan
SPAR	standardized plant analysis risk
SRP	Standard Review Plan
STP	South Texas Project
STS	standard technical specifications
SSC	structures, systems, and components
TMI	Three Mile Island

APPENDIX B-GLOSSARY

Activation: The process of making a radioisotope by bombarding a stable element with neutrons or protons.

Activity: The rate of disintegration (transformation) or decay of radioactive material per unit time. The units of activity are the curie (Ci) and the becquerel (Bq).

ALARA: Acronym for "as low as (is) reasonably achievable." Means making every reasonable effort to maintain exposures to ionizing radiation as far below the dose limits as practical, consistent with the purpose for which the licensed activity is undertaken, taking into account the state of technology, the economics of improvements in relation to state of technology, the economics of improvements in relation to benefits to the public health and safety, and other societal and socioeconomic considerations, and in relation to utilization of nuclear energy and licensed materials in the public interest.

Alpha Particle: A positively charged particle ejected spontaneously from the nuclei of some radioactive elements. It is identical to a helium nucleus that has a mass number of 4 and an electrostatic charge of +2. It has low penetrating power and a short range (a few centimeters in air). The most energetic alpha particle will generally fail to penetrate the dead layers of cells covering the skin and can be easily stopped by a sheet of paper. Alpha particles are hazardous when an alpha-emitting isotope is inside the body.

Annual Limit on Intake (ALI): The derived limit for the amount of radioactive material taken into the body of an adult worker by inhalation or ingestion in a year. ALI is the smaller value of intake of a given radionuclide in a year by the reference man that would result in a committed effective dose equivalent of 5 rems (0.05 sievert) or a committed dose equivalent of 50 rems (0.5 sievert) to any individual organ or tissue.

Atom: The smallest particle of an element that cannot be divided or broken up by chemical means. It consists of a central core of protons and neutrons, called the nucleus. Electrons revolve in orbits in the region surrounding the nucleus

Atomic Energy: Energy released in nuclear reactions. Of particular interest is the energy released when a neutron initiates the breaking up or fissioning of an atom's nucleus into smaller pieces (fission) or when two nuclei are joined together under millions of degrees of heat (fusion). It is more correctly called nuclear energy.

Atomic Energy Commission: Federal agency created in 1946 to manage the development, use, and control of nuclear energy for military and civilian applications. Abolished by the Energy Reorganization Act of 1974 and succeeded by the Energy Research and Development Administration (now part of the U.S. Department of Energy) and the U.S. Nuclear Regulatory Commission.

Atomic Mass (sometimes mistakenly called atomic weight): The mass of a neutral atom. Its value in atomic mass units (u) is approximately equal to the sum of the number of protons and neutrons in the nucleus of the atom.

Atomic Mass Number: *A*, the total number of nucleons (protons and neutrons) found in a nucleus.

Atomic Mass Unit (amu or u): Unit of mass defined by the convention that the atom **Carbon 12, C_{12}** has a mass of exactly 12 u; the mass of 1 u is **1.67×10^{-27} kg.**

Atomic Number: *Z*, the total number of protons found in a nucleus.

Atomic Weight: for an element is defined as the average atomic weight of the isotopes of the element. The atomic weight for an element can be calculated by summing the products of the isotopic abundance of the isotope with the atomic mass of the isotope.

Background Radiation: The radiation found in the natural environment originating primarily from the naturally radioactive elements of Earth and from cosmic rays. The term may also mean radiation extraneous to an experiment.

Becquerel (Bq): Unit of activity in the International System–one disintegration per second; 1 Bq = 27 pCi. The unit of radioactive decay equal to 1 disintegration per second. 37 billion (3.7×10^{10}) becquerels = 1 curie (Ci).

Beta Particle (beta radiation, beta ray): An electron of either positive charge (e^+ or b+) or negative charge (e, e^- or b-) emitted by an atomic nucleus or neutron in the process of a transformation. Beta particles are more penetrating than alpha particles but less than gamma rays or x-rays. Electron capture is a form of beta decay.

Binding Energy: The minimum energy required to separate a nucleus into its component neutrons and protons.

Boiling Water Reactor (BWR): A reactor in which water, used as both coolant and moderator, is allowed to boil in the core. The resulting steam can be used directly to drive a turbine and electrical generator, thereby producing electricity

Bone Seeker: A radioisotope that tends to accumulate in the bones when it is introduced into the body. An example is strontium-90, which behaves chemically like calcium

British Thermal Unit (Btu): One British thermal unit, or BTU, is roughly equivalent to burning one kitchen match. It is the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit. (one Btu = 1055 Joules)

Carbon Dioxide (CO_2): A colorless, odorless, non-poisonous gas that is a normal part of the ambient air. Carbon dioxide is a product of fossil fuel combustion.

Chain Reaction: A reaction that initiates its own repetition. In a fission chain reaction, a fissionable nucleus absorbs a neutron and fissions spontaneously, releasing additional neutrons. These, in turn, can be absorbed by other fissionable nuclei, releasing still more neutrons. A fission chain reaction is self-sustaining when the number of neutrons released in a given time equals or exceeds the number of neutrons lost by absorption in non-fissionable material or by escape from the system.

Charged Particle: An ion. An elementary particle carrying a positive or negative electric charge.

Cherenkov Radiation: Light emitted by particles that move through a medium in which the speed of light is slower than the speed of the particles.

Cladding: The thin-walled metal tube that forms the outer jacket of a nuclear fuel rod. It prevents corrosion of the fuel by the coolant and the release of fission products into the coolant. Aluminum, stainless steel, and zirconium alloys are common cladding materials.

Cleanup System: A system used for continuously filtering and demineralizing a reactor coolant system to reduce contamination levels and to minimize corrosion.

Collective Dose: The sum of the individual doses received in a given period by a specified population from exposure to a specified source of radiation.

Containment Structure: A gaslight shell or other enclosure around a nuclear reactor to confine fission products that otherwise might be released to the atmosphere in the event of an accident.

Contamination: Undesired radioactive material that is deposited on the surface of or inside structures, areas, objects, or people.

Control Rod: A rod, plate, or tube containing a material such as hafnium, boron, etc., used to control the power of a nuclear reactor. By absorbing neutrons, a control rod prevents the neutrons from causing further fissions.

Controls: when used with respect to nuclear reactors means apparatus and mechanisms, the manipulation of which directly affects the reactivity or power level of the reactor.

Control Room: The area in a nuclear power plant from which most of the plant power production and emergency safety equipment can be operated by remote control.

Controlled Area: At a nuclear facility, an area outside a restricted area but within the site boundary, access to which the licensee can limit for any reason.

Coolant: A substance circulated through a nuclear reactor to remove or transfer heat. The most commonly used coolant in the United States is water. Other coolants include heavy water, air, carbon dioxide, helium, liquid sodium, and a sodium-potassium alloy.

Core: The central portion of a nuclear reactor containing the fuel elements, moderator, neutron poisons, and support structures.

Core Meltdown Accident: An event or sequence of events that result in the melting of part of the fuel in the reactor core.

Cosmic Radiation: Penetrating ionizing radiation, both particulate and electromagnetic, originating in outer space. Secondary cosmic rays, formed by interactions in the

Earth's atmosphere, account for about 45 to 50 millirem of the 360 millirem background radiation that an average individual receives in a year.

Counter: A general designation applied to radiation detection instruments or survey meters that detect and measure radiation. The signal that announces an ionization event is called a count.

Criticality: A term used in reactor physics to describe the state when the number of neutrons released by fission is exactly balanced by the neutrons being absorbed (by the fuel and poisons) and escaping the reactor core. A reactor is said to be "critical" when it achieves a self-sustaining nuclear chain reaction, as when the reactor is operating.

Critical Mass: The smallest mass of fissionable material that will support a self-sustaining chain reaction.

Cross-Section: The cross-section of a Nuclear Reaction denoted by the Greek letter σ Is a measure of the probability of the occurrence of a particular reaction under prescribed conditions.

Cumulative Dose: The total dose resulting from repeated exposures of ionizing radiation to an occupationally exposed worker to the same portion of the body, or to the whole body, over time.

Curie (Ci): The basic unit used to describe the intensity of radioactivity in a sample of material. The curie is equal to 37 billion (3.7×10^{10}) disintegrations per second, which is approximately the activity of 1 gram of radium. A curie is also a quantity of any radionuclide that decays at a rate of 37 billion disintegrations per second. It is named for Marie and Pierre Curie, who discovered radium in 1898. This unit is no longer recognized as part of the International System of units. It has been replaced by the becquerel.

Decay Heat: The heat produced by the decay of radioactive fission products after a reactor has been shut down.

Decay, Radioactive: The change of one radioactive nuclide into a different nuclide by the spontaneous emission of radiation such as alpha, beta, or gamma rays, or by electron capture. The end product is a less energetic, more stable nucleus. Each decay process has a definite half-life.

Decay Rate: The ratio of activity to the number of radioactive atoms of a particular species.

Decommission: means to remove a facility or site safely from service and reduce residual radioactivity to a level that permits:

1. Release of the property for unrestricted use and termination of the license;
2. Release of the property under restricted conditions and termination of the license.

Decontamination: The reduction or removal of contaminating radioactive material from a structure, area, object, or person. Decontamination may be accomplished by (1) treating the surface to remove or decrease the contamination, (2) letting the material stand so that the radioactivity is decreased as a result of natural radioactive decay, or (3) covering the contamination to shield or attenuate the radiation emitted

Defense-in-depth: A design and operational philosophy with regard to nuclear facilities that calls for multiple layers of protection to prevent and mitigate accidents. It includes the use of controls, multiple physical barriers to prevent release of radiation, redundant and diverse key safety functions, and emergency response measures.

Density: The ratio of an object's mass to its volume.

Department and Department of Energy (DOE): means the Department of Energy established by the Department of Energy Organization Act (Pub. L. 95-91, 91 Stat. 565, 42 U.S.C. 7101 et seq.), to the extent that the department, or its duly authorized representatives, exercises functions formerly vested in the Atomic Energy Commission

Depleted Uranium: Uranium having a percentage of uranium-235 smaller than the 0.7 percent found in natural uranium. It is obtained from spent (used) fuel elements or as byproduct tails, or residues, from uranium isotope separation.

Design Bases: means that information which identifies the specific functions to be performed by a structure, system, or component of a facility, and the specific values or ranges of values chosen for controlling parameters as reference bounds for design. These values may be:

Design-Basis Accident: A postulated accident that a nuclear facility must be designed and built to withstand without loss to the systems, structures, and components necessary to assure public health and safety.

Detector: A material or device that is sensitive to radiation and can produce a response signal suitable for measurement or analysis. A radiation detection instrument.

Deterministic (probabilistic): Consistent with the principles of "determinism," which hold that specific causes completely and certainly determine effects of all sorts. As applied in nuclear technology, it generally deals with evaluating the safety of a nuclear power plant in terms of the consequences of a predetermined bounding subset of accident sequences. The term "probabilistic" is associated with an evaluation that explicitly accounts for the likelihood and consequences of possible accident sequences in an integrated fashion.

Deterministic Effect: The health effects of radiation, the severity of which varies with the dose and for which a threshold is believed to exist. Radiation-induced cataract formation is an example of a deterministic effect (also called a non-stochastic effect)

Deuterium: An isotope of hydrogen with one proton and one neutron in the nucleus.

Dose: The absorbed dose, given in rads (or in SI units, grays), that represents the energy absorbed from the radiation in a gram of any material. Furthermore, the biological dose or dose equivalent, given in rem or sieverts, is a measure of the biological damage to living tissue from radiation exposure.

Dose Equivalent: The product of absorbed dose in tissue multiplied by a quality factor and then sometimes multiplied by other necessary modifying factors at the location of interest. It is expressed numerically in rems or sieverts

Dose Rate: The ionizing radiation dose delivered per unit time. For example, rem or sieverts per hour.

Dosimeter: A small portable instrument (such as a film badge or thermoluminescent or pocket dosimeter) for measuring and recording the total accumulated personal dose of ionizing radiation.

Dosimetry: The theory and application of the principles and techniques involved in the measurement and recording of ionizing radiation doses.

Effective Dose Equivalent: The sum of the products of the dose equivalent to the organ or tissue and the weighting factors applicable to each of the body organs or tissues that are irradiated.

Effective Half-life: The time required for the amount of a radioactive element deposited in a living organism to be diminished 50 percent as a result of the combined action of radioactive decay and biological elimination.

Elastic Scattering: In this interaction of radiation with matter. The impinging particle approaches the target and

Electromagnetic Radiation: A traveling wave motion resulting from changing electric or magnetic fields. Familiar electromagnetic radiation range from x-rays (and gamma rays) of short wavelength, through the ultraviolet, visible, and infrared regions, to radar and radio waves of relatively long wavelength.

Electron: An elementary particle with a negative charge and a mass 1/1837 that of the proton. Electrons surround the positively charged nucleus and determine the chemical properties of the atom.

Electron-volt (eV): Energy unit used as the basis of measurement for atomic (eV), electronic (keV), nuclear (MeV), and subnuclear processes (GeV or TeV). One electron-volt is equal to the amount of energy gained by an electron dropping through a potential difference of one volt, which is 1.6 ´ 10-19 joules.

Element: One of the 103 known chemical substances that cannot be broken down further without changing its chemical properties. Some examples include hydrogen, nitrogen, gold, lead, and uranium.

Emergency Core Cooling Systems (ECCS): Reactor system components (pumps, valves, heat exchangers, tanks, and piping) that are specifically designed to remove residual heat from the reactor fuel rods should the normal core cooling system (reactor coolant system) fail.

Energy: The capacity for doing work as measured by the capability of doing work potential energy) or the conversion of this capability to motion (kinetic energy). Energy has several forms, some of which are easily convertible and can be changed to another form useful for work. Most of the world's convertible energy comes from fossil fuels that are burned to produce heat that is then used as a transfer medium to mechanical or other means in order to accomplish tasks. Electrical energy is usually measured in kilowatthours, while heat energy is usually measured in British thermal units.

Enthalpy: In thermodynamics the Quantity called enthalpy, denoted by **H** or **h** (for the specific enthalpy)

$$H = U + pV .$$

Where **U** is the internal energy,

p is the internal pressure

V is the volume.

Enthalpy is a property of a gas or liquid and it's units in the British System are **Btu/lbm.**

Entropy: In thermodynamics the Quantity called entropy, denoted by **S** or **s** (for the specific entropy) is a measure of the amount of energy in a physical system not available to do work. As a physical system becomes more disordered, and its energy becomes more evenly distributed, that energy becomes less able to do work. The amount of entropy is often thought of as the amount of disorder in a system.

Excited State: The state of an atom or nucleus when it possesses more than its normal energy. Typically, the excess energy is released as a gamma ray.

Exclusion Area: The area surrounding the reactor where the reactor licensee has the authority to determine all activities, including exclusion or removal of personnel and property.

Exposure: Being exposed to ionizing radiation or to radioactive material.

External Radiation: Exposure to ionizing radiation when the radiation source is located outside the body.

Feedwater: Water supplied to the reactor pressure vessel (in a BWR) or the steam generator (in a PWR) that removes heat from the reactor fuel rods by boiling and becoming steam. The steam becomes the driving force for the plant turbine generator.

Fertile Material: A material, which is not itself fissile (fissionable by thermal neutrons), that can be converted into a fissile material by irradiation in a reactor. There are two basic fertile materials: uranium-238 and thorium-232. When these fertile materials capture neutrons, they are converted into fissile plutonium-239 and uranium-233, respectively.

Fissile Material: Although sometimes used as a synonym for fissionable material, this term has acquired a more restricted meaning. Namely, any material fissionable by thermal (slow) neutrons. The three primary fissile materials are uranium-233, uranium-235, and plutonium-239.

Fission (fissioning): The splitting of a nucleus into at least two other nuclei and the release of a relatively large amount of energy. Two or three neutrons are usually released during this type of transformation.

Fission Gases: Those fission products that exist in the gaseous state. In nuclear power reactors, this includes primarily the noble gases, such as krypton and xenon.

Fission Products: The nuclei (fission fragments) formed by the fission of heavy elements, plus the nuclide formed by the fission fragments' radioactive decay.

Fissile Nucleus: A nucleus that may fission after collision with a thermal (slow) neutron or that fissions spontaneously (by itself).

Fission: The splitting of a heavy nucleus into two roughly equal parts (which are nuclei of lower-mass elements), accompanied by the release of a relatively large amount of energy in the form of kinetic energy of the two parts and in the form of emission of neutrons and gamma rays.

Fission products: Nuclei formed by the fission of higher mass elements. They are of medium atomic mass and almost all are radioactive. Examples: ^{90}Sr, ^{137}Ce.

Fissionable Material: Commonly used as a synonym for fissile material, the meaning of this term has been extended to include material that can be fissioned by fast neutrons, such as uranium-238.

Flux: A term applied to the amount of some type of particle (neutrons, alpha radiation, etc.) or energy (photons, heat, etc.) crossing a unit area per unit time. The unit of flux is the number of particles, energy, etc., per square centimeter per second.

Fuel Assembly: A cluster of fuel rods (or plates). Also called a fuel element. Many fuel assemblies make up a reactor core.

Fuel Cycle: The series of steps involved in supplying fuel for nuclear power reactors. It can include mining, milling, isotopic enrichment, fabrication of fuel elements, use in a reactor, chemical reprocessing to recover the fissionable material remaining in the spent fuel, re-enrichment of the fuel material, re-fabrication into new fuel elements, and waste disposal.

Fuel Reprocessing: The processing of reactor fuel to separate the unused fissionable material from waste material.

Fuel Rod: A long, slender tube that holds fissionable material (fuel) for nuclear reactor use. Fuel rods are assembled into bundles called fuel elements or fuel assemblies, which are loaded individually into the reactor core.

Fuel Temperature Coefficient of Reactivity: The change in reactivity per degree change in the fuel temperature. The physical property of fuel pellet material (uranium-238) that causes the uranium to absorb more neutrons away from the fission process as fuel pellet temperature increases. This acts to stabilize power reactor operations. This coefficient is also known as the Doppler coefficient.

Gamma Radiation: High-energy, short wavelength, electromagnetic radiation emitted from the nucleus. Gamma radiation frequently accompanies alpha and beta emissions and always accompanies fission. Gamma rays are very penetrating and are best stopped or shielded by dense materials, such as lead or depleted uranium. Gamma rays are similar to x-rays.

Gamma Ray: A highly penetrating type of nuclear radiation, similar to x-radiation, except that it comes from within the nucleus of an atom, and, in general, has a shorter wavelength.

Gas-Cooled Reactor: A nuclear reactor in which a gas is the coolant.

Gases: A substance possessing perfect molecular mobility and the property of indefinite expansion, as opposed to a solid or liquid; any such fluid or mixture of fluids other than air. Normally, these formless substances completely fill the space, and take the shape of, their container.

Gas-Turbine Electric Power Plant: A plant in which the prime mover is a gas turbine. A gas turbine typically consists of an axial-flow air compressor and one or more combustion chambers which liquid or gaseous fuel is burned. The hot gases expand to drive the generator and then are used to run the compressor.

Geiger Counter: A **Geiger-Müller** detector and measuring instrument. A radiation detection and measuring instrument. It consists of a gas-filled tube containing electrodes, between which there is an electrical voltage, but no current, flowing. When ionizing radiation passes through the tube, a short, intense pulse of current passes from the negative electrode to the positive electrode and is measured or counted. The number of pulses per second measures the intensity of the radiation field. It was named for Hans Geiger and W. Mueller, who invented it in the 1920s. It is sometimes called simply a Geiger counter or a G-M counter and is the most commonly used portable radiation instrument.

Gigawatt: One billion watts.

Gigawatthour: One billion watt-hours.

Graphite: A form of carbon, similar to that used in pencils, used as a moderator in some nuclear reactors.

Gray (Gy): The international system (SI) unit of absorbed dose. One gray is equal to an absorbed dose of 1 Joule/kilogram (one gray equals 100 rads)

Half-life: The time in which one half of the atoms of a particular radioactive substance disintegrate into another nuclear form. Measured half-lives vary from millionths of a second to billions of years. Also called physical or radiological half-life.

Head, Reactor Vessel: The removable top section of a reactor pressure vessel. It is bolted in place during power operation and removed during refueling to permit access of fuel handling equipment to the core.

Health Physics: The science concerned with the recognition, evaluation, and control of health and environmental hazards that may arise from the use and application of ionizing radiation.

Heat Exchanger: Any device that transfers heat from one fluid (liquid or gas) to another fluid or to the environment.

High-enriched Uranium: Uranium enriched to 20 percent or greater in the isotope Uranium-235.

High-level Waste: Radioactive materials at the end of a useful life cycle that should be properly disposed of, including--

Highly Enriched Uranium: (**HEU**) fuel means fuel in which the weight percent of U-235 in the uranium is 20% or greater. Target material, special instrumentation, or experimental devices using HEU are not included.

Infrared Radiation: Electromagnetic radiation of longer wavelength than visible light.

Induced Radioactivity: Radioactivity that is created when stable substances are bombarded by ionizing radiation. For example, the stable isotope cobalt-59 becomes the radioactive isotope cobalt-60 under neutron bombardment.

Ion: **1**. An atom that has too many or too few electrons, causing it to have an electrical charge, and therefore, be chemically active.

2. An electron that is not associated (in orbit) with a nucleus.

Ion-exchange: A common method for concentrating uranium from a solution. The uranium solution is passed through a resin bed where the uranium-carbonate complex ions are transferred to the resin by exchange with a negative ion like chloride. After build-up of the uranium complex on the resin, the uranium is eluted with a salt solution and the uranium is precipitated in another process.

Ionization: The process of adding one or more electrons to, or removing one or more electrons from, atoms or molecules, thereby creating ions. High temperatures, electrical discharges, or nuclear radiations can cause ionization.

Ionization Chamber: An instrument that detects and measures ionizing radiation by measuring the electrical current that flows when radiation ionizes gas in a chamber, taking the gas a conductor of electricity.

Ionizing Radiation: Any radiation capable of displacing electrons from atoms or molecules, thereby producing ions. Some examples are alpha, beta, gamma, x-rays, neutrons, and ultraviolet light. High doses of ionizing radiation may produce severe skin or tissue damage.

isotope: Isotopes of a given element have the same atomic number (same number of protons in their nuclei) but different mass numbers (different number of neutrons in their nuclei). ^{238}U and ^{235}U are isotopes of uranium.

Isotopic Enrichment: A process by which the relative abundance of the isotopes of a given element are altered, thus producing a form of the element that has been enriched in one particular isotope and depleted in its other isotopic forms.

joule (J): Unit of energy, equivalent to the work done in lifting a one-newton weight a distance of one meter.

keV: One thousand electron-volts.

Kilo: A Greek prefix meaning "thousand" in the nomenclature of the metric system. This prefix multiplies a unit by 1000.

Kilovolt: The unit of electrical potential equal to 1000 volts.

Kilowatt (kW): One thousand watts of electricity (see Watt).

Kilowatthour (kWh): One thousand watthours.

Kinetic energy: The energy that a body possesses by virtue of its mass and velocity. Also called the energy of motion.

Lethal Dose (LD): The dose of radiation expected to cause death to 50 percent of an exposed population within 30 days (LD 50/30). Typically, the LD 50/30 is in the range from 400 to 450 rem (4 to 5 sieverts) received over a very short period.

Light Water: Ordinary water as distinguished from heavy water..

Light Water Reactor: A term used to describe reactors using ordinary water as coolant, including boiling water reactors (**BWR**s) and pressurized water reactors (**PWR**s), the most common types used in the United States.

Loop: In a pressurized water reactor, the coolant flow path through piping from the reactor pressure vessel to the steam generator, to the reactor coolant pump, and back to the reactor pressure vessel. Large PWRs may have as many as four separate loops.

Loss of Coolant Accident (LOCA): Those postulated accidents that result in a loss of reactor coolant at a rate in excess of the capability of the reactor makeup system from breaks in the reactor coolant pressure boundary, up to and including a break equivalent in size to the double-ended rupture of the largest pipe of the reactor coolant system.

Low enriched uranium: (**LEU**) fuel means fuel in which the weight percent of U-235 in the uranium is less than 20%.

Low Population Zone (LPZ): An area of low population density often required around a nuclear installation before it's built. The number and density of residents is of concern in emergency planning so that certain protective measures (such as notification and instructions to residents) can be accomplished in a timely manner

Low-level Waste: A general term for a wide range of wastes having low levels of radioactivity. Industries; hospitals and medical, educational, or research institutions; private or government laboratories; and nuclear fuel cycle facilities (e.g., nuclear power reactors and fuel fabrication plants) that use radioactive materials generate low-level wastes as part of their normal operations. These wastes are generated in many physical and chemical forms and levels of contamination

Mass Energy: Energy a particle has by virtue of its mass (given by $\mathbf{E = MC^2}$).

Mass Number: The total number of protons and neutrons in the nucleus**: A=Z+N.** This is also the total nucleon number of the nucleus.

Mass-energy Equation: The equation developed by Albert Einstein, which is usually given as $\mathbf{E = mc^2}$**,** showing that, when the energy of a body changes by an amount E (no matter what form the energy takes), the mass (m) of the body will change by an amount equal to E/c^2. The factor c squared, the speed of light in a vacuum (3×10^8), may be regarded as the conversion factor relating units of mass and energy. The equation predicted the possibility of releasing enormous amounts of energy by the conversion of mass to energy. It is also called the Einstein equation.

Megacurie: One million curies.

Megawatt (MW): One million watts.

Megawatt Hour (MWh): One million watt-hours.

Metric Ton: Approximately 2200 pounds in the English system of measurements. (Note: In the international system of measurements, 1 metric ton = 1000 kg.)

Micro: A prefix that divides a unit into one million parts (0.000001).

Microcurie: One millionth of a curie. That amount of radioactive material that disintegrates (decays) at the rate of 37 thousand atoms per second.

Milli: A prefix that divides a basic unit by 1000.

Millirem: One thousandth of a rem (0.001 rem).

Milliroentgen (mR): One thousandth of a roentgen (R). $1mR = 10^{-3}\ R = 0.001\ R$.

Mixed Oxide (MOX) Fuel: A mixture of uranium oxide and plutonium oxide used to fuel a reactor. Mixed oxide fuel is often called "MOX." Conventional nuclear fuel is made of pure uranium oxide.

Moderator: A material, such as ordinary water, heavy water, or graphite, that is used in a reactor to slow down high-velocity neutrons, thus increasing the likelihood of fission.

Moderator Temperature Coefficient of Reactivity: As the moderator (water) increases in temperature, it becomes less dense and slows down fewer neutrons, which results in a negative change of reactivity. This negative temperature coefficient acts to stabilize atomic power reactor operations.

Molecule: A group of atoms held together by chemical forces. A molecule is the smallest unit of a compound that can exist by itself and retain all of its chemical properties.

MeV: One million electron-volts.

Microwaves: Electromagnetic radiation with wavelength intermediate between radio wave and infrared radiation.

Nano: A prefix that divides a basic unit by one billion (10^{-9}).

Nanocurie: One billionth 10^{-9} of a curie.

Natural Circulation: The circulation of the coolant in the reactor coolant system without the use of the reactor coolant pumps. The circulation is due to the natural convection resulting from the different densities of relative cold and heated portions of the system.

Natural Uranium: Uranium as found in nature. It contains 0.7 percent uranium-235, 99.3 percent uranium-238, and a trace of uranium-234 by weight. In terms of the amount of radioactivity, it contains approximately 2.2 percent uranium-235, 48.6 percent uranium-238, and 49.2 percent uranium-234.

Neutron: One of the basic particles that make up a nucleus. A neutron and a proton have about the same mass, but the neutron has no electrical charge.

Neutron Capture: The reaction that occurs when a nucleus captures a neutron. The probability that a given material will capture a neutron is proportional to its neutron capture cross section and depends on the energy of the neutrons and the nature of the material.

Neutron Chain Reaction: A process in which some of the neutrons released in one fission event cause other fissions to occur. There are three types of chain reactions:

1. Non-sustaining--An average of less than one fission is produced by the neutrons released by each previous fission (reactor sub-criticality);
2. Sustaining--An average of exactly one fission is produced by the neutrons released by each previous fission (reactor criticality);
3. Multiplying--An average of more than one fission is produced by the neutrons released by previous fission (reactor super-criticality).

Neutron Flux: A measure of the intensity of neutron radiation in neutrons/cm^2-sec. It is the number of neutrons passing through 1 square centimeter of a given target in 1 second. Expressed as nv, where n = the number of neutrons per cubic centimeter and v = their velocity in centimeters per second.

Neutron Generation: The release, thermalization, and absorption of fission neutrons by a fissile material and the fission of that material producing a second generation of neutrons. In a typical nuclear power reactor system, there are about 40,000 generations of neutrons every second.

Neutron Leakage: Neutrons that escape from the vicinity of the fissionable material in a reactor core. Neutrons that leak out of the fuel region are no longer available to cause fission and must be absorbed by shielding placed around the reactor pressure vessel for that purpose.

Neutron Number: The total number of neutrons in the nucleus, N.

Neutron Source: Any material that emits neutrons, such as a mixture of radium and beryllium, that can be inserted into a reactor to ensure a neutron flux large enough to be distinguished from background to register on neutron detection equipment.

Neutron, Thermal: A neutron that has (by collision with other particles) reached an energy state equal to that of its surroundings, typically on the order of 0.025 eV (electron volts).

Noble Gas: A gaseous chemical element that does not readily enter into chemical combination with other elements. An inert gas. Examples are helium, argon, krypton, xenon, and radon.

Non-vital Plant Systems: Systems at a nuclear facility that may or may not be necessary for the operation of the facility (i.e., power production) but that would have little or no effect on public health and safety should they fail. These systems are not safety related.

Non-power Reactor: Reactors used for research, training, and test purposes, and for the production of radioisotopes for medical and industrial uses.

Nuclear Binding Energy: The energy that free nucleons give up in order to be bound inside a nucleus.

Nuclear Energy: The energy liberated by a nuclear reaction (fission or fusion) or by radioactive decay.

Nuclear Force: A powerful short-ranged attractive force that holds together the particles inside an atomic nucleus.

Nuclear Power Plant: An electrical generating facility using a nuclear reactor as its heat source to provide steam to a turbine generator.

Nuclear Reactor: means an apparatus, other than an atomic weapon, designed or used to sustain nuclear fission in a self-supporting chain reaction.

Nuclear Steam Supply System (NSSS): The reactor and the reactor coolant pumps (and steam generators for a pressurized water reactor) and associated piping in a nuclear power plant used to generate the steam needed to drive the turbine generator unit.

Nuclear Waste: A particular type of radioactive waste that is produced as part of the nuclear fuel cycle (i.e., those activities needed to produce nuclear fission, or splitting of the atom). These include extraction of uranium from ore, concentration of uranium, processing into nuclear fuel, and disposal of byproducts. Radioactive waste is a broader term that includes all waste that contains radioactivity. Residues from water treatment, contaminated equipment from oil drilling, and tailings from the processing of metals such as vanadium and copper also contain radioactivity but are not "nuclear waste" because they are produced outside of the nuclear fuel cycle. NRC generally regulates only those wastes produced in the nuclear fuel cycle (uranium mill tailings, depleted uranium, spent fuel rods, etc.).

Nucleon: Common name for a constituent particle of the atomic nucleus. At present, applied to protons and neutrons, but may include any other particles found to exist in the nucleus.

Nucleus: The small, central, positively charged region of an atom. Except for the nucleus of ordinary hydrogen, which has only a proton, all atomic nuclei contain both protons and neutrons. The number of protons determines the total positive charge or atomic number. This number is the same for all the atomic nuclei of a given chemical element. The total number of neutrons and protons is called the mass number.

Nuclide: A general term referring to all known isotopes, both stable (279) and unstable (about 2,700), of the chemical elements.

Occupational Dose: The dose received by an individual in the course of employment in which the individual's assigned duties involve exposure to radiation or to radioactive material from licensed and unlicensed sources of radiation, whether in the possession of the licensee or other person. Occupational dose does not include dose received from background radiation, from any medical administration the individual has received, from exposure to individuals administered radioactive materials and released in accordance with NRC regulations, from voluntary participation in medical research programs, or as a member of the general public.

Photon: A quantum (or packet) of energy emitted in the form of electromagnetic radiation. Photons have momentum and energy, but no rest mass or electrical charge. Gamma rays and x-rays are examples of photons.

Pico: A prefix that divides a basic unit by one trillion (10^{-12}).

Picocurie: One trillionth (10^{-12}) of a curie.

Pile: A colloquial term describing the first nuclear reactors. They are called piles because the earliest reactors were "piles" of graphite and uranium blocks.

Plutonium (Pu): A heavy, radioactive, manmade metallic element with atomic number 94. Its most important isotope is fissile plutonium-239, which is produced by neutron irradiation of uranium-238. It exists in only trace amounts in nature.

Pocket Dosimeter: A small ionization detection instrument that indicates ionizing radiation exposure directly. An auxiliary charging device is usually necessary.

Poison, Neutron: In reactor physics, a material other than fissionable material in the vicinity of the reactor core that will absorb neutrons. The addition of poisons, such as control rods or boron, into the reactor is said to be an addition of negative reactivity.

Pressure Vessel: A strong-walled container housing the core of most types of power reactors. It usually also contains the moderator, neutron reflector, thermal shield, and control rods.

Pressurized Water Reactor (PWR): A power reactor in which heat is transferred from the core to an exchanger by high temperature water kept under high pressure in the primary system. Steam is generated in a secondary circuit. Many reactors producing electric power are pressurized water reactors.

Pressurizer: A tank or vessel that acts as a head tank (or surge volume) to control the pressure in a pressurized water reactor.

Proton: One of the basic particles that makes up an atom. The proton is found in the nucleus and has a positive electrical charge equal to the negative charge of an electron and a mass similar to that of a neutron**:** a hydrogen nucleus.

Proton Number: The total number of protons in the nucleus, Z.

Quality Factor: The factor by which the absorbed dose (rad or gray) is to be multiplied to obtain a quantity that expresses, on a common scale for all ionizing radiation, the biological damage (rem or sievert) to an exposed individual. It is used because some types of radiation, such as alpha particles, are more biologically damaging internally than other types.

Rad (Radiation Absorbed Dose): The special unit for radiation absorbed dose, which is the amount of energy from any type of ionizing radiation (e.g., alpha, beta, gamma, neutrons, etc.) deposited in any medium (e.g., water, tissue, air). A dose of one rad means the absorption of 100 ergs (a small but measurable amount of energy) per gram of absorbing tissue (100 rad = 1 gray).

Radiation (Ionizing Radiation): Alpha particles, beta particles, gamma rays, x-rays, neutrons, high-speed electrons, high-speed protons, and other particles capable of producing ions. Radiation, as used in 10 CFR Part 20, does not include non-ionizing radiation, such as radio- or microwaves, or visible, infrared, or ultraviolet light (see also 10 CFR 20.1003).

Radiation, Nuclear: Particles (alpha, beta, neutrons) or photons (gamma) emitted from the nucleus of unstable radioactive atoms as a result of radioactive decay.

Radiation Shielding: Reduction of radiation by interposing a shield of absorbing material between any radioactive source and a person, work area, or radiation-sensitive device.

Radiation Sickness (Syndrome): The complex of symptoms characterizing the disease known as radiation injury, resulting from excessive exposure (greater than 200 rads or 2 gray) of the whole body (or large part) to ionizing radiation. The earliest of these symptoms are nausea, fatigue, vomiting, and diarrhea, which may be followed by loss of hair (epilation), hemorrhage, inflammation of the mouth and throat, and general loss of energy. In severe cases, where the radiation exposure has been approximately 1000 rad (10 gray) or more, death may occur within two to four weeks. Those who survive six weeks after the receipt of a single large dose of radiation to the whole body may generally be expected to recover.

Radioactive Decay: Large unstable atoms can become more stable by emitting radiation. This process is called radioactive decay. This radiation can be emitted in the form of a positively charged alpha particle, a negatively charged beta particle, or gamma rays or x-rays.

Radioactive Waste: Materials that are radioactive and for which there is no further use.

Radioactivity: The spontaneous emission of radiation, generally alpha or beta particles, often accompanied by gamma rays, from the nucleus of an unstable isotope. Also, the rate at which radioactive material emits radiation. Measured in units of becquerels or disintegrations per second.

Radioisotope: An unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation. Approximately 5,000 natural and artificial radioisotopes have been identified.

Radionuclide: A radioactive nuclide. An unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation.

Radiosensitivity: The relative susceptibility of cells, tissues, organs, organisms, or other substances to the injurious action of radiation.

Radium (Ra): A radioactive metallic element with atomic number 88. As found in nature, the most common isotope has a mass number of 226. It occurs in minute quantities associated with uranium in pitchblende, camotite, and other minerals.

Radon (Rn): A radioactive element that is one of the heaviest gases known. Its atomic number is 86. It is a daughter of radium.

Reaction: Any process involving a chemical or nuclear change.

Reactivity: A term expressing the departure of a reactor system from criticality. A positive reactivity addition indicates a move toward super-criticality (power increase). A negative reactivity addition indicates a move toward sub-criticality (power decrease).

Reactor, Nuclear: A device in which nuclear fission may be sustained and controlled in a self-supporting nuclear reaction. The varieties are many, but all incorporate certain features, including fissionable material or fuel, a moderating material (unless the reactor is operated on fast neutrons), a reflector to conserve escaping neutrons, provisions of removal of heat, measuring and controlling instruments, and protective devices. The reactor is the heart of a nuclear power plant.

Rem (Roentgen Equivalent Man): The acronym for roentgen equivalent man is a standard unit that measures the effects of ionizing radiation on humans. The dose equivalent in rems is equal to the absorbed dose in rads multiplied by the quality factor of the type of radiation (see 10 CFR 20.1004).

Risk-informed Regulation: Incorporating an assessment of safety significance or relative risk in NRC regulatory actions. Making sure that the regulatory burden imposed by individual regulations or processes is commensurate with the importance of that regulation or process to protecting public health and safety and the environment.

Roentgen (R): A unit of exposure to ionizing radiation. It is the amount of gamma or x-rays required to produce ions resulting in a charge of 0.000258 coulombs/kilogram of air under standard conditions. Named after Wilhelm Roentgen, the German scientist who discovered x-rays in 1895.

Safe Shutdown: (non-design basis accident (non-DBA)) for station blackout means bringing the plant to those shutdown conditions specified in plant technical specifications as Hot Standby or Hot Shutdown, as appropriate (plants have the option of maintaining the RCS at normal operating temperatures or at reduced temperatures).

Scram: The sudden shutting down of a nuclear reactor, usually by rapid insertion of control rods, either automatically or manually by the reactor operator. May also be called a reactor trip. It is actually an acronym for "safety control rod axe man," the worker assigned to insert the emergency rod on the first reactor (the Chicago Pile) in the U.S.

Shielding: Any material or obstruction that absorbs radiation and thus tends to protect personnel or materials from the effects of ionizing radiation.

Shutdown: A decrease in the rate of fission (and heat production) in a reactor (usually by the insertion of control rods into the core).

Shutdown Margin: The instantaneous amount of reactivity by which the reactor is sub-critical or would be sub-critical from its present condition assuming all full-length rod cluster assemblies (shutdown and control) are fully inserted except for the single rod cluster assembly of highest reactivity worth that is assumed to be fully withdrawn.

Standard Industrial Classification (SIC): A set of codes developed by the Office of Management and Budget which categorizes industries according to groups with similar economic activities.

Scaler: An electronic instrument for counting radiation induced pulses from radiation detectors such as a Geiger-Müller tube.

Sievert (Sv): A measure of dose (technically, dose equivalent) deposited in body tissue, averaged over the body. Such a dose would be caused by an exposure imparted by ionizing x-ray or gamma radiation undergoing an energy loss of 1 joule per kilogram of body tissue (l gray). One sievert is equivalent to 100 rem.

Spent Nuclear Fuel: Fuel that has been removed from a nuclear reactor because it can no longer sustain power production for economic or other reasons.

Stable Isotope: An isotope that does not undergo radioactive decay.

Standard Technical Specifications: NRC staff guidance on model technical specifications for an operating license. (See also Technical Specifications.)

Startup: An increase in the rate of fission (and heat production) in a reactor (usually by the removal of control rods from the core).

Steam Generator: The heat exchanger used in some reactor designs to transfer heat from the primary (reactor coolant) system to the secondary (steam) system. This design permits heat exchange with little or no contamination of the secondary system equipment.

Transmutation: The transformation of one element into another by a nuclear reaction.

Technical Specifications: Part of an NRC license authorizing the operation of a nuclear production or utilization facility. A Technical Specification establishes requirements for items such as safety limits, limiting safety system settings, limiting control settings, limiting conditions for operation, surveillance requirements, design features, and administrative controls. (See also Standard Technical Specifications.)

Terrestrial Radiation: The portion of the natural background radiation that is emitted by naturally occurring radioactive materials, such as uranium, thorium, and radon in the earth.

Thermal Breeder Reactor: A breeder reactor in which the fission chain reaction is sustained by thermal neutrons.

Thermal power: The total core heat transfer rate to the reactor coolant.

Thermal Reactor: A reactor in which the fission chain reaction is sustained primarily by thermal neutrons. Most current reactors are thermal reactors.

Thermal shield: A layer, or layers, of high-density material located within a reactor pressure vessel or between the vessel and the biological shield to reduce radiation heating in the vessel and the biological shield.

Total Effective Dose Equivalent (TEDE): The sum of the deep-dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures).

Transient: A change in the reactor coolant system temperature and/or pressure due to a change in power output of the reactor. Transients can be caused by:

1. adding or removing neutron poisons,
2. increasing or decreasing electrical load on the turbine generator,
3. accidental conditions.

Trip, Reactor: A term that is used by pressurized water reactors for a reactor scram (see Scram).

Tritium: A radioactive isotope of hydrogen (one proton, two neutrons). Because it is chemically identical to natural hydrogen, tritium can easily be taken into the body by any ingestion path. It decays by beta emission. It has a radioactive half-life of about 12.5 years.

Thorium: Thorium is an element with an atomic number of 90. This element occurs in nature almost entirely as a single nuclear isotope, with mass number of 232. Thorium is called a fertile material because when it absorbs a neutron it becomes $\mathbf{U^{233}}$ which is fissile.

Turbine: A machine for generating rotary mechanical power from the energy of a stream of fluid (such as water, steam, or hot gas). Turbines convert the kinetic energy of fluids to mechanical energy through the principles of impulse and reaction, or a mixture of the two.

Turbine generator (TG): A steam (or water) turbine directly coupled to an electrical generator. The two devices are often referred to as one unit.

Uranium: A radioactive element with the atomic number 92 and, as found in natural ores, an atomic weight of approximately 238. The two principal natural isotopes are uranium-235, $\mathbf{U^{235}}$**.** (0.7 percent of natural uranium), which is fissile, and uranium-238, $\mathbf{U^{238}}$ (99.3 percent of natural uranium), which is fissionable by fast neutrons and is fertile. Natural uranium also includes a minute amount of uranium-234, $\mathbf{U^{234}}$.

Uranium Hexafluoride Production Facility: A facility that receives natural uranium in the form of ore concentrate, processes the concentrate, and converts it into uranium hexafluoride ($\mathbf{UF_6}$).

Utilization Facility means any nuclear reactor other than one designed or used primarily for the formation of plutonium or $\mathbf{U^{233}}$.

Void: In a nuclear power reactor, an area of lower density in a moderating system (such as steam bubbles in water) that allows more neutron leakage than does the more dense material around it.

Void Coefficient of Reactivity: A rate of change in the reactivity of a water reactor system resulting from a formation of steam bubbles as the power level and temperature increase.

Waste, Radioactive: Radioactive materials at the end of a useful life cycle or in a product that is no longer useful and should be properly disposed of.

Watt: An electrical unit of power. 1 watt = 1 Joule/second. It is equal to the power in a circuit in which a current of one ampere flows across a potential difference of one volt.

Watt-hour: An electrical energy unit of measure equal to 1 watt of power supplied to, or taken from, an electrical circuit steadily for 1 hour.

Weighting factor (WT): Multipliers of the equivalent dose to an organ or tissue used for radiation protection purposes to account for different sensitivities of different organs and tissues to the induction of stochastic effects of radiation

Whole-body Counter: A device used to identify and measure the radioactive material in the body of human beings and animals. It uses heavy shielding to keep out naturally existing background radiation and ultrasensitive radiation detectors and electronic counting equipment.

X-ray: Electromagnetic radiation with wavelengths between ultraviolet and gamma rays. Radiation from cosmic sources; naturally occurring radioactive materials, including radon (except as a decay product of source or special nuclear material) and global fallout as it exists in the environment from the testing of nuclear explosive devices. It does not include radiation from source, byproduct, or special nuclear materials regulated by the Nuclear Regulatory Commission. The typically quoted average individual exposure from background radiation is 360 millirems per year.

Yellowcake: Yellowcake is the product of the uranium extraction (milling) process; early production methods resulted in a bright yellow compound, hence the name *yellowcake*. The material is a mixture of uranium oxides that can vary in proportion and in color from yellow to orange to dark green (blackish) depending at which temperature the material was dried (level of hydration and impurities). Higher drying temperatures produce a darker, less soluble material. Yellowcake is commonly referred to as U3O8 and is assayed as pounds U3O8 equivalent. This fine powder is packaged in drums and sent to a conversion plant that produces uranium hexafluoride (UF6) as the next step in the manufacture of nuclear fuel.