The POWER of ENGINEERING

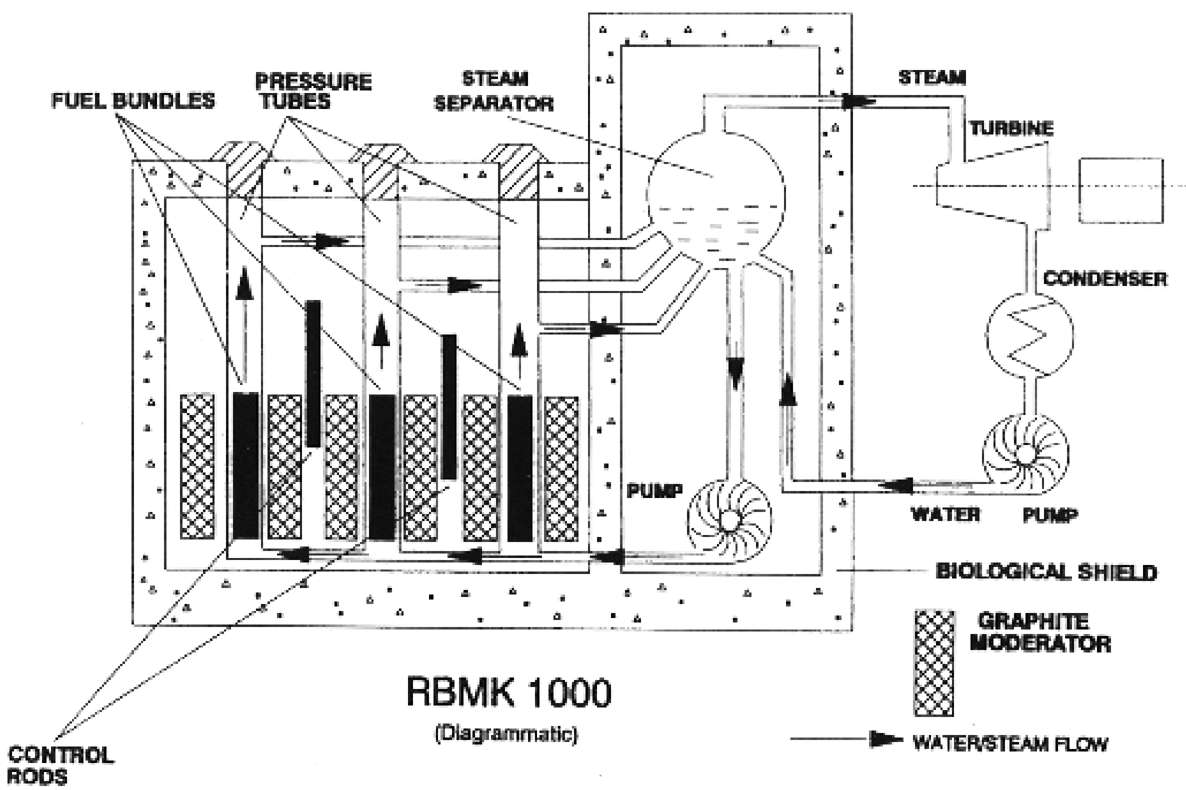
INTRODUCTION TO THE RUSSIAN RBMK NUCLEAR REACTOR AND THE CHERNOBYL NUCLEAR ACCIDENT FOR STAKEHOLDERS AND CONSULTANTS OF ASCENTRUST, LLC. AND NUCLEAR TECHNOLOGIES, INC.

SECTION ONE: THE RBMK NUCLEAR REACTOR

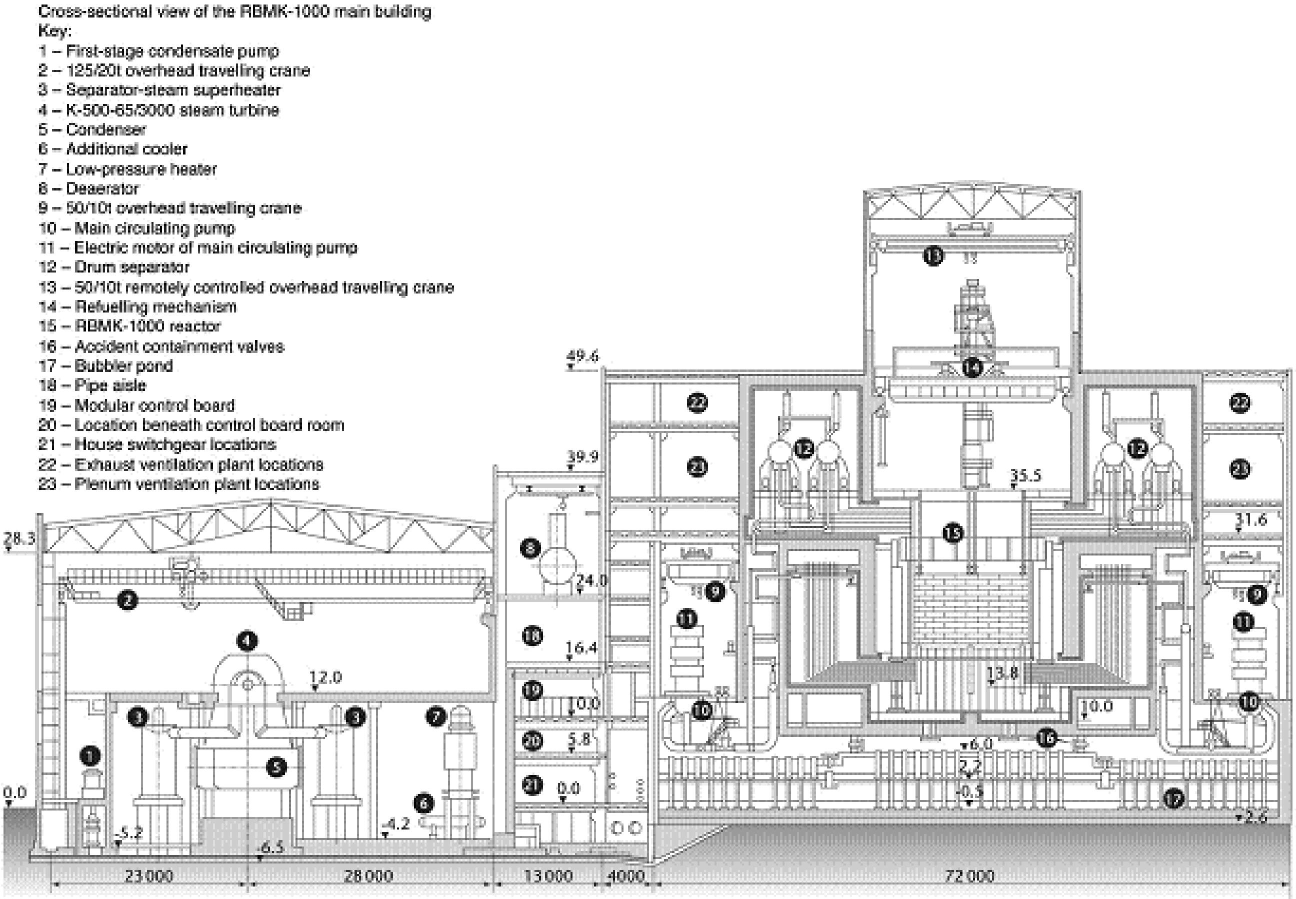
The Soviet-designed RBMK (*reaktor bolshoy moshchnosty kanalny*, high-power channel reactor) is a pressurized water-cooled reactor with individual fuel channels and using graphite as its moderator. It is very different from most other power reactor designs as it is derived from a design principally used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



PART ONE: 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.

PART TWO: 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.
- In order 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.

A. 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.

B. 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.

After the Chernobyl accident, Soviet safety standards were revised again (OPB-88). One RBMK (Smolensk 3) has been built to these third-generation standards. Additional design changes were being incorporated in the construction of Kursk 5.

In 2006, Rosatom said it was considering lifetime extensions and uprating of its 11 operating RBMK reactors. Following significant design modifications made after the Chernobyl accident, as well as extensive refurbishment including replacement of fuel channels, a 45-year lifetime is seen as realistic for the 1000 MWe-class units. In 2005, they provided 48% of Russia's nuclear-generated electricity. The R&D Institute of Power Engineering is preparing plans for 5% uprating of them.

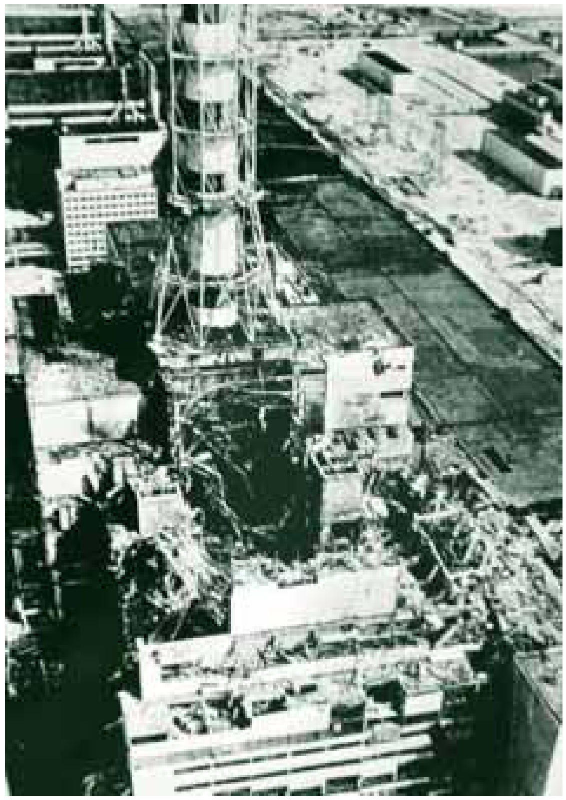
In the Table below, the 'operating until' dates are the scheduled shutdown for these plants, with 15-year lifetime extensions in some cases. Lithuania, on the other hand, closed Ignalina 1 &2 early as a condition for entry into the European Union.

Russia's long-term plans had earlier included the possibility of replacing the Leningrad units, at the end of their extended service life, by new MKER-1000 units. These are a modification of the RBMK design. The main differences are in the spacing of the graphite lattice in the core and the incorporation of passive safety systems.

SECTION TWO: THE CHERNOBYL NUCLEAR ACCIDENT

PHOTOGRAPH OF FOUR REACTORS AT CHERNOBYL

CLOSE-UP PHOTOGRAPH OF REACTOR #4 AT CHERNOBYL



2.1. INTRODUCTION

The April 1986 disaster at the Chernobyl nuclear power plant in the Ukraine was the product of a flawed Soviet reactor design coupled with serious mistakes made by the plant operators. It was a direct consequence of Cold War isolation and the resulting lack of any safety culture.

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, lying about 130 km north of Kiev, Ukraine, and about 20 km south of the border with Belarus, 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.

2.2. SEQUENCE OF EVENTS.

On 25 April, prior to a routine shutdown, the reactor crew at Chernobyl 4 began preparing for a test to determine how long turbines would spin and supply power to the main circulating pumps following a loss of main electrical power supply. This test had been carried out at Chernobyl the previous year, but the power from the turbine ran down too rapidly, so new voltage regulator designs were to be tested.

A series of operator actions, including the disabling of automatic shutdown mechanisms, preceded the attempted test early on 26 April. By the time that the operator moved to shut down the reactor, the reactor was in an extremely unstable condition. A peculiarity of the design of the control rods caused a dramatic power surge as they were inserted into the reactor

The interaction of very hot fuel with the cooling water led to fuel fragmentation along with rapid steam production and an increase in pressure. The design characteristics of the reactor were such that substantial damage to even three or four fuel assemblies can – and did – result in the destruction of the reactor. The overpressure caused the 1000 t cover plate of the reactor to become partially detached, rupturing the fuel channels and jamming all the control rods, which by that time were only halfway down. Intense steam generation then spread throughout the whole core (fed by water dumped were only halfway down. Intense steam generation then spread throughout the whole core (fed by water dumped into the core due to the rupture of the emergency cooling circuit) causing a steam explosion and releasing fission products to the atmosphere. About two to three seconds later, a second explosion threw out fragments from the fuel channels and hot graphite. There is some dispute among experts about the character of this second explosion, but it is likely to have been caused by the production of hydrogen from zirconium-steam reactions.

Two workers died as a result of these explosions. The graphite (about a quarter of the 1200 tonnes of it was estimated to have been ejected) and fuel became incandescent and started a number of fires, causing the main release of radioactivity into the environment. A total of about 14 EBq (14 x10^{18} Bq) of radioactivity was released, over half of it being from biologically-inert noble gases. About 200-300 tonnes of water per hour was injected into the intact half of the reactor using the auxiliary feed-water pumps but this was stopped after half a day owing to the danger of it flowing into and flooding units 1 and 2. From the second to tenth day after the accident, some 5000 tonnes of boron, dolomite, sand, clay and lead were dropped on to the burning core by helicopter in an effort to extinguish the blaze and limit the release of radioactive particles.

2.3. 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.

2.4. ENVIRONMENTAL AND HEALTH EFFECTS OF THE CHERNOBYL 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.

2.5. 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.

2.6. 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 part 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.

2.7. 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 cesium 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.

2.8. LESSONS LEARNED FROM THE CHERNOBYL DISASTER

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. These initiatives are backed by funding arrangements. The Nuclear Safety Assistance Coordination Centre database lists Western aid totaling almost US$1 billion for more than 700 safety-related projects in former Eastern Bloc countries. 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.