CHERNOBYL ACCIDENT

4/9/2011

INTRODUCTION

The accident on April 26, 1986 at unit 4 of the RBMK-1000 reactors plant at Chernobyl in the Ukraine is considered as the worst accident in the history of nuclear power generation.

RBMK is an acronym standing for: “Reaktory Bolshoi Moshchnosti Kanalynye,” or “High Power Pressure-Tube Reactors.” In some English-language publications, the RBMK reactors are designated as LWGR, for Light Water Graphite-moderated, pressure tube Reactors with boiling, light-water coolant.

Ironically, the accident resulted from the human error violations of the safety rules during none other than an intended safety test. The safety test was carried out to determine if one of the turbo-generators could supply power to the feed-water pumps until the standby diesel generators came on line in the case of a local power failure.

Figure 1. Damaged unit 4 of the Chernobyl plant, before being enclosed in a concrete silo.

DESCRIPTION OF REACTOR PLANT

The Chernobyl power station is composed of 4 reactor units. Unit number 4, completed in 1984, was involved in the accident. Two other units, 5 and 6, were under construction at the time of the accident. Units 3 and 4 shared the same building.

The flow diagram shows the power cycle and the pressure tubes embedded in the graphite moderated core. Light water as a coolant boils in the pressure tubes and rises to a steam drum where the steam is separated and sent to the turbine plant while the liquid coolant is pumped back to the pressure tubes by the reactor coolant pumps.

The four RBMK-1000 units at Chernobyl represent 30-year old technology. The 1000 indicates a 1,000 MegaWatts electrical (MWe) nominal power production capability.

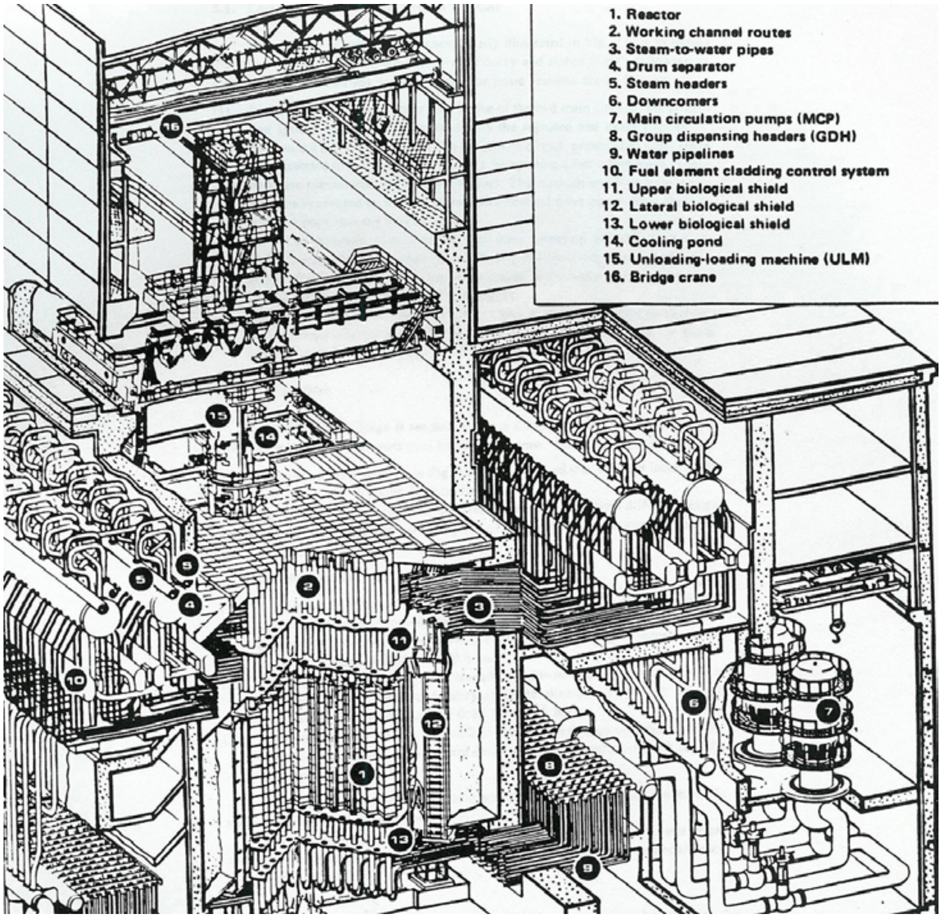

Figure 2. Cutout of the RBMK-1000 reactor design. Source: IAEA Bulletin.

The reactor had a power of 3,140 MWth and 1,000 MWe. Its coolant flow rate was 37.5 x 10^3 t/hr and a steam capacity of 5.4 x 10^3 t/hr.

The coolant inlet temperature was 270 ^oC and the saturated steam temperature was 284 ^oC. Its pressure at the steam drums separators was 70 kg/cm^2.

Its initial fuel enrichment was 1.8 percent in U^{235}.

The design feature of having more than 1,000 individual primary circuits gave the complacent impression that it: “increases the safety of the reactor system; a serious loss of coolant accident is practically impossible.”

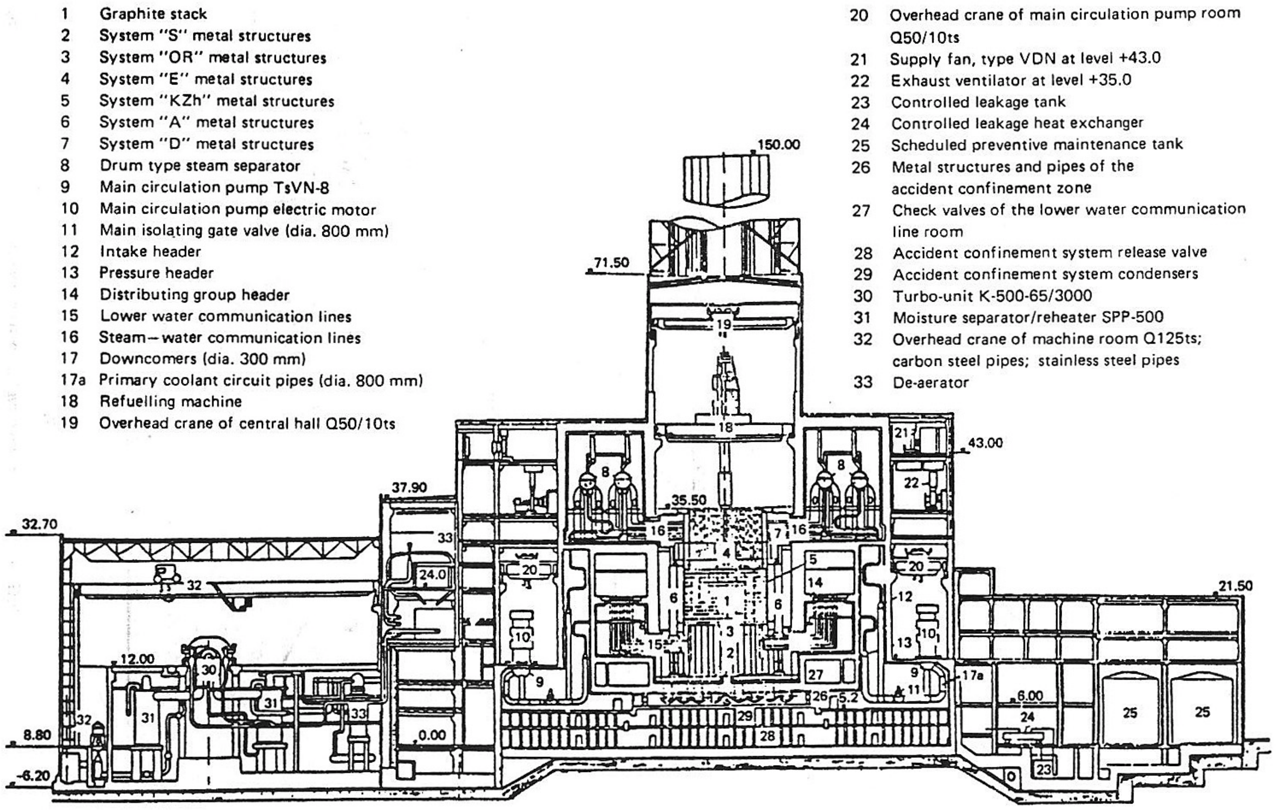

Figure 3. Vertical section showing the main components of Chernobyl unit 4. Dimensions in meters. Source: IAEA.

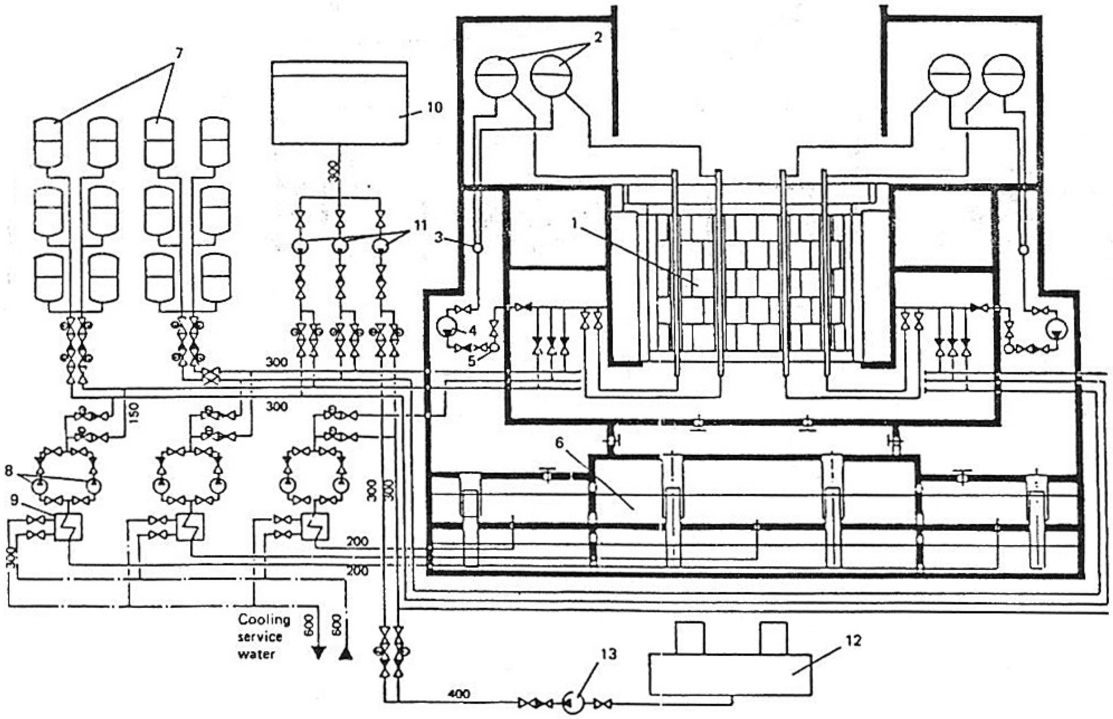

Figure 4. Emergency Core Cooling System, ECCS of the RBMK-1000. 1: Reactor, 2: Steam separators, 3: Suction header, 4: Main circulation pump, 5: Pressure header, 6: Pressure suppression pool, 7: ECCS vessels, 8: ECCS pumps, 9: Heat exchangers, 10: Clean condensate container, 11: ECCS pumps, 12: Deaerator, 13: Feedwater pump. Source: IAEA.

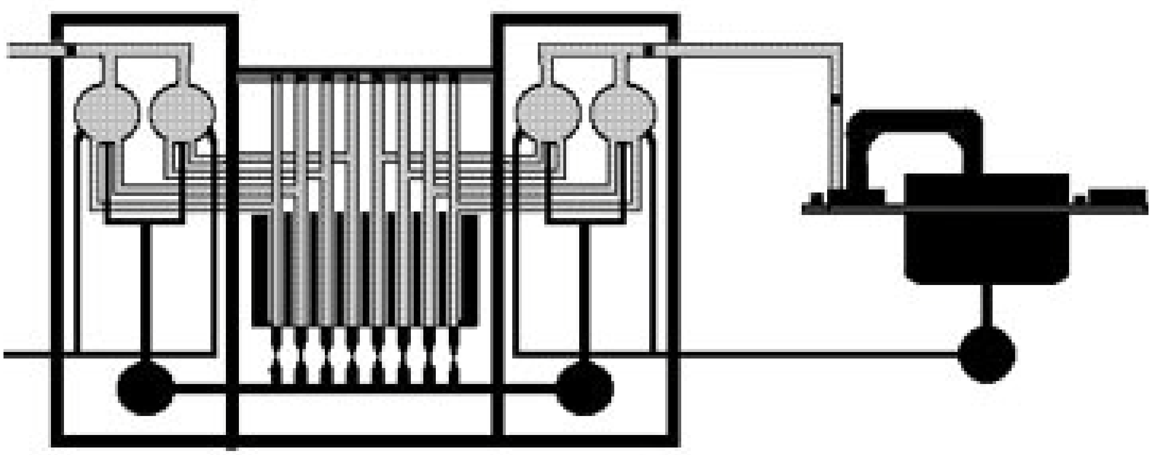

Figure 5. Main coolant circuits of the RBMK-1000 reactor.

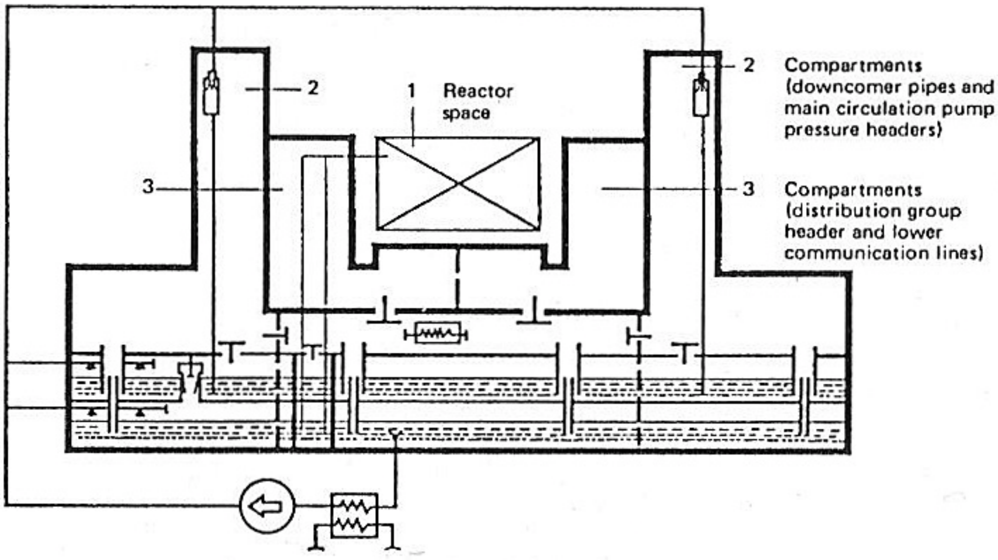

Figure 6. Schematic diagram of the containment system designated as the "accident isolation system." A design flaw involves the placing of the pressure suppression pool under the reactor core creating the possibility of a steam explosion from the possible interaction of molten corium material with the water. Source: IAEA.

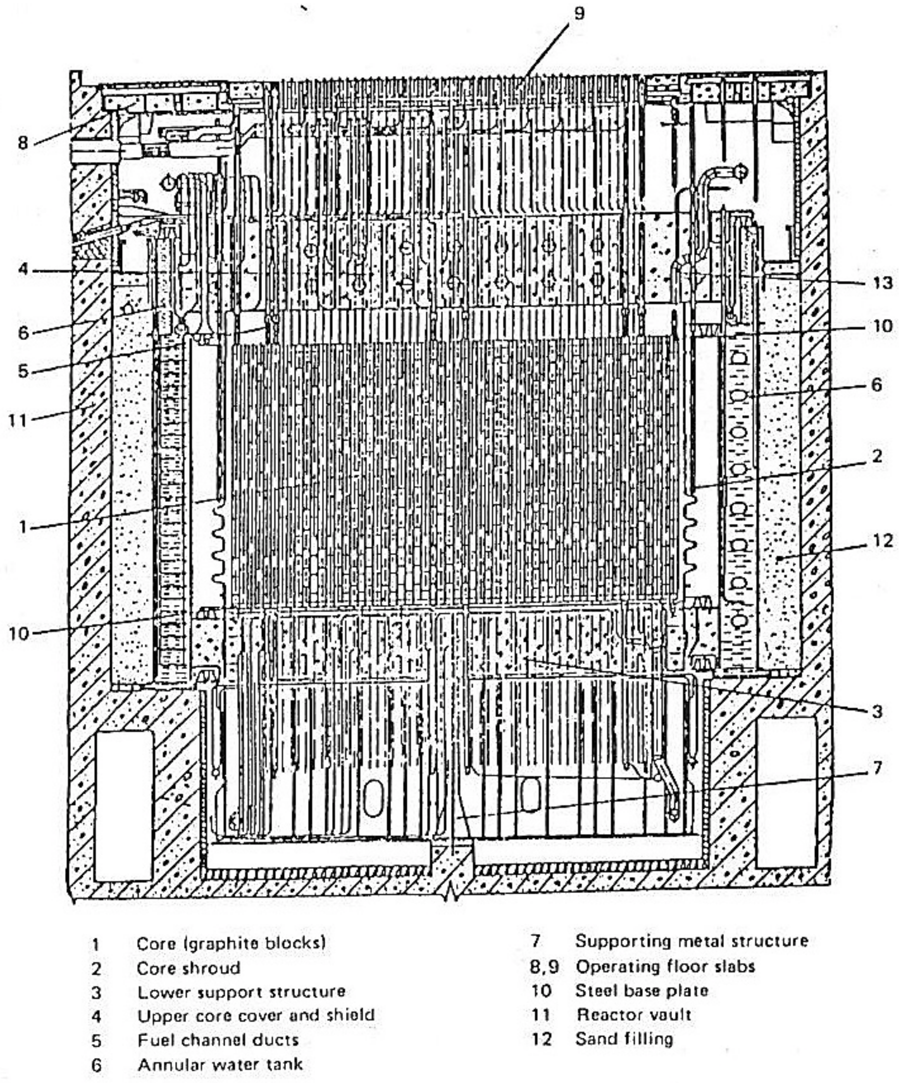

Figure 7. Core detail of the RBMK-1000. The boiling light water coolant pipes are surrounded by the graphite moderator.

REACTOR CHARACTERISTICS

The RBMK reactors were built only in Russia and the former Eastern block nations. It is a boiling light water reactor, with pressure tubes containing the fuel elements. The moderator is graphite. The core consists of a graphite stack with drill holes for the pressure tubes. The coolant flows through the channels from bottom to the top of the core. The reactor cooling system consists of 2 loops. The steam water mixture leaving the core is led to two steam drums, from where the separated steam is fed into the turbines where electricity is produced.

The graphite provides the major part of the moderation needed to sustain the chain reaction. The light water coolant acts primarily as a neutron absorber and does not provide significant moderation. This means that a void in the water coolant could actually reduce its neutron absorption characteristic and increase the fission reaction rate, hence increase the power level. An increase in reactor power increases the coolant boiling, which increases the steam void fraction, which in turn increases core reactivity and causes the power to rise even further. This positive feedback mechanism characterizes unstable systems. The positive power coefficient or void coefficient of reactivity for the RBMK exists under most operating conditions and makes them particularly difficult to control at low power levels.

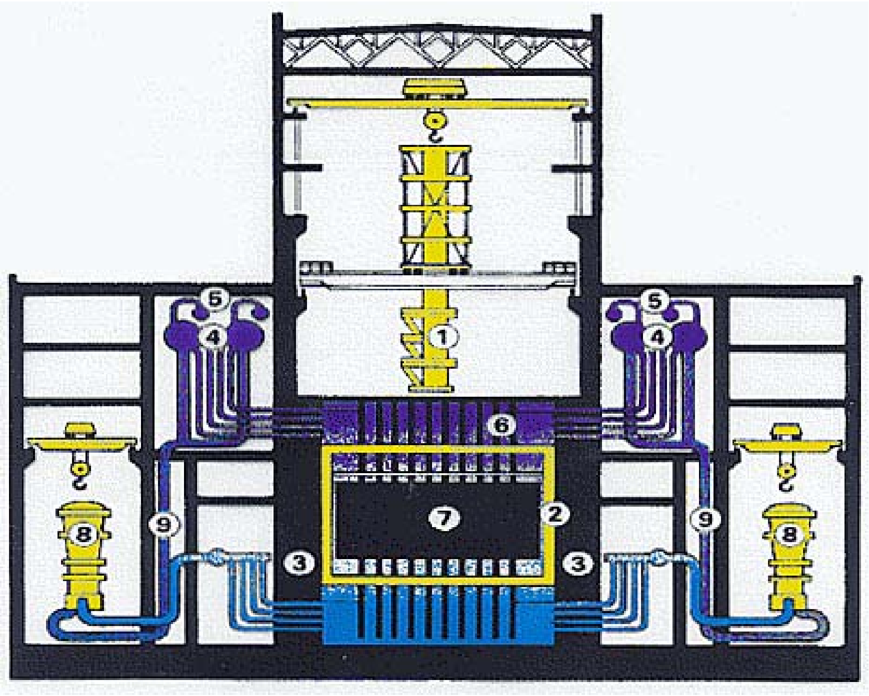

Figure 8. Vertical cutout of RBMK-1000 design. 1: On-line refueling machine, 2: Reactor core enclosure, 3: Concrete shield, 4: Steam drums, 5: Steam headers, 6: Reactor upper plate shield, 7: Reactor core, 8: Circulation pumps, 9: Feedwater return pipe.

The fuel consists of uranium dioxide (UO_2) ceramic enriched to 1.8 percent in the U^{235} isotope. The fuel is clad in zirconium cylindrical fuel elements joined in bundles of 18 elements in each fuel assembly placed in the channels. There are 1,659 fuel assemblies in the core with about 114.7 kgs of uranium in each assembly. Each Zircaloy fuel tube is 3.65 m long. Two sets of 18 fuel rods are arranged cylindrically in a carriage to form a fuel assembly of about 10 m length. These fuel assemblies can be lifted into and out of the reactor by the refueling machine, allowing fuel replenishment while the reactor is in operation.

The cylindrical core has a radius of 6 m and height of 7 m. The total mass of uranium in the core is 190.2 metric tonnes.

The control rods are inserted into the core from the top. The different components of the system are:

1. An on-line refueling machine.
2. A gas-tight containment steel vessel.

3. A concrete biological shield and structure.
4. Steam drum for steam and water separation.
5. Steam line to the turbines.
6. Refueling channels through top plate.
7. Reactor core.
8. Main coolant pump.
9. Return cooling water from steam drum.

Within the reactor each fuel assembly is positioned in its own pressure tube or channel. Each channel is individually cooled by pressurized boiling light water.

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. This is necessary for continuous fission to be maintained. Heat conduction between the blocks is enhanced by a mixture of helium and nitrogen gas.

The reactor design is meant for dual purpose electrical energy production as well as Pu for nuclear devices as a contingency in a time of strategic need. In contrast to reactor-grade Pu that contains a large proportion of the isotope Pu^{240} that makes unsuitable for weapons manufacture through its spontaneous fission and alpha radiation emission, a short-time irradiation of fertile U^{238} for about 2 weeks produces Pu that is primarily composed of the Pu^{239} isotope suitable for nuclear devices manufacture. Accordingly, the reactor design allows for on line refueling when a reactor is in operation. There were fuel assemblies with different levels of burn-up at the moment of the accident.

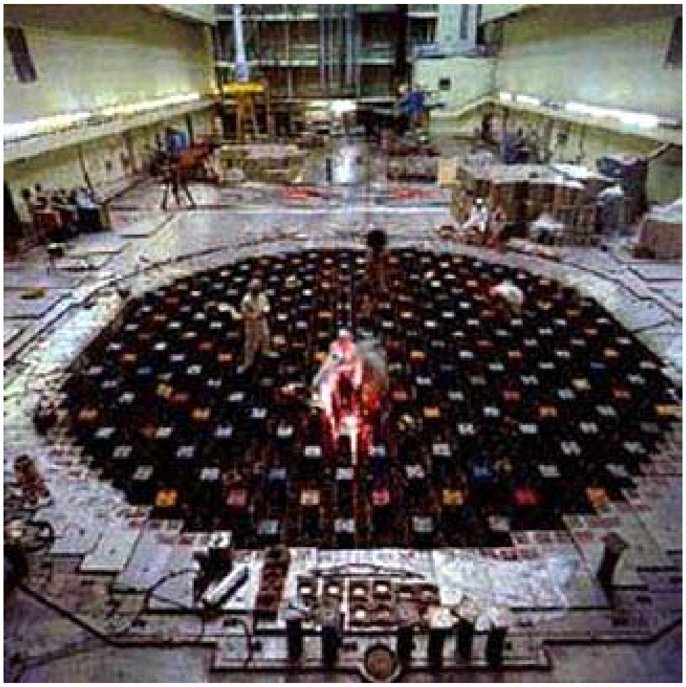

Figure 9. Top view of RBMK-1000 reactor, with workers involved in the on-line refueling process.

SAFETY FEATURES

The reactors was equipped with multiple safety features and had as a design limiting-fault-condition a Loss of Coolant Accident (LOCA) with break in the pipe work of 90 cms in diameter.

The primary circuit piping, including the steam drums, was enclosed in concrete vaults designed to withstand pressures up to 4 bars.

The reactor is able to operate its 2,000 metric tonnes of graphite moderator at a temperature of about 700 ^{o}C. The moderator was enclosed during operation in an inert atmosphere of a mixture of helium and nitrogen gas.

The containment system consists of several engineered safety features which condense and collect any coolant water release in closed spaces under the reactor. A pressure-suppression pool, similar to the Boiling Water Reactor (BWR) design was situated beneath the structure. This was an unsatisfactory design choice since in the event of core meltdown the molten corium material would cause a steam explosion if it came in contact with the water pool. An emergency core cooling system (ECCS) would come into operation if either coolant circuit is interrupted.

Boron carbide control rods absorb neutrons to control the rate of fission. The system of control and protection of the reactor is based on the motion of 211 control rods in special channels of the core meant to provide automatic control of a given power level, rapid decrease of the power in response to signals in case of main equipment failures, or accidental termination of the reactor operation in response to dangerous deviations of parameters.

A few short rods, inserted upwards from the bottom of the core, even-out 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 the in-core detectors. If there is a deviation from normal operating parameters, the rods can be dropped into the core to reduce the reactor's reactivity. A number of rods normally remain in the core during operation.

Two separate water coolant circuits each with four pumps circulate water through the pressure tubes. Ninety-five percent of the heat from fission is transferred to the coolant. Steam from the heated coolant is fed to the turbines to produce electricity in the generator. The steam is then condensed and fed back into the circulating coolant.

The reactor core is located in a concrete-lined cavity that acts as a biological radiation shield. The upper shield or pile cap above the core is made of steel and supports the fuel assemblies. The steam drums separators of the coolant systems are housed in their own concrete shields for protection against the short-lived gamma radiation emitted from N^{16} during operation of typical of boiling water reactors.

The reactor core is surrounded by a biological shield in the form of a cylindrical coaxial tank filled with water and 16.6 m in diameter. It remained practically undamaged after the accident. The biological shield and the core are closed from above and below by cylindrical covers filled with serpentine shaped shielding materials through which multiple communication pipes pass. These parts of the reactor were displaced during the accident, and they formed passages through which the contents of the core were released.

DESIGN CHARACTERISTICS

The use of the pressure tube design concept generated a false sense of security, for it was thought that should an accident happen in the cooling circuit, it would happen in one of the tubes which can then be isolated from the rest of the system. This is unlike the use of a single pressure vessel with light water as a coolant and a moderator in the Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) designs.

The very hot graphite core is prevented from oxidizing by the inert He and N gas atmosphere. Graphite possesses a peculiar property in that it is subject under neutron irradiation to energy accumulation in its lattice structure caused by atomic displacements through a phenomenon known as the Wigner Effect.

To avoid the occurrence of hot spots, the graphite needs to be annealed at regular intervals. Such a phenomenon is thought to have caused the earlier graphite fire accident at the Windscale reactor in the UK. The accepted practice is to nuclearly heat the graphite to bring the graphite moderator up to temperature where the displaced atoms return back to their original positions. This process releases more energy appearing as heat. This heat release is sufficiently large allowing the discontinuance of the nuclear heating. In fact the Windscale accident occurred while performing such an annealing process. The structure of the Windscale reactor had pockets of non annealed graphite which required a second nuclear annealing process, during which the accident occurred. The nuclear heating occurred too fast, leading to the bursting of a fuel cartridge. Oxidation of the uranium metal used to produce plutonium caused a fire which spread to the graphite. The air circulating through the core kept the hot graphite on fire until water was eventually used to quench the fire.

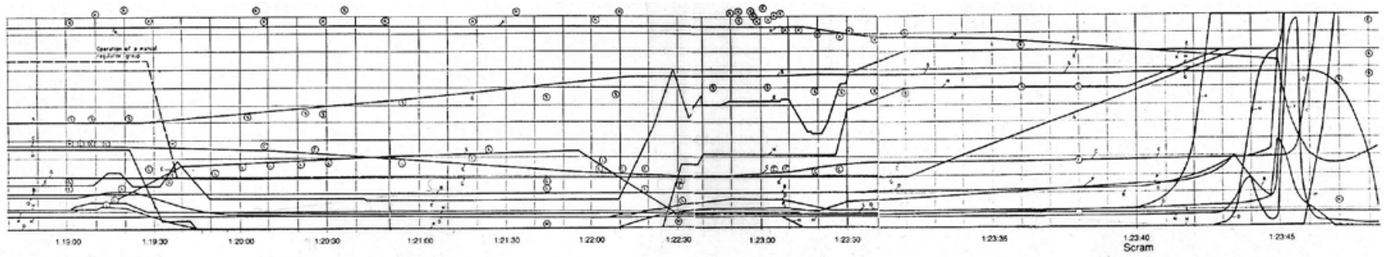

Figure 10. Accident sequence of the Chernobyl unit 4 accident. Vertical lines represent 10 second intervals from 1:19:00 to 1:23:30. At that point vertical lines represent 1 second intervals. At 1:23:43, the neutron power curve switches from A to D, with a change in the vertical scale.

Steam is chemically reactive with graphite producing a mixture of CO and H_2 called producer gas. The latter gases can themselves burn with a high calorific value. Moreover at the high operational temperature the Zircaloy cladding itself would react auto catalytically with the steam releasing even more hydrogen. This hydrogen can react explosively with air producing water.

The Zircaloy pressure tubes adjacent to the hot graphite were cooled only as long as the water pressure within the tube is maintained. A loss of water pressure would raise the temperature of the Zircaloy to that of the graphite.

The positive void and power coefficient resulting from a neutron population increase if the water coolant is boiled off or lost from a coolant channel required careful operational procedures.

ACCIDENT SEQUENCE

Table 1. Parameter scales in the accident sequence.

	Parameter	Scale Min	Scale Max
A	Neutron power, low range, percent	0	120
B	Reactivity, sum, percent	-1	+5
C	Steam drum pressure, bar	54	90
D	Neutron power, high range, percent	0	480
E	Auto rod, group 1, fraction in	0	1.2
G	Auto rod, group 2, fraction in	0	1.2
H	Auto rod, group 3, fraction in	0	1.2
K	Main circulation flow, m^3/hr	2	8
L	Feedwater flow, kg/sec	0	600
M	Steam flow, kg/sec	0	600
N	Fuel Temperature, ^oC	200	2,000
O	Mass steam quality, percent	0	6
P	Volumetric steam quality, void fraction	0	1.2
S	Steam drum water level, mm	-1,200	0

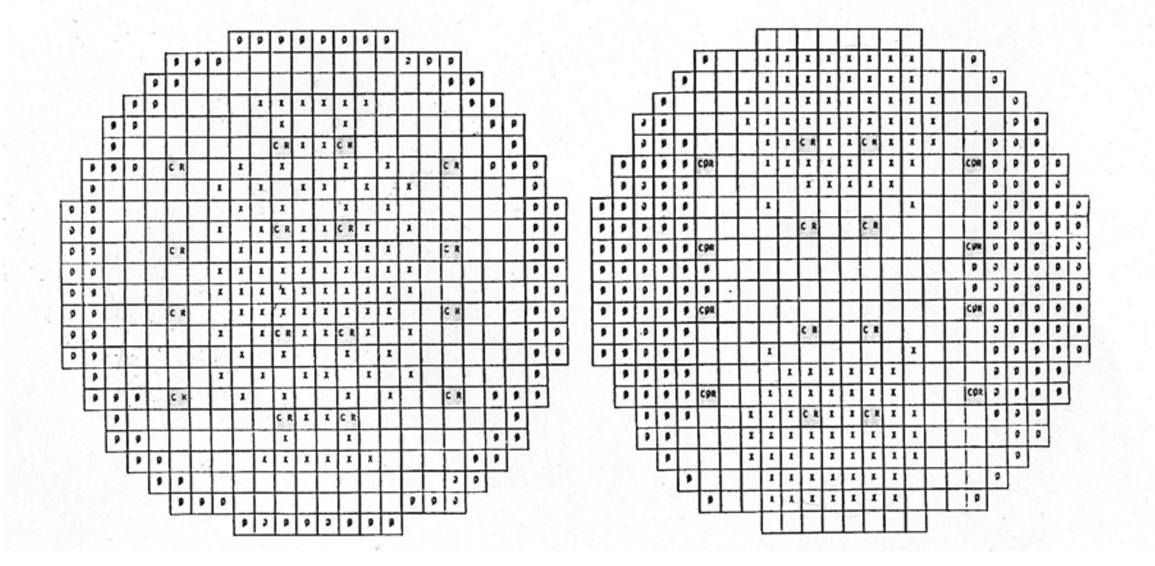

Figure 11. Initial radial power distribution (left) and radial power distribution at the time of the power excursion (right). CR: control rods, x: $P > 1.3\ P_{average}$, φ: $P < 0.7\ P_{average}$. At the time of the accident, the core had split into two cores.

1. The reactor was powered down for a test sequence to determine whether one of the turbo generators could supply power to the feed-water pumps until the standby diesel generators came on line in the case of a local power failure. The test sequence involved the following steps:

> a. Instead of the design based reduction to 22-32 percent of full power, the power was inadvertently lowered to just 1 percent of full power, an unstable situation because of the positive void coefficient. The operator failed to reprogram the computer to maintain the power level at the planned 700-1,000 MWth.
>
> b. All the control rods were pulled out of the core, to the point where they could not shut down the reactor rapidly if needed. This step was taken to get the power back up, but it only reached 7 percent, still well below the design parameters for the test. The reason the power could not be brought back up was that the reactor dead time resulting from the xenon poisoning effect. Xenon is a decay product of I^{135} and is a strong neutron absorber which poisons the fission reaction. It reaches an equilibrium level at normal operating power levels by being burned away by neutron absorption and by radioactive decay. When the power level was decreased from the 1,600 MWth level, there existed a large amount of the I^{135} fission product to decay into xenon, but a low neutron flux incapable of burning it out; so it built up rapidly.
>
> c. In order to keep the reactor from automatically shutting down under these conditions, the operators disconnected the automatic emergency core cooling system and several of the automatic scram circuits.
>
> d. All eight cooling water pumps were running at the low power level, compared with a normal six even at full power, so there was nearly solid water with almost no void fraction, which increased the vulnerability to any power excursion which produced boiling.

2. The turbo-generator was tripped to initiate the test, which caused the switching off of four of the eight recirculation pumps. This would have normally tripped the reactor if the automatic scram circuit had not been disconnected.

3. The reduced coolant flow caused voids to form rapidly in the pressure tubes, increasing the reactivity because of the positive void power coefficient.

4. Within seconds, with rapidly rising power, an emergency manual scram was ordered, but the almost fully withdrawn rods could not insert sufficient negative reactivity fast enough because of their slow speed. Also, an unexpected displacement of water from the control rod tubes occurred, further adding to the positive reactivity.

5. The control rods were reported to have graphite followers. Inserting the fully withdrawn rods with their graphite followers would have initially added reactivity rather

than decreasing it. These followers probably were part of the shielding of the top of the reactor for access during on-line operation.

6. The core went into prompt criticality, overheating and shattering fuel rods and flashing the coolant into steam. The fuel channels were ruptured.

7. The built-up steam pressure blew the 1,000-tonnes steel and cement-filled biological shield off the top of the reactor, severing all 1,600 pressure tubes and exposing the hot core to the atmosphere.

8. The reactor power level reached 100 times its operating maximum and the explosive energy release was equivalent to about 1 ton of TNT.

ACCIDENT CHRONOLOGY

April 25, 1986: Preparation for the next day's safety test

01:06: The scheduled shutdown of the reactor started. A gradual lowering of the power level began

03:47: Lowering of reactor power halted at 1,600 MWth.

14:00: The Emergency Core Cooling System (ECCS) was isolated as part of the test procedure, to prevent it from interrupting the test later. The fact that the ECCS was isolated did not contribute to the accident. However, had it been available, it might have mitigated the consequences.

14:00: The power was due to be lowered further; however, the controller of the electricity grid in the city of Kiev, Ukraine requested the reactor operator to keep supplying electricity to enable demand to be met. Consequently, the reactor power level was maintained at 1,600 MWth and the experiment was delayed. Without this delay, the test would have been conducted during the day-shift, where more experienced operators would have been available.

23:10: Power reduction restarted.

24:00: Shift change.

April 26, 1986: Accident Occurrence

Test preparation

00:05:00 Power level had been decreased to 720 MWth and continued to be reduced. It is now recognized that the safe operating level for a pre-accident configuration RBMK was about 700 MWth because of the positive void coefficient.

00:28:00 Power level was now 500 MWth. Control was transferred from the local to the automatic control system. Either the operator failed to give the hold power at the required level signal or the control system failed to respond to this signal. This led to an unexpected fall in power, which rapidly dropped to 30 MWth.

~00:32:00	In response to the unexpected power drop, the operator retracted a number of control rods in an attempt to restore the power level. The station’s safety procedures required that approval of the chief engineer should be obtained to operate the reactor with fewer than the effective equivalent of 26 control rods. It is estimated that there were less than this number remaining in the reactor at this time.
01:00:00	The reactor power had risen to 200 MWth.
01:03:00	An additional pump was switched into the left hand cooling circuit in order to increase the water flow to the core as part of the test procedure.
01:07:00	An additional pump was switched into the right hand cooling circuit as part of the test procedure. Operation of additional pumps removed heat from the core more quickly. This reduced the water level in the steam drum separator.
01:15:00	The automatic trip systems to the steam separator were deactivated by the operator to permit continued operation of the reactor.
01:18:00	Operator increased the feed water flow in an attempt to address the problems in the cooling system.
01:19:00	Some manual control rods were withdrawn to increase power and raise the temperature and pressure in the steam separator. The operating policy required that a minimum effective equivalent of 15 manual control rods be inserted in the reactor at all times. At this point it is likely that the number of manual rods was reduced to probably only eight. However, automatic control rods were in place, thereby increasing the total number.
01:21:40:	Feed-water flow rate reduced to below normal by the operator to stabilize the steam separator’s water level, decreasing heat removal from the core.
01:22:10:	Spontaneous generation of steam in the core began.
01:22:45:	Indications received by the operator, although abnormal, gave the appearance that the reactor was stable.

Safety Test

01:23:04:	The operators thought the reactor was stable enough for the experiment to start, and the turbo-generator's emergency regulation valve was closed. Turbine feed valves were closed to start turbine coasting. This was the beginning of the actual test. The steam pressure in the system rose slowly, because steam delivery was reduced. The cooling water in the reactor came near the boiling point, such that a small rise in power would mean a considerable increase in steam generation, something that had to lead to a dramatic increase in power due to the reactor's inherent physical characteristics.
01:23:10:	Automatic control rods withdrawn from the core. An approximately 10 second withdrawal was the normal response to compensate for a decrease in the reactivity following the closing of the turbine feed valves. Usually this decrease is caused by an increase in pressure in the cooling system and a consequent decrease in the quantity of steam in the core. The

expected decrease in steam quantity did not occur due to the reduced feed-water to the core.

01:23:21: Steam generation increased to a point where, owing to the reactor's positive void coefficient, a further increase of steam generation would lead to a rapid increase in power.

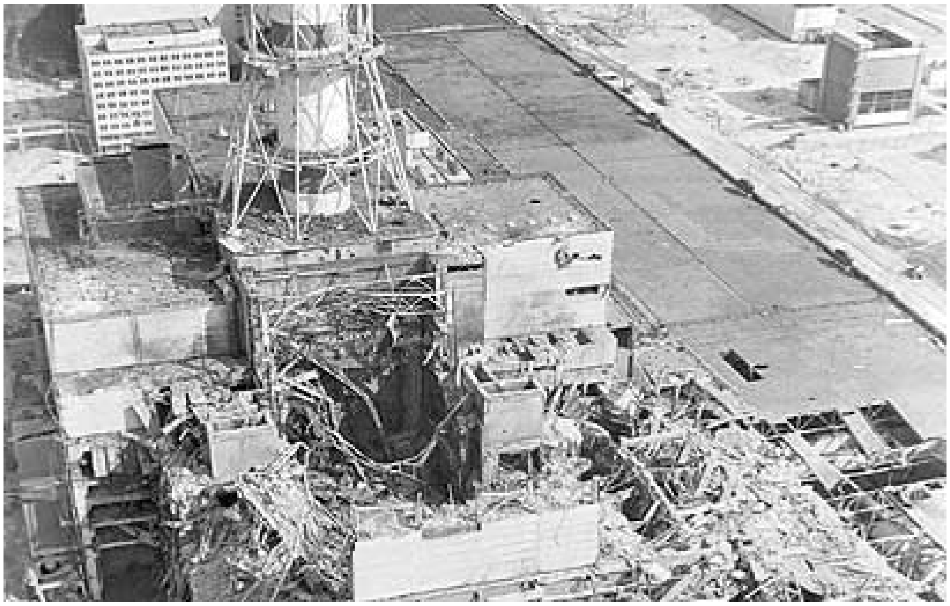

Figure 12. Aerial picture into the Chernobyl damaged unit 4 reactor core.

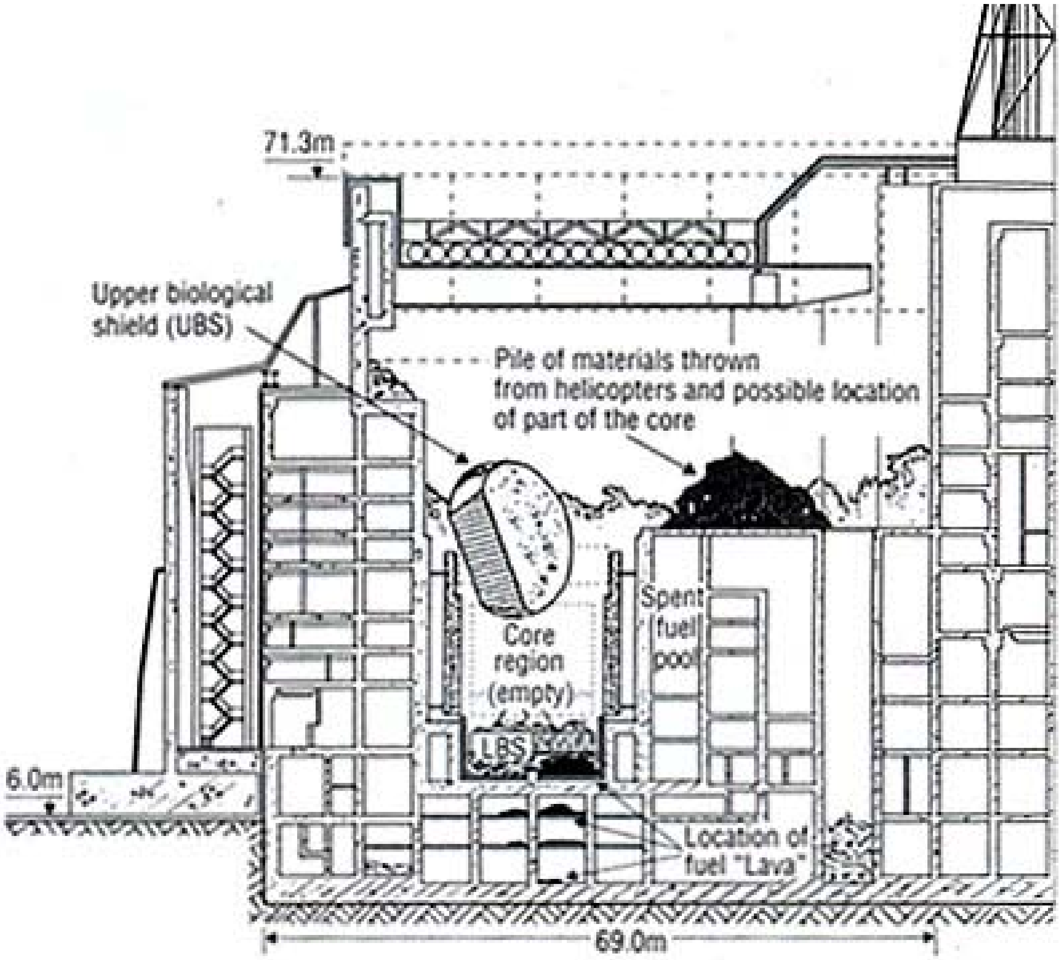

Figure 13. Concrete silo constructed around the Chernobyl unit 4 damaged core.

01:23:35:	Steam generation in the core begins to increase uncontrollably.
01:23:40:	The operator noticed a sudden increase in power and the emergency reactor trip button (AZ-5) was pressed by the operator. The control rods started to enter the core. The insertion of the rods from the top concentrated all of the reactivity at the bottom of the core. It was, however, too late: the control rods could not move quickly enough to prevent an accelerating increase in power. This power increase was at first slow, thereafter increasing to an exponential power doubling time under one second. A short time afterwards, the power doubling time was down to around one millisecond.

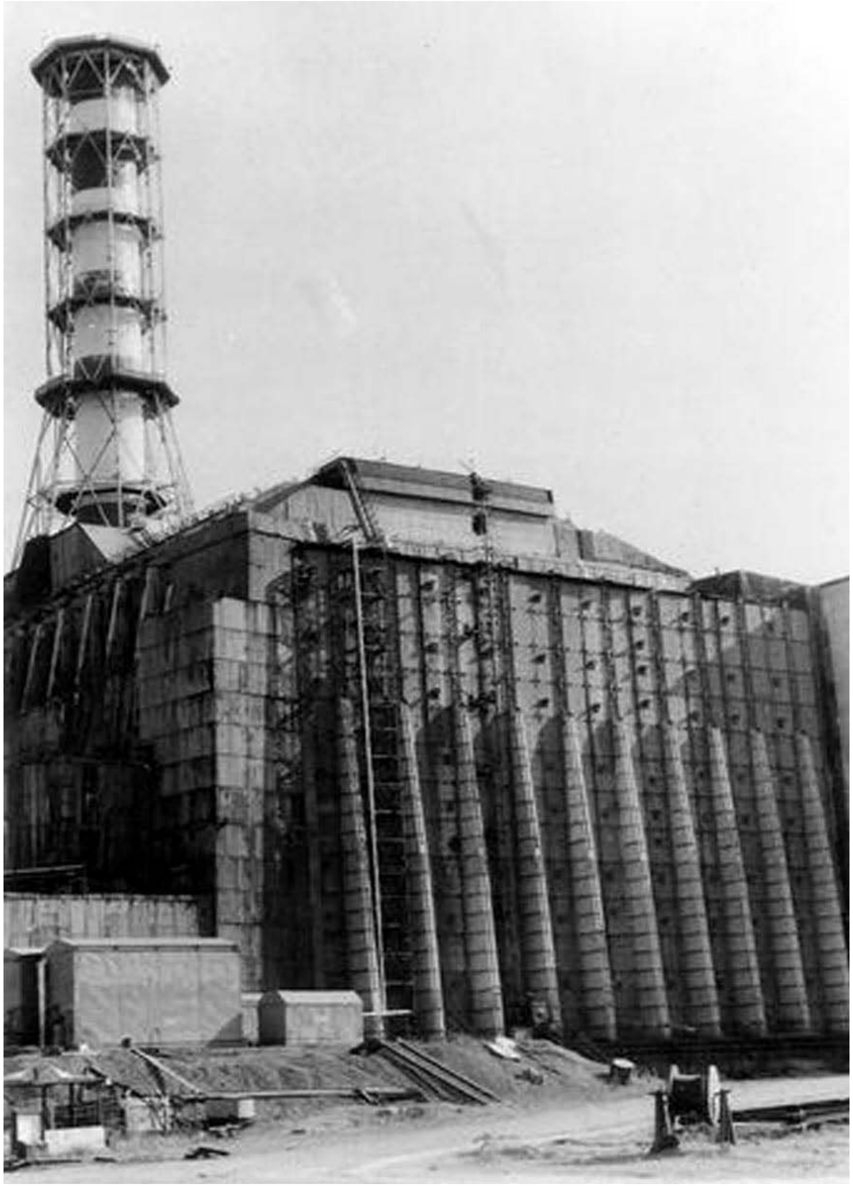

Figure 14. Chernobyl unit 4 enclosed in concrete silo.

01:23:44: Reactor power rose to a peak of about 100 times the design value. The water in the core exploded into steam.

01:23:45: Fuel pellets started to shatter, reacting with the cooling water to produce a pulse of high pressure in the fuel channels.

01:23:49; Fuel channels ruptured.

01:24:00 Two explosions are thought to have occurred. One was a steam explosion; the other resulted from the expansion of fuel vapor. A hydrogen explosion may have also simultaneously occurred. The explosions lifted the reactor top lid, allowing the entry of air. The air reacted with the hot graphite moderator blocks generating heat from the exothermic reaction:

$$C + O_2 \rightarrow CO_2 (\Delta H = -393.5\ kJ / mol) \tag{1}$$

The available heat could drive an endothermic reaction between the steam and hot graphite forming “water gas”; a synthesis gas or “syngas” as a mixture of carbon monoxide (CO) and hydrogen (H_2):

$$C + H_2O \rightarrow CO + H_2 (\Delta H = +131\ kJ / mol) \tag{2}$$

This hydrogen gas could have ignited explosively:

$$2H_2 + O_2 \rightarrow 2H_2O \tag{3}$$

More hydrogen could have been formed by the “water shift reaction”:

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{4}$$

The fuel elements were destroyed by the explosion, which also blew away the reactor roof and gave free access for fresh air to the reactor. The zirconium cladding could have formed further hydrogen formation through the reaction:

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 \tag{5}$$

The white-hot graphite in the reactor continued to burn. The fire lasted several days and led to a large amount of radioactivity being carried 1,000 meters up into the atmosphere. To help put out the fire, 5,000 metric tonnes of lead and stone were dropped on the fire by helicopter.

Aftermath, nine days period:

About 8 of the 140 tonnes of fuel, which contained fission products and actinides, were released from the reactor along with a portion of the graphite moderator, which was also radioactive. These materials were scattered around the site. In addition, cesium^{137} and iodine^{135} vapors were released both by the explosion and during the subsequent fire.

RADIOACTIVE RELEASE

A review panel suggested that if the operators had failed to complete the test they could not have repeated it for a year. This probably influenced them to take more risks than normal. A review of the accident assesses the total activity release at about 100 mega Curies (MCi) or 3.7 x 10^{18} Becquerels, including some 2.5 MCi of Cs^{137}.

The cesium release is the most serious release in terms of long term consequences. This is around 4 percent of the total accumulated activity of the core and compares to a release of just 15 Ci released from the Three Mile Island (TMI) accident. The release was then about $100 \times 10^6/15 = 6.66 \times 10^6$, or about 7 million times that at

TMI. For another comparison, the cesium release from all of the atmospheric nuclear weapons tests is estimated to be about 30 MCi.

All the noble gases and about half of the volatile elements: iodine^{131}, cesium^{134} and cesium^{137} were released. The noble gas releases are about 45 MCi of xenon^{133} and 5 MCi of krypton^{85}.

About 3-5 percent of the core inventory of the relatively refractory elements such as strontium^{90}, plutonium, and ruthenium were released, much more than from a light water reactor meltdown.

It is estimated that all of the xenon gas, about half of the iodine and cesium, and at least 5 percent of the remaining radioactive material in the Chernobyl-4 reactor core 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 a lesser extent over Scandinavia and Europe.

SAFETY IMPROVEMENTS OF RBMK REACTORS

After the accident at Chernobyl unit 4, the primary concern was to reduce the positive void coefficient. All operating RBMK reactors, in the former Soviet Union therefore, had the following changes implemented to improve their operating safety:

1. To improve the operational reactivity margin the effective number of manual control rods was increased from 30 to 45.
2. The installation of 80 additional absorbers in the core to inhibit operation at low power.
3. An increase in fuel enrichment from 1.8 percent to 2.4 percent to maintain fuel burnup with the increase in neutron absorption.

These factors have reduced the positive void coefficient from +4.5 β to +0.7 β, eliminating the possibility of power excursion. β is the delayed neutron fraction, which is neutrons emitted with a measurable time delay.

The next consideration was to reduce the time taken to shut the reactor down and eliminate the positive void reactivity. Improvements include:

1, Scram or shut down rod insertion time cut from 18 to 12 seconds.
2. The redesign of the control rods.
3. The installation of a fast scram system (-2 β / 2.5s).
4. Precautions against unauthorized access to the emergency safety systems.

In addition to the safety changes, it has been recommended that RBMKs are modified according to a procedure which was implemented at the Leningrad RBMK site.

Chernobyl unit 1 was licensed for return into operation in October 1995, following extensive maintenance which included the removal of some fuel channels to evaluate the metal and a modification process or some back-fitting, which consists of:

1. Replacement of the fuel channels at all units except Smolensk-3.
2. Replacement of the group distribution headers and addition of check valves.
3. Improvements to the Emergency Core Cooling Systems (ECCS).

4. Improvements of the reactor cavity over-pressure protection systems.
5. Replacement of the process computer by a more modern one.

ENVIRONMENTAL AND HEALTH EFFECTS

The main casualties were among the firefighters, including those who attended the initial small fires on the roof of the turbine building. All these were put out in a few hours. In terms of immediate deaths it was a limited disaster: 32 people died in the accident and in efforts to put out the fire, 38 more people died of acute radiation sickness in the following months.

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 or “liquidators” from all over the old Soviet Union were involved in the recovery and clean-up effort during 1986 and 1987. They received effective doses of radiation, around 10 centiSieverts (cSv) (1 cSv =1 rem). Some 20,000 of them received about 25 cSv (rem) and a few received 50 cSv (rem). Later, the number of liquidators swelled to over 600,000 but most of these received only insignificantly low radiation doses.

Figure 15. Liquidators decontamination effort in the damaged unit 4 of the Chernobyl plant.

On May 2-3 of 1986, some 45,000 residents were evacuated from within a 10 km radius of the plant, notably from the plant operators' town of Pripyat. On May 4, 1986, all those living within a 30 kilometers radius, a further 116,000 people; were evacuated and later relocated. About 1,000 of these have since returned unofficially to live within the contaminated zone. Most of those evacuated received radiation doses of less than 5 cSv (rem), although a few received 10 cSv (rem) or more.

In the years following the accident a further 210,000 people were resettled into less contaminated areas, and the initial 30 km radius exclusion zone or 2,800 km^2 was modified and extended to cover 4,300 square kilometers.

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, the year of the accident. For instance, children in the surrounding areas, being more susceptible than adults to the effects of radiation, were reported to have been exposed to radiation doses sufficient to lead to the formation of thyroid nodules, which is usually not fatal if diagnosed and treated early. Initial radiation exposure in the contaminated areas was due to the short-lived $iodine^{131}$. Later on, $cesium^{137}$ became the main radiation hazard.

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.

An International Atomic Energy Agency (IAEA) study involving more than 200 experts from 22 countries published in 1991 was more substantial. 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, none was radiation related.

Subsequent studies in the Ukraine, Russia and Belarus were based on national registers of over 1 million people possibly affected by radiation. These confirmed a rising incidence of thyroid nodules among exposed children. Late in 1995, the World Health Organization linked nearly 700 cases of thyroid nodules among children and adolescents to the Chernobyl accident and among these some 10 deaths are attributed to radiation.

No increase in leukemia was discernible, but this is expected to become evident on a long time scale along with a greater, though not statistically discernible, incidence of other cancers. There has been no substantiated increase attributable to Chernobyl in congenital abnormalities, adverse pregnancy outcomes or any other radiation-induced disease in the general population either in the contaminated areas or further afield.

Psycho-social effects among those affected by the accident emerged as a major problem, and are similar to those arising from other major disasters such as earthquakes, tsunamis, floods and fires.

A United Nations (UN) report has confirmed that there is no scientific evidence of any significant radiation-related health effects to most people exposed to the Chernobyl disaster. The United Nations Scientific Commission on the Effects of Atomic Radiation, which is the UN body with a mandate from the General Assembly to assess and report levels and health effects of exposure to ionizing radiation, UNSCEAR 2000 Report is consistent with earlier World Health Organization (WHO) findings. The report points to some 1,800 cases of thyroid nodules, but: " … apart from this 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 remain at increased risk of cancer in the long term.

A publication by the UN Office for the Coordination of Humanitarian Affairs (OCHA) entitled: “Chernobyl, a continuing catastrophe,” came out with a more pessimistic and contradictory view and has created a controversy that is bound to last for some time.

CHERNOBYL’S AFTERMATH

The Chernobyl unit 4 is now enclosed in a large concrete silo which was erected quickly to allow continuing operation of the other reactors at the plant. However, the structure is neither strong nor durable and there are plans for its reconstruction. The international Shelter Implementation Plan involves remedial work including removal of the fuel-containing materials. Some work on the roof has already been carried out.

Construction of a radioactive waste management facility to treat the spent fuel and other operational wastes, as well as material from decommissioning units 1-3 was started in 2001

In the early 1990s some 400 million dollars were spent on improvements to the remaining reactors at Chernobyl, considerably enhancing their safety. Energy shortages necessitated the continued operation of 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 6,000 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 kms from the plant. This was built following the evacuation of Pripyat, which was just 3 kms away.

The Ukraine depends upon, and is in debt to Russia for energy supplies, particularly oil and natural gas, but also nuclear fuel. Although this dependence is gradually being reduced, continued operation of nuclear power stations, which supply 45 percent of the total electricity, is now even more important than in 1986. The Ukraine is also planning to develop its own nuclear fuel cycle facilities to further increase its independence.

It was announced in 1995 that the two operating reactors at Chernobyl would be closed with a memorandum of understanding that was signed by the Ukraine and the group of seven nations (G7), but its implementation remained in doubt. Alternative generating capacity was needed, either gas-fired, which has ongoing fuel cost and supply implications, or nuclear, by completing the Khmelnitski unit 2 and Rovno unit 4 in the Ukraine. Construction of these was halted in 1989 and then resumed, with financing which had been contingent upon Chernobyl's closure.

METALLIC VAULT FOR CHERNOBYL UNIT 4

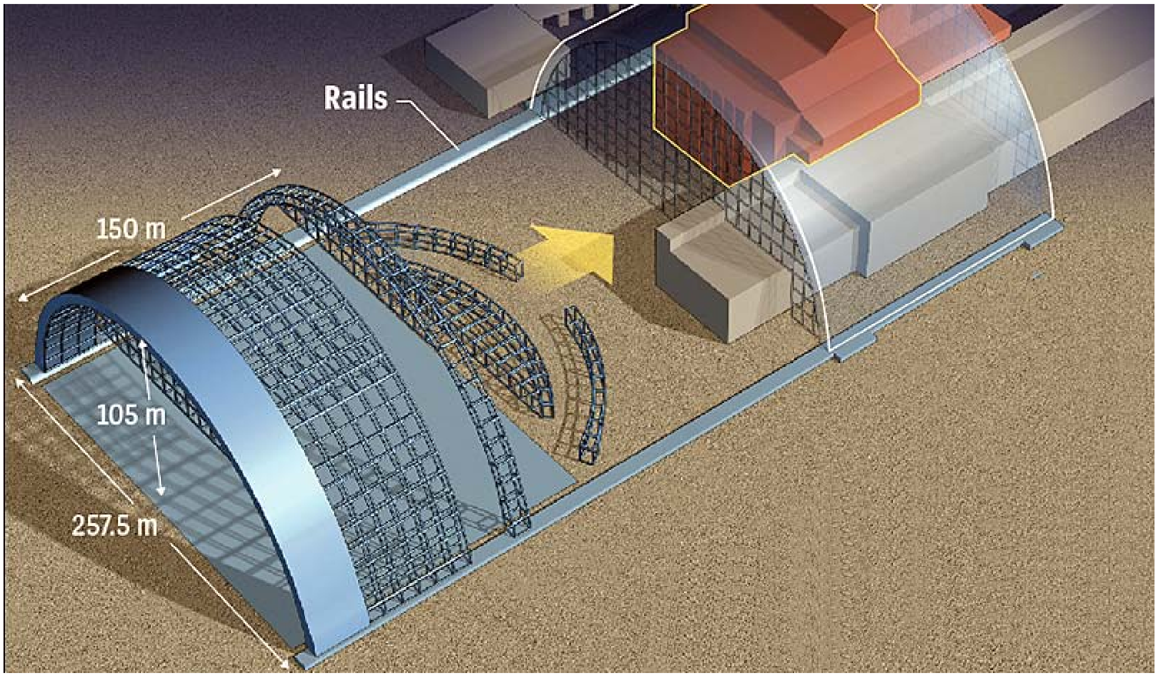

Figure 16. Proposed metallic vault for the damaged Chernobyl unit 4 reactor. The metallic shield would be constructed near the reactor then moved on rails to cover it. Source: Der Spiegel.

The concrete silo encasing the burned reactor at Chernobyl is crumbling, threatening to leak radiation through the effects of wind, rain and snow.

A European consortium has agreed to entomb the site in a metal vault. Yet it is not clear exactly where the financing will come from.

When the accident occurred at the Chernobyl's reactor No. 4 on April 26, 1986, the Ukraine was politically still part of the Soviet Union. Now it is an independent state.

The metallic vault project is expected to cost around €2 billion or $2.6 billion. The new metal shield will resemble an airplane hangar, 150 meters or 490 feet in length. It is meant to be constructed away from the reactor unit then slid over it using rails to enclose it for about 100 years. The covering should make it possible for workers to dismantle the reactor within that time.

A French company, Vinci, described the project in 2007. A consortium of French and German nuclear-engineering firms collectively called Novarka won a contract to build the steel vault.

When finished by 2015, the vault is expected to be the largest movable structure in the world.

Financing the vault has been a joint project of the EU and G8 governments. Russia belongs to the G8 group, but it has promised only 1 percent of the final cost. Half of the funding comes from European governments or from the European Commission in Brussels.

CONCLUSIONS

In terms of immediate deaths the Chernobyl qualifies as a small disaster: 32 firemen heroically died on the line of duty in the accident and in efforts to put out the fire, and 38 more people died of acute radiation sickness in the following months. Airplane crashes and mines cave-ins cause casualties in the hundreds.

Figure 17. Chernobyl plant view as of 2010. Source: AP.

Figure 18. Memorial to the first responders fire fighters heroic effort in containing the Chernobyl accident.

Regarding the long term effects of radiation exposure, the largest estimates of those affected are in the low thousands which would make Chernobyl a disaster comparable to the Bhopal Union Carbide chemical plant accident in India. On the other hand, these large estimates are small compared with the casualties in each of several recent large earthquakes in countries using stone, adobe or sod houses, e. g. 30,000-50,000 victims in the Bam earthquake in Iran in 2003. The large estimates depend on the linear extrapolation hypothesis which is used for regulatory purposes because it is so conservative.

The Russian government pays the Chernobyl survivors in the Ukraine a compensation of about €50 each per month.

The most disturbing aspect of the Chernobyl accident has to do with the side effects of the use of complex systems by uninformed individuals. This is an information technology problem.

The Russian scientist Legasov is quoted to have described the violations of the safety rules as: “It was like airplane pilots experimenting with the engines in flight.”

The test was conducted by an electrical engineer who obviously did not know the physics of the reactor that he was responsible for, so that one can extend the analogy to:

“It was like a passenger airplane pilot experimenting with the engine of a fighter jet in flight.”