The July Lectures in Physics - 1988

Lecture 1

CHERNOBYL: WHAT ACTUALLY HAPPENED

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Very early in the morning of 26th April, 1986, in fact just 1 hour 23 minutes and 44 seconds after midnight, the core of number 4 reactor at the Chernobyl power station exploded. Why did this happen? How did it happen? What are the results of its having happened?

Ironically, it happened while tests were being carried out on improved safety systems. These were emergency systems designed to cope with failure of the normal electric power supply to the operating systems of the reactor. So let us first see, in greatly simplified form, what the power supply arrangements for this type of reactor are. These are illustrated schematically in figure 1. The electrical systems of the reactor can be divided broadly into two categories. There are the essential systems which operate all the safety features of the reactor, and there are the non-essential systems which are indeed essential for the proper operation of the reactor and its associated plant but are not related to safety.

![Diagram](image)

**FIG. 1. SCHEMATIC DIAGRAM OF ELECTRICAL SYSTEMS**
Under normal operating conditions, the electric power for most of the essential and non-essential systems is provided by two steam turbine generators (turbogenerators) both of which supply both essential and non-essential systems. In the event of one or both of these turbogenerators being shut down for maintenance, or simply failing owing to some malfunction, the circuits normally fed by the failed turbogenerator are automatically switched to the 750 kV local grid. Should this grid supply fail concurrently with the turbogenerators then an independent 350 kV grid takes over, and in the event that both turbogenerators and both grids are all out at the one time three diesel generators start up and are connected to the electrical system within 15 seconds, although it may be as long as 40 or 50 seconds before some systems are brought back on line. One of the means used to bridge the time gap involved in the changeover to the diesel generators is to make use of the electric power generated by the turbogenerators as they run down, converting the kinetic energy of their rotors into electrical energy. Modifications had been made to improve the efficiency of this conversion and it was planned to test the effectiveness of these modifications while number 4 reactor was being shut down for routine maintenance on 25th April 1986. Similar tests had been carried out on previous occasions and the established procedure was straightforward:

1. The thermal power output of the reactor is slowly reduced to 50% of maximum, maximum being the normal operating power of 3.2 GW(th). This takes 12 hours.

2. One turbogenerator is switched off.

3. The power is then reduced to between 20% and 30% of maximum, and the second turbogenerator is switched off. This automatically trips the reactor, so the test is carried out under safe conditions.

4. To provide an appropriate load for the second turbogenerator as it runs down, a non-standard configuration of cooling water pumps is used.

This test procedure was varied, without the permission of the safety authorities, for the 25th April 1986 exercise because the staff wanted to carry out a number of tests, and therefore did not want the reactor to be tripped when the second turbogenerator was shut off. The variation involved holding the reactor at between 20% and 30% of maximum power, which in turn entailed vetoing the turbogenerator/reactor trip. This was a violation of normal safety regulations and was the act which ultimately led to the destruction of the reactor.

To understand the problems which arose during the 25th April test and how they led to the eventual explosion, it is necessary to know some details of the design and operating principles of the type of reactor installed at Chernobyl. The reactor type, known as RBMK (I do not know what the letters stand for), is water cooled and graphite moderated. It uses enriched fuel, as do all light water cooled reactors. The RBMK fuel is uranium dioxide enriched to 2% in uranium-235. The main features of the reactor are illustrated schematically in figure 2.
FIG. 2. SCHEMATIC DIAGRAM OF RBMK REACTOR

The RBMK reactor is a thermal reactor, i.e., one in which the fission reaction,

$$235\text{U} + n \rightarrow 236\text{U}^* \rightarrow ^{140}\text{X} + ^{96}\text{Y},$$

is initiated by thermal neutrons, neutrons with energies corresponding to the temperature of the surroundings. Fast neutrons subsequently emitted by one of the fission fragments, X or Y, are thermalised (moderated) as a result of elastic collisions with carbon nuclei in the graphite core, before re-entering the fuel rods and initiating further fission. Water at 270°C and at a pressure of 8.4 megapascals (~1220 p.s.i.) is pumped up through the pressure tubes which contain the fuel rods. As the water flows past the fuel rods its temperature rises to 284.5°C and 14.5% of it is converted to steam, which is separated from the water in the steam separator drum and used to drive steam turbines which in turn drive electric generators. The thermal power output of the reactor is governed by the flux of thermal neutrons which is controlled automatically by a system of neutron absorbing control rods which move further into the core if the temperature rises and further out if the temperature falls.

Water acts also as a neutron absorber, by way of the reaction

$$^1\text{H} + n \rightarrow ^2\text{H} + \gamma;$$

a neutron combines with a proton (hydrogen nucleus) to form a deuteron (heavy hydrogen nucleus). This can have serious implications because water
is converted to steam as it rises past the fuel rods, and volume for volume the steam contains fewer water molecules, and therefore fewer protons, than does liquid water. It therefore follows that if, for any reason, the temperature in the core should rise, more water will be converted to steam, fewer neutrons will be absorbed leaving more neutrons to initiate fission, a further rise in temperature will ensue, and a vicious circle is established. In other words, the potential exists for a thermal runaway to develop. The reason it does not develop under normal operating conditions is that uranium-238, which constitutes 98% of the uranium in the fuel, is also a neutron absorber, by way of the reaction

\[ ^{238}\text{U} + \text{n} \rightarrow ^{239}\text{U} + \gamma, \]

and the probability of this reaction occurring increases with increasing temperature. Furthermore, under normal operating conditions, the increase in neutron absorption by uranium-238 exceeds the decrease in absorption due to the conversion of water to steam, so the reactor is self regulating in this regard. It is said to have a negative power coefficient. However, when the reactor is running below 20% of normal operating power, it is possible for a situation to develop in which the reverse is true. The reactor is then said to have a positive power coefficient and the potential for a thermal runaway indeed exists. This situation can develop because, below 20% of normal operating power, small variations in such things as control rod positions and cooling water flow rate have large effects on the steam volume and temperature, and hence on the neutron flux and power output. The changes occur so rapidly that the regulating systems are unable to keep up with them. Hence, during start-up, and to a lesser extent during shut-down, the operators need a great deal of skill and alertness to nurse the reactor through this unstable regime and ensure that at no time does a positive power coefficient develop. Continued operation of the reactor below 20% of normal operating power is totally forbidden.

Let us now return to the account of what happened on 25th and 26th April, 1986. The power reduction commenced at 1 a.m. on 25th April and over the next 12 hours the power was gradually reduced to 50%. At this stage, one turbogenerator was shut down and all power requirements were switched to the remaining turbogenerator. Power was held at 50% for a further 9 hours during which time the control room staff made final preparations for the test. At 11.10 p.m. power reduction was resumed, and 28 minutes after midnight the operator switched from local to global automatic regulation of the reactor. This is normal procedure when the power is at a low level. However at this stage there was an operator error. This error was not in itself what caused the accident, but it set in train the whole sequence of events which ultimately led to the explosion. It had been planned to hold power at between 20% and 30%, i.e., just above the minimum safe level, for the duration of the test. This required a "hold power" instruction to be entered into the computer which controlled the automatic response systems. This instruction was not entered and, as a result of this and the changed response with the changeover to global regulation, the power fell rapidly to less than 1%. In an attempt to restore power, the operator removed some of the control rods by manual control and at 1 a.m. managed to stabilise the power at about 7%, well below the minimum permissible 20% level. Never-the-less the operator decided to continue with the test.

At 1.03 a.m. and 1.07 a.m. two additional water pumps were switched into the system to provide the load configuration required for the test. This caused serious instabilities in the water and steam levels. Under normal conditions instabilities such as these would, at some level, have triggered an
automatic shut-down, but at 1.19 a.m. the operator blocked this signal so as to keep the reactor operating for the test. The automatic control systems were no longer able to cope and the operator was struggling to stabilise the reactor with manually controlled systems. This led to greatly increased water flow and massive withdrawal of control rods in response to the consequent sudden drop in neutron flux. At 1.22\(\frac{1}{2}\) a.m. the operator obtained a computer printout giving the power distribution throughout the core and the location of all control rods. These were grossly outside the permissible limits and safety regulations demanded immediate shut-down of the reactor. The decision was taken to continue the test.

Four seconds after 1.23 a.m. the "two turbogenerators trip signal" was blocked, so that the reactor would not be shut down automatically the moment the test began. At this stage the only automatic shut-down system which had not been immobilised was one which responded to a total power output of 110% of normal operating power and the reactor was running under non-standard and very unstable conditions at only 7% of normal power, i.e., in a regime well removed from that at which the safety trip would operate. The steam to the second turbogenerator was then shut off. This introduced further instabilities which were too rapid for the automatic control system. The control rods were driving in and out as they tried to respond to the changing neutron flux and at 1.23\(\frac{1}{2}\) a.m. they lost control. One second later the power coefficient became positive and at 1.23.40 a.m., the operator threw the manual trip, which started driving the control rods into the core. They were at this stage mostly fully withdrawn and from this position the time required for them to become fully inserted is about 18 seconds. Under free fall they would take approximately 1 second but that option is available only if manually triggered by the operator. With the power coefficient positive the reactor became prompt critical, and it is estimated that by 1.23.44 a.m., i.e., just 4 seconds later, the power had risen to about 100 times normal power, giving rise to an explosion within the core.

It is not easy to give an accurate assessment of the damage caused by the explosion but it appears that about a third of the fuel was fragmented at temperatures up to perhaps 5000 K. The remaining fuel was ejected partly into neighbouring rooms but mainly downwards, and about a quarter of the graphite blocks making up the core were ejected into various parts of the reactor building and its immediate surroundings. The subsequent graphite fire burned about a tenth of the core and carried high levels of radioactivity into the atmosphere.

From 26th April until 10th May large quantities of materials chosen specifically to trap the radioactive species present, either by absorption or by chemical reaction, and to smother the graphite fire, were dropped from the air. The effect was dramatic, with the activity release being reduced to a third of its peak value on the first day and it was halved again over the next 4 or 5 days. However, over the following 4 or 5 days it steadily rose again until it reached two thirds of its initial value. It then dropped abruptly to almost zero following the injection of large volumes of nitrogen beneath the core. This suggests that the graphite fire had not been extinguished by the previous action and had continued to play an important role over the ten days following the explosion.

Two staff members died at the reactor. Of the remaining staff who were on site at the time of the accident, or who were brought in to deal with the emergency, mostly firemen, about 300 later received hospital treatment,
203 for acute radiation syndrome, of whom 29 died.

The general population group at greatest immediate risk from the released radioactivity were the 45,000 inhabitants of Pripyat which is about 5 km north from the power station. On the morning of 26th April they were instructed to remain inside with doors and windows closed, and potassium iodide tablets were delivered to them by hand on a house to house basis. The reason for this was that the most serious immediate radiation risk was from the radioactive iodine isotope iodine-131. Ingested iodine tends to concentrate in the thyroid gland and if one consumes enough iodine the thyroid becomes saturated and any additional iodine is rejected and passes into the urine. Saturate the thyroid with natural stable iodine and the body will not take up the iodine-131 when it arrives. Throughout the day the integrated radiation dose rose towards what is known as the intervention level for evacuation, which in the U.S.S.R. is 250 times normal background for one year. On 27th April, in a time of less than 3 hours, the entire 45,000 population was evacuated by bus, and over the following few days all the remaining 90,000 people living within 30 km of the power station were evacuated. The average radiation dose received by the 135,000 people who were evacuated was about 120 times normal background for a year. From the known relationship between radiation dose and cancer risk one can conclude that about 200 additional cases of fatal cancer will eventually occur among those 135,000 people than would have occurred had the accident not happened. The number to be expected had the accident not happened is about 27,000.

Statements concerning the levels of radioactivity deposited in other parts of the U.S.S.R. and in Europe are less informative. This is because the spread of the radioactive cloud and the extent to which its contents were deposited on the ground depended very much on the vagaries of the weather. Hence there were pockets of comparatively high dose and regions of low dose. We can therefore speak usefully only of average doses over reasonably large regions. For example, the average for the whole of Britain corresponded to an increase of about 0.1% over the normal background level. In heavy rainfall areas the dose is significantly higher, perhaps by a factor of 10, but more importantly it is now largely in the form of caesium-137 which has a 30 year half-life and is taken up by grazing animals and behaves similarly to potassium in the food chain. It is for this reason that the sale of sheep from certain districts was forbidden until the caesium-137 level in the meat should no longer constitute a significant hazard. Similar precautions were taken in continental European countries, first with regard to iodine-131 (half-life = 8 days) and later with respect to caesium-137. The highest estimated average doses are, not surprisingly, for Poland and Roumania where the figure represents an increase of about 50% over normal background for the first year and diminishing.

To put these figures in perspective it is instructive to note that this is less than the variations in natural background level from place to place thoughout the world. It is also instructive to make some estimates based on data published by the International Commission for Radiation Protection. Background radiation may be held responsible for about 10 ultimate cancer deaths in a population of 1 million, and if we work with the rough estimate of one fifth of the population eventually dying from cancer, this means that 1 in 20,000 cancer deaths may be attributed to background radiation. It therefore follows that a realistic figure for the long term effect of the Chernobyl accident on the European population will be to increase the number of cancer deaths by about 1 in 50,000, which is less than 0.5% of the increase in the rate expected for the 135,000 people evacuated from the
neighbourhood of Chernobyl. In short, the effects of radioactive fall-out from Chernobyl on the population of Europe will be too small ever to show up in the statistics.

In making these statements I am in no way attempting to make light of the events which occurred at Chernobyl. They led to by far the most serious accident in the history of the nuclear power industry, an accident which killed 31 people and made small but finite increases in the cancer risk for many millions of people. Also many square kilometres of land around the reactor site have probably been made uninhabitable for many years to come. The accident should never have occurred, but given the sequence of events leading up to it, it is clear that something similar was bound to occur some time. Because of the lessons learned from it, it will not be repeated. The Russians have now followed the western practice of installing automatic shut-down systems which cannot be bypassed by the operator, and have adopted free fall safety rods.

While Chenobyl was, by any standard, a major industrial accident, I should never-the-less like to end on a positive note. As a result of lessons learned the hard way at Chernobyl, there has been a major upgrading of the safety systems on reactors throughout the U.S.S.R. Accordingly, the generation of electric power, when viewed globally, has been made safer than it was before 26th April 1986.

Further reading:
Chernobyl: A technical appraisal
British Nuclear Energy Society
Robert Harnoll; Bodmin, Cornwall 1985
ISBN: 0 7277 0394 3

Nuclear energy in general:
How safe is nuclear energy?
Allan Cottrell
Heinemann; London 1982
ISBN: 0 435 54175 7

Before it's too late
Bernard L. Cohen
Plenum; New York 1983
ISBN: 0 306 41425 2

Power production in general:
Power Production: What are the risks?
J.H. Fremlin
Adam Hilger; Bristol 1985
ISBN: 0 85274 479 X