AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT

LUCAS HEIGHTS RESEARCH LABORATORIES

THE CHERNOBYL NUCLEAR ACCIDENT

AND ITS CONSEQUENCES

Prepared by

an AAEC Task Group

SEPTEMBER 1986

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CONTENTS

PREFACE

An AAEC Task Group was set up shortly after the accident at the Chernobyl Nuclear Power Plant to monitor and evaluate initial reports and to assess the implications for Australia. The Task Group issued a preliminary report on 9 May 1986.

On 25-29 August 1986, the USSR released details of the accident and its consequences and further information has become available from other sources notably the Nuclear Energy Agency of OECD and the World Health Organisation.

The Task Group now presents a revised report summarising this information and commenting on the consequences from the Australian viewpoint.

SUMMARY

At 0123 hours on 26 April 1986, a major accident occurred in Unit 4 of the Chernobyl Nuclear Power Station, located about 130 km north of Kiev in the Ukraine (USSR).

In the accident two major explosions occurred in the reactor core, the first being associated with the rapid expansion of steam as the water coolant vaporised and the second with the explosion of hydrogen generated by reaction between water and zirconium in the core. The accident was caused by a sudden and uncontrolled increase in the power being generated in the reactor. The reactor control system was unable to arrest this power surge.

The accident arose from an experiment being performed on one of the turbo-generators connected to Unit 4. It was brought about by the disregard by the operators of safe operating procedures, and their actions to over-ride the engineered safety systems on the reactor to ensure completion of the experiment. The USSR reported at least six major violations of safety procedures by the operators which contributed to this accident.

The accident caused 31 deaths and 203 people in the USSR were diagnosed to have acute radiation sickness. Some 135,000 people were evacuated from the zone within 30 km of the station and part of this zone will remain uninhabitable on a normal basis for some time.

A plume containing radioactive material from the accident spread over European USSR and most of Eastern and Western Europe. The extent of contamination from this plume varied greatly according

to the local weather conditions, but most countries were forced to introduce some measures to protect their populations from the possible effects of radiation and contamination.

Estimates of the potential long term effects of radiation and contamination on these populations can only be tentative at this stage. However the available data suggest that exposure to radiation from the accident might cause an additional 10,000 deaths from cancer over the next 50 years or so. A similar number of cancer deaths could arise from long term ingestion of radionuclides through the food chain. These estimates may be compared with the expectation that some 100 million people in this population will die from all forms of cancer over the same period.

The accident has prompted a review of nuclear programs in some Western World countries. In the longer term however, major nuclear power programs are unlikely to be affected. The USSR in particular has re-affirmed its commitment to the continued development of nuclear power.

The accident is still being analysed but there are no obvious implications for the design or operation of nuclear reactors in the West, except to ensure that the high standards of operator competence and training, and safety surveillance,are maintained.

The accident has highlighted the need for improved international cooperation in nuclear safety issues and two international nuclear safety conventions have already been drafted to provide an improved legal framework for handling such emergencies.

The accident has had minimal impact on Australia, mainly because of our location in the Southern Hemisphere. Actions taken in Australia in response to the accident have been timely and effective. Study of the report of the accident has not shown up any deficiency in the operation of the reactors at Lucas Heights.

1. INTRODUCTION

The accident at the Number 4 Unit of the nuclear power plant at Chernobyl in the USSR on 26 April 1986 was the worst recorded in the nuclear industry. Nevertheless, USSR authorities have firmly restated their commitment to nuclear power as a major energy source on the basis that it is the most appropriate means to meet the rapidly growing demand for energy for industrial and social development in that country and because they believe that the accident has not invalidated their nuclear power program.

In the Western World, the immediate response to the accident has been adverse, reflecting concern at the apparent wide spread of contamination, and the initial confusion over the causes of the accident and its implications. Whether this will continue is uncertain, although many would argue that, like the USSR, major Western countries have no option but to include nuclear power in their plans for future development.

Central to this attitude and future response is an understanding of the causes of the accident and its consequences in terms of the radiation and contamination released and the impact on affected populations.

2. BRIEF DESCRIPTION OF THE POWER PLANT

The Chernobyl Nuclear Power Plant is 130 km north of Kiev in an area known as the Byelorussian-Ukrainian Woodlands between the Pripyat and Dnieper Rivers (Figure 1). The region is sparsely populated except for the towns of Pripyat (49,000) and Chernobyl (12,500) which are respectively 5 km and 15 km from the plant site.

The site is being developed to contain six units, four of which

(Units 1-4) are complete and two (Units 5 and 6) are under construction. All units are of 1000 megawatts electrical capacity. This electrical output is achieved from a thermal capacity of 3200 megawatts (MW(Th)). Units 1 and 2 were built between 1970 and 1977; Units 3 and 4 were completed in 1981 and 1983 respectively and Units 5 and 6 were scheduled for operation in 1986 and 1988.

Although the units are basically similar, the layout of the buildings housing Units 3 and 4 was changed from that of Units 1 and 2 to improve economics and operating convenience. Units 3 and 4 share certain plant facilities and buildings, and presumably some operating and maintenance staff.

The reactors are of a type designated RBMK and their design is unique to the USSR. They are light water-cooled, graphite-moderated, pressure tube reactors fuelled with slightly enriched uranium oxide. The development of the RBMK reactor and its role in the nuclear power program of the USSR are discussed in Appendix 1. Table 1 gives technical details of the units.

The layout of Units 3 and 4 at Chernobyl and general features of the RBMK reactor and a fuel channel are shown in Figures 2 and 3.

The core is seven metres high and about twelve metres in diameter, and is blanketed by a helium/nitrogen gas mixture to prevent oxidation of the graphite moderator and to control its temperature. Each vertical zirconium alloy pressure tube contains two fuel element assemblies placed end to end. Each assembly contains 18 fuel rods and each rod is a zirconium alloy tube containing pellets of uranium dioxide. The uranium is enriched to 2.0% uranium-235. The core contains 1700 tonnes of graphite and 215 tonnes of uranium dioxide (190 tonnes U). A further 800 tonnes of graphite is in the reflector around the core.

Cooling water flows upward through the pressure tubes and over the fuel assemblies extracting the heat of fission and converting

part of the water to steam. The steam-water mix passes from the top of the pressure tubes to the steam separators from which steam is drawn off to drive the turbines and generate electricity. The water from the separators, together with condensed steam from the turbines is returned to the core through main circulation pumps.

There are two identical cooling loops in the core; each loop has four pumps, of which three are normally operational and one is on stand-by.

Spent fuel assemblies are replaced while the reactor is operating by means of a charge-discharge machine above the top face of the reactor (Figure 2).

The major components of the primary cooling circuit are enclosed in compartments designed to contain radioactive emissions in the event of an accident involving loss of coolant. The compartments vent into a large water pond beneath the reactor which condenses any sudden steam bursts, hence controlling the excess pressure. The pressure containment structure does not appear to extend over the top of the reactor.

In the event of rupture of the main coolant circuit, and loss of cooling in the core, the reactor is automatically shut down and an emergency cooling system actuated. This comprises a fast acting gas-driven water injection system, followed by emergency pumping via the feedwater circuit and the pressure suppression pond.

The reactor is controlled by inserting into or raising out of the core, some of the 211 solid neutron-absorber rods; these rods move in specially designated channels in the graphite and have their own coolant supply. The reactor is designed to shut down automatically if certain operating anomalies occur. The extent of shutdown depends on the type of anomaly, but those relevant to the accident include rapid automatic shutdown if:

- Thermal power output exceeds the nominated level by more than 10%.

- Neutron flux increases with a doubling time of less than 10 seconds.

- The level of water in the steam separators or the rate of feedwater flow varies outside preset limits.

- The pressure in the steam separators exceeds preset limits.

- There is evidence of steam leakage into any of the compartments around the core, or into the reactor cavity.

- The cooling water flow to the control rods is disturbed.

- Both turbo-generators trip off-line (or one generator if only one is working).

- Three of the four operating circulation pumps on either circuit fail.

- There is a loss of voltage on the plant auxiliary power system.

3. THE ACCIDENT

On 25 April, Unit 4 at the Chernobyl Nuclear Power Plant was completing its second operating period since commissioning in December 1983, and was being shut down for scheduled maintenance. Before shutdown, it was intended to carry out certain experiments on one of the two turbo-generators connected to Unit 4 to determine whether the mechanical energy of the turbine would be sufficient to maintain the plant electrical emergency supply for a period if the steam supply to that turbine were to fail suddenly. This assumption is included in the design of the emergency core cooling system, but the period over which the

generator could maintain supply can only be determined by experiment. If carried out in an appropriate manner the experiment would have been perfectly safe. It is important to note however, that the experiment did not require the reactor to be operating at any given power level, provided that the generator was at normal operating speed. The choice of a thermal power level of 700-1000 MW* for the experiment was a compromise between the requirements to dump steam at higher powers and difficulty of maintaining normal operating conditions at lower powers.

Similar experiments had already been carried out successfully at Chernobyl and other plants. At Chernobyl it had been found that the voltage available at the generator fell off rapidly in the event of a disruption to steam supply; in the experiment, the operators planned to test a new magnetic field regulator which was expected to solve this problem.

The experiment was badly planned and full consideration was not given to all the implications. It was conceived as a test of the electrical plant which would have no effect on reactor behaviour. There was therefore little communication with the plant operators, and formal safety approvals were either by-passed or given perfunctory attention.

Up to 0100 hours on 25 April, the reactor was operating normally at full rated output of 3200 MW. The operators then commenced to reduce power to the level of 700-1000 MW required for the experiment. At 1305 hours on 25 April, No.7 turbo-generator was switched off with the reactor power at 1600MW and the electrical power supply for four main circulators and two feedwater pumps transferred to the remaining operating turbo-generator (No.8).

At 1400 hours, the unit's emergency core cooling system was disconnected on the argument that if it operated during the turbo-generator run-down it would place an extra load on the

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* All powers are thermal power unless otherwise stated.

generator and invalidate the experiment. At about this time, the station controller asked that the unit be kept at a power level of 1600 MW because electricity demand was higher than expected. The unit therefore continued to operate at a power level of 1600 MW with the emergency cooling system shut off, in violation of operating regulations.

At 2310 hours on 25 April, electrical demand on the station had decreased and reduction of power to the target of 700-1000 MW was resumed. Standard operational procedures required that the local automatic control system (which controls radial instabilities in neutron power levels in the core) should be changed to manual operation at low power. The value of this switchover power is not known but it would appear that the change was made at too high a power; the operators could not control the instabilities in the core and the power level continued to decrease, only stabilising at 30 MW. At this low power level the reactor tended to shut itself down due to xenon poisoning. (Xenon, a fission product, is a very strong absorber of neutrons). In attempting to correct for the low reactivity of the core, and to raise power to the desired level, the operators withdrew most control rods from the core, and in doing so entered a forbidden operating mode. This operating mode was only forbidden by written procedures, not by engineered controls.

By 0100 hours on 26 April, the operators had succeeded in stabilising power at 200 MW and it was decided to proceed with the experiment. At 0103 and 0107 hours, the fourth circulation pump on each coolant loop was switched in, so that when the experiment was completed, with four main pumps operating in the run-down mode, four pumps would remain available for cooling of the core to a safe condition.

At the low power level, the increased coolant flow from eight pumps further cooled the core, reducing the rate of steam formation which led to a decrease in the hydraulic resistance of the primary coolant circuit and thus a further increase in coolant flow to a value where pump cavitation and vibration probably occurred.

The operators attempted to control the situation by increasing the feedwater flow to the steam separators, but both steam pressure and water level in the separators dropped below control limits. To avoid shutting the reactor down under these conditions, the operators blocked the emergency protection systems involved.

As the cooler water from the feedwater entered the core, the steam quality further decreased and reactivity continued to decrease slowly, requiring further withdrawal of the manual control rods to maintain power. At about this time, the operators partially stabilised the core coolant conditions by reducing feedwater flow and the automatic control rods dropped partly into the core to compensate. At this stage the experiment commenced.

At 0123.04 hours, the emergency regulating valves on No.8 turbo-generator were shut and turbine run-down commenced. Since No.7 turbo-generator was already shut down, the effect of shutting the valves on No.8 turbo-generator should have been to shut the reactor down immediately. However the operators had also blocked this protection system on the argument that, if the reactor were fully shut down, xenon poisoning would prevent the return to power to enable the experiment to be repeated if necessary.

With the reduced steam flow from the separators, the steam pressure began to rise. At the same time coolant flow through the core decreased because four of the eight pumps in service were running down with the drop of turbo-generator voltage. The reactor entered a regime whereby a small increase in power caused a marked increase in steam volume in the core.

A characteristic of RBMK reactors is that an increase in steam volume causes an increase in reactivity and hence power in the core (and vice versa) - the so-called "positive void coefficient" effect. This is normally controlled by the movement of control rods and, assuming that an adequate reactivity margin is

maintained in the rods, would present no difficulty. In this case all the (slow acting) manual control rods had been withdrawn from the core and the automatic rods were partially or fully inserted in the core; only the 24 emergency rods were available to control the reactivity increase.

As a consequence of the positive void coefficient effect, power began to rise and at 0123.40 hours, the operators activated the emergency shutdown system. This should have immediately reduced the power but for reasons attributed to "violations committed by the staff" (presumably the blocking of controls), the emergency shutdown system was ineffective, the emergency control rods did not go fully into the core and power continued to rise. Within 3 seconds, it rose above 530 MW before the action of control rods caused the power to fall. However, a short time after the power had returned to several hundred megawatts, a further power transient occurred which peaked at a very high level, reported to be about one hundred times nominal power of 3200 MW.

At about 0124 hours an explosion occurred in the core which is attributed to the power surge and over-pressurising of the steam circuit. About 3 seconds later, a second explosion occurred which may have been caused by hydrogen, generated by reaction between zirconium and steam, reacting with air.

Appendix 2 sets out comment on the progress of the accident.

4. CAUSES OF THE ACCIDENT

The USSR statement lists at least seven breaches of safe operating procedures relating to the accident:

- The planning of the experiment was inadequate, poorly coordinated with reactor operating staff, and safety approvals were either ignored or by-passed.
  The experiment was conceived as an electrical experiment which would not interfere with reactor operations. In the sense that the turbine run-down was independent of reactor power (but not the electrical load of the four main

circulators connected to the turbine) this was correct and such an experiment would normally be approved if properly planned and coordinated.

- The emergency core cooling system was switched off by the operators at 1600 MW and not reactivated.
  The system was made inoperable to avoid it being activated by spurious signals during the experiment and to avoid the additional load of the emergency core cooling pumps on the turbo-generator. However non-operation of the system did not contribute to the accident; nor would its operation have significantly reduced the consequences of the accident.

- The local automatic power control system was inactivated by the operators, thereby introducing radial neutron flux instabilities which were difficult to control.
  The automatic control system apparently operates in a different mode at high and low power levels and was not correctly programmed. The resulting instabilities in the core drove the power level down to 30 MW where poisoning by fission products became significant, requiring the main reactor control system to be operated in a forbidden mode to maintain (and increase) power.

- The operational reactivity margin in the main reactor control system was reduced below an adequate level.
  To overcome fission product poisoning of the core, most rods in the main control system were withdrawn, leaving the reactor in a dangerously unstable operating mode. During the power excursion, the reactivity control of these rods was minimal. The minimum reactivity control to be maintained was specified in written procedures (and hence under control of the operator), rather than being guaranteed by engineered safety measures.

around the site; a further 1.5% was carried in the plume up to 20 km from the site and 1.0-1.5% was carried beyond this distance.

Following destruction of the reactor and entry of air, the graphite in the core (which normally operates at 600-700^{o} C) ignited and about 250 tonnes of graphite is estimated to have burned. The fire maintained the high temperatures in the core and carried fission products, released from the fuel, into the plume which rose above 1500 metres before being dispersed over the USSR and Europe. About 100 million curies of fission products were released, about half of which was in the form of noble gases, notably xenon and krypton.

The material ejected from the core also caused a number of fires on the roofs of the turbine hall and adjacent buildings. The immediate danger was that these fires might spread along the top of the turbine hall to Unit 3, and to hydrogen, oil and diesel fuel storage areas. Fire-fighting units from the site, Pripyat and Chernobyl attended these fires which were all extinguished by 0500 hours on 26 April. In fighting these fires, firemen were severely irradiated and a number subsequently died.

Later actions were mainly concerned with limiting the escape of radioactive materials from the core which was aggravated by the high temperatures caused by continued burning of the graphite. Immediate attempts were made to cool the core with water from the feedwater circuit, but these were unsuccessful. On 27 April, some 40 tonnes of boron carbide was dumped onto the core from helicopters to ensure that the fission reaction was completely extinguished. Between then and 6 May, about 800 tonnes of dolomite, 2400 tonnes of lead shot and 1800 tonnes of a clay-sand mixture was also dumped onto the core: dolomite produces carbon dioxide when heated, thereby helping to extinguish fires; lead helped to remove heat from hot spots in the core and the clay-sand mixture tended to smother the fire and trap some fission product aerosols and particles which would otherwise have escaped.

The estimated daily discharge rates of radioactivity are shown in Figure 4 and these correlate with the temperatures in the core and the remedial actions taken. After the first release on 26 April, the releases decreased steadily as the core cooled. There followed a period to 2 May during which releases were relatively low. By 2 May however, the material which had been dumped on the core was acting as a thermal blanket, the temperatures rose, and the escape of fission products increased sharply. Only by flooding the core with liquid nitrogen on 6 May was it cooled, and emissions effectively stopped.

The plume containing the fission products initially travelled north-west over Poland, to Scandinavia. It then moved to the east, and later to the south-west and west, as the wind direction changed. Analyses have shown that in the initial burst and for a few days afterwards, most of the species of fission products present in the core, and also traces of plutonium and neptunium, were present in the plume. After 6 May, when core temperatures reduced, the non-volatile fission products were retained in the core and the plume was therefore enriched in the volatile fission product species notably iodine, tellurium and caesium.

Casualties

When the accident occurred, 176 operations staff and 268 other persons were on the site. Persons at the accident site were immediately affected by heat, ionising radiation and radioactive contamination. Medical staff assisted the first 29 victims who left by themselves within the first thirty minutes or so. Additional first aid teams provided assistance during the next four hours and by 0600 hours on 26 April, 108 persons had been hospitalised.

Within twelve hours, a team of specialists (physicists, radiology therapists and haematologists) had arrived and within thirty six hours, 350 persons had been examined. Using USSR criteria, it was determined that 203 had acute radiation sickness in varying degrees; their radiation doses were estimated to be in the range 1 to 16 grays (100 to 1600 rads). They were sent to hospitals

near Kiev and to a specialised infirmary in Moscow. A special aspect of their radiation exposure was the prevalence of beta radiation effects causing major skin damage. In many cases, radiation injuries were complicated by thermal burns.

One person died about four and a half hours after the accident as a result of severe thermal burns. One person was not found; it is presumed that he was working in the area where major physical damage occurred and where high levels of radioactivity were present. Another 29 persons died later from radiation, thermal burns or a combination of these injuries. Most deaths were of fire fighting personnel.

The criteria for classifying patients in the first few days were based on clinical observations and various medical and bio-chemical tests. Radiological measurements detected the presence of radioiodine in patients'thyroids and other radionuclides elsewhere in their bodies consistent with acute exposure. Composition of the latter was found to vary in individual cases. To counteract the effect of radioiodine, stable iodine prophylaxis, which had been implemented earlier, was continued to protect the thyroids of victims. Specimens of organs and tissues of patients who had died were examined to determine their radionuclide content.

Bone marrow transplants were carried out for a small number of patients (about 20 in the first four days). USSR experts concluded that this treatment is not necessarily a decisive factor for heavily irradiated persons and that it is only successful for patients within a narrow range of radiation exposure.

6. COUNTERMEASURES

The following countermeasures were implemented to protect the population in the region after the accident.

Sheltering

The population of Pripyat was immediately recommended to spend minimal time outdoors and to keep windows closed in dwellings. On 26 April, all open air activities were banned at creches, kindergartens and schools. Most of the population of Pripyat remained indoors on 26 and 27 April, thus reducing their exposure to gamma radiation.

Evacuation

About 135,000 persons were evacuated from areas within the 30 km zone around the accident site. The decision to evacuate was made after considering actual and possible future radiation doses to the population.

For 24 hours or so from the start of the accident, the wind direction caused emitted radioactive materials to by-pass the town of Pripyat. A change in the near-ground wind direction then caused the plume to cover the town area and contaminate it. As the radiation conditions worsened, evacuation began at 1400 hours on 27 April. This was completed within about three hours using more than 1000 buses. About 45,000 persons were evacuated from Pripyat and about 12,000 from the town of Chernobyl. Evacuees were escorted by a large number of medical personnel who subsequently participated in their medical examinations.

Stable Iodine Prophylaxis

Stable iodine was administered to children at Pripyat on 26 April; at 2000 hours on that day, stable iodine was provided to the population by door-to-door distributors.

Food Restrictions

Immediately after the accident, restrictions governing permissible levels of iodine-131 in milk, milk products and leafy green vegetables were introduced in the region. Restrictions

were also introduced relating to permissible levels of radioactivity in meat, poultry, eggs and berries.

Some of the population consumed locally-grown products for several days before being evacuated (4-5 May) and in these cases, high radioactive content in thyroids ensued. However, USSR authorities have stated that the thyroid radiation doses they received are lower than those which cause health changes.

Decontamination

Decontamination measures were implemented both at the nuclear power plant site and in surrounding areas.

Equipment and buildings of Units 1, 2 and 3 at the site were contaminated significantly by radioactive materials entering through the ventilation systems which continued to operate for some time after the accident. Unit 3, which was closely linked with Unit 4 where the accident occurred, suffered no damage and was closed down at 0500 hours on 26 April. Units 1 and 2 were shut down at 0113 hours and 0213 hours respectively on 27 April.

Decontamination at Units 1, 2 and 3 involved wet methods (water and decontaminating solutions, steam spraying) and dry methods with quick drying polymerising solutions (latex emulsions) used to form a covering film on surfaces.

In other parts of the site, these methods were used together with:

- removal of debris and contaminated equipment,
- removal of soil to a depth of 5 to 10 cm, and
- filling with clean soil or laying of concrete slabs.

The damaged Unit 4 is being entombed in metal and concrete to give a structure with protecting walls of at least one metre thickness.

Radioactive contamination of the 30 km zone around the accident site is likely to present problems over an extended period because of redistribution of long-lived radioactive contaminants. Some years will elapse before agricultural production can be resumed safely in this area, and some areas near the site will be uninhabitable on a normal basis indefinitely.

7. RADIOLOGICAL CONSEQUENCES

The accident dispersed radioactive material over a large part of European USSR and other parts of Europe, and it was subsequently dispersed around the Northern Hemisphere. The radiological consequences of this are discussed below. Appendix 3 reviews the effects of radiation on persons, and the measurement units used, but the following background is important in understanding the methodology and significance of the data in this Section.

General

The long term adverse consequences of exposure to radiation at doses of more than 0.1 sievert are observed to be an increased risk of leukaemia and many forms of cancer, and, by inference from observations of irradiated animals, an increased risk of genetic disability in the children and descendants of irradiated parents. The latter risk is smaller than the cancer risk.

Because the risk of cancer induction for doses over the range 0.1 to 5 sieverts or so is found in many cases to be proportional to dose it is assumed that the same proportionality holds at lower doses. This assumption leads to the conclusion that the sum of all individual doses in an irradiated population can be used as a measure of total detriment in terms of radiation induced cancers resulting from that irradiation. It should be noted that this assumption of linearity between risk and dose is not supported by some observations, which suggest that risk falls off more rapidly at low doses; nor does it have a very strong theoretical basis. Some experts maintain that its use to determine detriments from

low doses overestimates adverse effects. However, in the absence of convincing evidence on this point, radiation protection conventionally employs the linear hypothesis to evaluate long-term individual and collective risks. Consequently the assessment of the radiological impact of the Chernobyl accident concentrates on assessing doses to individuals most exposed, to determine the risks which they have had placed on them, and the collective impact in terms of the sum of individual doses, or the collective dose.

On the Chernobyl Site

The radiation doses received by operators, site workers and firemen immediately exposed to the accident ranged up to 16 grays. The approximate distribution of radiation doses to those people diagnosed to have acute radiation sickness was:

No.	Dose (grays)	Outcome
22	6-16	19 died over the period 10-50 days*
23	4.2-6.3	7 died over the period to 50 days*
53	2-4	No deaths
27	0.8-2.1	No deaths
78	< 0.8	No deaths
Total 203		

* With the two immediate deaths, these total 28 not 31 deaths as now reported by the USSR. The data above may therefore relate to a situation earlier than late August.

The early deaths of most of the patients with exposures greater than 4 Gy were due to severe skin radiation from deposited fission products and thermoradiation damage from heat.

Within the 30km Evacuation Zone

Approximately 135,000 people were evacuated; 45,000 of them from the town of Pripyat, beginning at 1400 hours on 27 April, and

90,000 from various locations within 30 km of the site over the next seven days.

Evacuation was based on projections of likely whole body doses from airborne and deposited activity. Measurements of external dose rates began in Pripyat within a few hours of the accident, with levels of about 0.3mGy/h being detected, rising to 4 to 15 mGy/h at 36 hours. These levels remained steady or declined only slowly over the next four days.

Before evacuation, the population of Pripyat had been recommended to stay indoors and take stable iodine to minimise uptake of radioiodines. The average whole body, skin and thyroid doses received by these people have been estimated at:

Whole body	0.015-0.05 Gy	(1.5-5.0 rads)
Skin dose	0.1-0.2 Gy	(10-20 rads)
Thyroid dose	0.015-0.25 Gy	(1.5-25 rads)

According to the USSR, the doses from external radiation received by the population of Pripyat are significantly lower than those which might cause any immediate health effects. However, further examination will be required to determine whether any of the population has been selectively exposed to radiation via ingestion or inhalation. The fact that the population was evacuated promptly would tend to confirm that health effects would be negligible.

Beyond Pripyat, but within the 30 km evacuation zone, radiation doses appear to have been higher, probably as a consequence of the variable wind pattern over the first day or so. The estimated collective doses at varying distances from the accident site were:

Collective Dose Estimates

Area around the Chernobyl plant	Population	Collective dose (thousand person-sieverts)	Mean dose (Sv)
Pripyat	45000	1.5	0.033
3-7 km	7000	3.8	0.54
7-10 km	9000	4.1	0.46
10-15 km	8200	2.9	0.35
15-20 km	11600	0.6	0.05
20-25 km	14900	0.9	0.06
25-30 km	39200	1.8	0.05
	135000	15.6	0.12

Estimates of thyroid doses to children in this population ranged from 0.25 to 1.2 Gy, with whole body doses in the range 0.018-0.17 Gy.

For a collective dose of about 16 thousand person-sieverts as shown above, the inferred deaths from cancer in this population are estimated to be less than 280 (i.e. less than 2 per cent of the 14,000 deaths from cancer expected in this population over the next 70 years).

No estimate has been given by USSR authorities of the collective thyroid doses to this population, although some estimates can be made on the basis of the quoted ratios of whole body to thyroid doses received by the population at Pripyat. These estimates suggest that between 160 and 6400 thyroid cancers will occur in the population, resulting in 8 to 160 deaths. As thyroid cancers are unusual, particularly in the young, it should be possible to detect this increase in frequency of thyroid cancer in the population through epidemiological studies.

Within European USSR

Measurements of external gamma radiation levels were made at

sixteen locations in European USSR and extrapolated to cover the whole of the population of 74.5 million people. Because of differences in lifestyle, rural dwellers are estimated to receive larger doses than town dwellers by a factor of nearly two.

The collective dose for the whole of the European USSR was estimated as 86 thousand person-sieverts in 1986 and 290 thousand person-sieverts over the next 50 years giving mean individual doses of 1.2 and 3.9 millisieverts respectively. If the normal radiation risk factors are applied to these estimates, the inferred increase in cancer mortality rate in this population would be less than 0.05 per cent or about 5000 cases of cancer above the normal expectation of 9.5 million deaths from cancer over the next 70 years in the same population.

No estimates have been given of average or collective thyroid doses received by this population although the increased mortality from ingestion of iodine-131, estimated by the USSR to be about 1 per cent, "hardly increases the mortality indices in the region".

Other pathways for ingestion of contamination in this region are through drinking water and foodstuffs. Widescale monitoring and sorting of milk, vegetables and other food products was introduced in the region by early to mid-May.

The intervention level for iodine in milk was set at 3700Bq/L (10^{-7} curies per litre) and although individual measurements are not available, some milk apparently reached levels of nearly 370,000 Bq/L (10^{-4} Ci/L) and was presumably discarded. Leafy green vegetables were found to be contaminated with fission products (importantly iodine-131 and caesium-137) and restrictions were placed on consumption to limit whole body or individual organ doses to less than 50 millisieverts.

No estimates of the collective dose received by the population through the ingestion of these products is available, except for caesium-137. For this, a preliminary estimate is that the

population might receive a collective dose of 2.1 million person-sieverts corresponding to an inferred increase in mortality rate of less than 0.4 per cent of the natural mortality rate from malignant causes.

Outside the USSR

The first indications outside the USSR of the accident were the detection of airborne fission products and increases in external radiation levels in Sweden and Finland. These were soon followed by the detection of iodine-131 in milk, and of mixed fission products in or on leafy vegetables. Literally hundreds of thousands of measurements followed, as local and state authorities endeavoured to assess the magnitude of the associated radiation risks to their nationals. Table 2 gives some early measurements which indicated the need for countermeasures in some cases to avoid excessive doses to individuals.

The distribution of radioactive contamination in Europe and within each country was extremely uneven. This was due in part to the varying distances from the source of release and the long duration of release which gave rise to different plumes transported in different directions by variable winds.

However, a major contributor to the unevenness of contamination was the presence in Europe of an unusually variable meteorological situation, characterised by frequent and localised heavy rain.

As a consequence, the concentration of radioactivity in air was very variable, differing even by one or two orders of magnitude between localities situated a few tens of kilometres apart. When considering food contamination, an additional variable, besides the differences in population dietary habits, was the fact that in some parts of Europe, cattle were still being fed on stored fodder, while in other parts animals were already grazing outdoors on fresh grass.

The resulting differences of contamination, particularly of radioiodines in milk and other dairy products were very large.

In addition to the variability in the distribution of contamination, a number of countries introduced restrictions on the use and distribution of foodstuffs and the like, aimed at reducing the impact of contamination on their populations.

Table 3 lists emergency actions in various countries following the accident, and Table 4 lists intervention levels used to determine restrictions on consumption of various foods. The actions taken and intervention levels used varied widely. The lack of consistency in the application of bans on consumption and on imports led to widespread confusion, and to economic disruption, which were and remain matters for concern. In part the inconsistencies arose from differing decisions on the likely persistence of the raised levels of radioactivity. This was highlighted by the UK advice on an intervention level for caesium-137 in sheep meat based on the assumption that persistence of the contaminant would be short (the effective biological half-life of caesium-137 in sheep is about 20 days following an acute intake). It was later determined that spring lambs are all slaughtered at roughly the same time and stored frozen for consumption throughout the year, thus turning an acute contamination case into a chronic one and requiring a proportionately lower intervention level.

In these circumstances, the radiological impact of the accident in terms of doses to individuals in the various countries has been extremely variable. In each country the doses to the individuals of the critical groups may well be higher by an order of magnitude than the average individual dose over the whole population. In view of all these elements of variability and the fact that the long-term contamination by long-lived radionuclides and its radiological impact are still being assessed, it is not yet possible to draw a detailed and comprehensive map of the distribution of individual and collective doses resulting from the Chernobyl accident.

However, OECD countries have prepared preliminary assessments of the radiological impact(which fell almost exclusively on OECD countries in Europe), in terms of individual doses received by those most at risk, to illustrate the maximum degree of individual risk likely to have been experienced in their countries. The data are given in Table 5.

The parameters of interest are the collective doses and the doses to the critical groups. The former can be used as a measure of inferred effect, in terms of expected radiation-induced cancers, and the latter as a measure of risks to individuals, again in terms of radiation-induced cancer.

The current estimate of total collective effective dose equivalent in Western Europe is 65 thousand person-sieverts (Table 5). The established cancer mortality risk relationship suggests that this dose will result in 800 radiation-induced cancer deaths in Western Europe over the next 70 years or so. This number of excess deaths will be indiscernible against the normal expectation of 80-100 million deaths due to all forms of cancer in the same population over the same period.

The estimates of individual doses in Table 5 suggest that the risks to individuals, even those in the groups receiving the highest doses, are small. Except for the figures from Turkey (where the data relate to a small part of the country) average doses are all less than 1 mSv, and critical group doses do not appear to be more than a few millisieverts. The inferred cancer mortality risk from an effective dose of 1 millisievert is about one in one hundred thousand. As the risk of cancer from all causes is high (about one in three for incidence, or one in five for mortality) the additional individual risk from Chernobyl in these countries is very small.

An alternative perspective on the significance of these individual risks is provided by noting that natural background averages 2 mSv each year. The additional contribution from

Chernobyl, generally less than 1 mSv in total, is therefore again small, compared with natural background.

In the analysis of radiological consequences given above, no data are available for countries in Eastern Europe which were affected by the accident. By interpolation between the committed doses in European USSR and Western Europe, the inferred increase in cancer deaths in these countries is about 3000 - 5000.

In summary therefore, the available data suggests that the number of excess cancer deaths arising from radiation from the accident might be some 10,000 or so. Of these, a few hundred may occur in the immediate evacuation zone, about 5000 elsewhere in the USSR, some 3000 - 5000 in Eastern Bloc countries other than the USSR, and about 1000 elsewhere in Europe.

The number of excess cancer deaths arising from ingestion of radionuclides (notably caesium-137) through the food chain cannot be determined accurately from the data at this stage, but indications are that the number of these deaths would be comparable to those arising from external radiation effects.

8. THE ISSUES ARISING

Understandably, the immediate response to the accident has been adverse and there is no doubt that the performance of the industry will be under closer scrutiny than ever before. Nevertheless it would be wrong to draw conclusions from Chernobyl which are subsequently invalidated as a more thorough understanding emerges. This analysis, and an appreciation of the significance of the accident, will take years to conclude.

This Section discusses some of the more important issues.

Nuclear Power Development

The accident is unlikely to affect the nuclear power construction program of the USSR. Soviet authorities have strongly

endorsed both the large program and the RBMK design concept. Measures are being taken to prevent any recurrence of the accident at other reactors and Units 1 and 2 of the Chernobyl plant are being prepared for restart in October. Unit 3 is expected to be linked to the grid again next year.

There is a strong desire throughout the Western World to learn as much as possible from the accident and to reduce further the risk that any such accident could occur again. However, because the RBMK design is substantially different to Western designs, it seems unlikely that Western reactors will need to incorporate significant modifications such as those required by regulatory changes introduced after the accident at Three Mile Island.

There are signs of renewed opposition to nuclear power in some Western countries particularly in Europe where life was disrupted by the spread of contamination, although as noted earlier, the adverse health effects from this were minimal. Anti-nuclear sentiment appears to be stronger in European countries which are not yet committed, or have only a small commitment, to nuclear power.

Eight countries have indicated their intention to either reduce their nuclear power programs or postpone a decision until after the accident has been thoroughly examined and the lessons learned (Table 6). It should be noted however that considerable restraints on the expansion of nuclear power existed in these countries even before the accident.

One critical test of the future of nuclear power will be the UK Government's decision on the Sizewell nuclear power station. This has been the subject of a major public investigation and a decision was expected to be made early in 1986 but has been delayed for reasons not necessarily associated with Chernobyl.

Although some countries may reconsider their energy options, there is little doubt that nuclear programs will continue in countries with major nuclear power commitments (USA, France,

Japan and probably FRG). Against this, few new orders are expected until the world economic situation improves. Projections of nuclear power capacity to the year 2000 are therefore not likely to be significantly affected by the accident.

International Cooperation

The Chernobyl accident has also drawn attention to the possible international consequences of major industrial (particularly nuclear) accidents, the need to manage trans-boundary contamination, and the need for a consistent international response to such accidents. The late notification and the initial lack of detailed advice on the accident by the USSR contributed to the uncertainty (and at times the confusion) of response in Europe and highlights the need for more formal notification procedures. It was also evident that there was an absence of agreed multilateral emergency assistance arrangements in place to facilitate the provision of assistance to affected countries.

Following the accident, the Australian Government encouraged international cooperation to address these questions which have been taken up mainly by the International Atomic Energy Agency (IAEA) in collaboration with other relevant international bodies.

A meeting of governmental experts convened by the IAEA on 21 July - 15 August successfully drafted two international conventions, one committing States to provide early notification and information about nuclear accidents with possible trans-boundary effects, and the other to establish a framework for States and the IAEA to offer prompt assistance to affected States following a nuclear accident or radiological emergency.

A vast amount of work has been undertaken, particularly by the International Atomic Energy Agency (IAEA), since the inception of nuclear power to develop a series of detailed guidelines on nuclear safety. These guidelines provide the basis of nuclear safety standards in Western countries. The guidelines are how-

ever primarily advisory and not mandatory. World-wide nuclear safety standards are likely to be even more difficult to impose and indeed there are substantial arguments against such action, particularly if it implies the removal of any responsibility for safety from the State or authority involved. The best that may be hoped for might be broad agreement on safe operation objectives (i.e. an expanded form of guidelines) which could be met universally.

A series of recommendations have been made by the IAEA, OECD/Nuclear Energy Agency, World Health Organisation and other international organisations for follow-up work. These recommendations include:

- re-examination of the man-machine interface in nuclear power stations;

- harmonising criteria for intervention levels and specific countermeasures following radioactive releases. These countermeasures range from evacuation of an area around an accident to restrictions on the sale and use of milk, dairy products, fresh leafy vegetables and some types of meat;

- establishing an agreed format for the acquisition, presentation and reporting of data on airborne activity, measurements of ground deposition and levels of radionuclides in foodstuffs;

- a definitive assessment of the global radiological and health impact of the accident; and

- the establishment of a global environmental monitoring system.

As explained in Appendix 3, much of the information on the effects of radiation on humans has been derived from animal experiments, radiation therapy, and epidemiological studies of atom bomb survivors. The misfortune of Chernobyl provides a

unique opportunity to extend these earlier epidemiological studies and provide better information on the effects of low doses of radiation on humans. The USSR has promised to make available all information relating to the radiation doses received by persons exposed to the accident, together with their medical histories extending over the next 50 years or so. Because this is a closely controlled and monitored population, the results should contribute greatly to knowledge.

Reactor Design

A number of statements have been made about the inherent safety of the USSR reactor design, and specifically the containment philosophy employed in the USSR. Many of these statements have been shown to be irrelevant to the accident. An important reason for this is that the accident was associated with a reactivity excursion (power surge) rather than a loss-of-coolant accident as postulated earlier. The principles for containment under these circumstances are quite different.

Each reactor type has different inherent characteristics, and hence requires different design features and special systems to ensure that it can be safely operated under all foreseeable conditions. Every reactor has a variety of engineered safety systems for its protection, and a containment structure is only one of these. The type and degree of containment required for any reactor depends upon the reactor characteristics, and the extent to which other engineered safety features may limit the requirements for performance of the containment system.

Usually, the main design purpose of a containment, particularly in a water-cooled system, is to contain fission products released from fuel elements following a loss-of-coolant accident (LOCA). It does appear that the containment and other safety provisions of the RBMK reactor were designed to be capable of limiting the consequences of a foreseeable LOCA, and there seems no reason to doubt that they would have been able to do so.

However, the Chernobyl causative event was not a LOCA, but apparently more akin to a "transient without scram". This class of accident has been the subject of considerable analytical attention and safety assessment for various reactor types. Because severe accidents of this type would be capable of causing severe transient pressures, with the possibility of generating missiles, it is uneconomic to provide defence against them by the design of the containment. Rather, protection is provided by designing the core and system with inherent physical characteristics and redundant shutdown systems to preclude such events.

In RBMK reactors, the presence of the two-phase coolant with a positive void coefficient of reactivity necessitates complex, high-performance control and safety systems. The complexity is further increased because the reactor is sufficiently large to allow spatial power instabilities, which require specific control provisions. These features undoubtedly increased the susceptibility of the Chernobyl reactor to the type of reactivity insertion accident which it now appears occurred.

In this context, the renewed emphasis on so-called "inherently safe" reactors following the Chernobyl accident may be of little relevance to that event. The design concepts of these systems are directed towards the provision of inherent protection against the severe adverse consequences of loss of coolant accidents, not of reactivity transients without scram.

Reactor Siting

The Chernobyl accident has also revived the debate over siting of nuclear facilities. As noted in the discussion on containment, the question of adequate siting of nuclear power reactors can only be resolved by a thorough analysis of the possible accidents, and consideration of the risks and consequences associated with these accidents, in relation to the site and its characteristics. In short, the first and over-riding requirement is to ensure that an accident (particularly one having off-site consequences) cannot occur. The history of the nuclear

industry shows that this requirement can be (and has been) met and that nuclear reactors can be safely sited close to populated areas. There will always be a finite probability, however, that an accident will occur which will have off-site consequences. In any well engineered design, this probability is so low as to be negligible.

Similarly, the possible consequences vary enormously between reactors according to their fuel inventory and use; low power research reactors, for example, have a much lower consequence potential than large power reactors.

The Chernobyl accident demonstrated that, however remote the probability, the consequences of an accident in a large power reactor can be grave, causing disruption to social and economic activities in the surrounding areas. The fact that 135,000 people were evacuated so quickly is commendable but if an accident of this magnitude had happened in a more populated area, evacuation and relocation of five or ten times this number may have been required.

These facts will promote a re-assessment of emergency arrangements in relation to the siting of a number of nuclear power reactors in the West.

Reactor Operation and Training

Although details of the accident are still to be resolved, there is little doubt that, without the numerous, apparently unauthorised and unaudited infractions of rules and procedures which took place, the plant conditions which made the accident possible could never have been reached.

Knowledge is required of the management structure at Chernobyl (and, indeed, the personalities in that structure) and of the safety review and authorisation organisation and procedures before specific comment and criticism of the operations can be made. It does, however, seem probable that operations staff,

supervisors and safety authorities at all levels were complacent and must shoulder some share of responsibility for the accident.

Reportedly, the Chernobyl station operating record was excellent, and its staff widely regarded as outstandingly competent - a situation in which growing familiarity with the plant probably engendered complacency and corner-cutting of rules and safe practices if management and safety audits were in any way lax. Such attitudes have tended to be a contributing factor in most of the very small number of reactor accidents on record. Unremitting vigilance, even to the level of encumbrance and irritation, appears, unfortunately, to be the only effective countermeasure.

Contributing factors in the Chernobyl accident which appear to have been particularly significant are:

(i) Inadequately detailed instructions for the "non-standard" experiment to be performed.

(ii) Lack of an adequate analysis of the safety aspects of the proposed experiment and of reactor conditions which might occur during its course.

(iii) Lack of an adequate independent safety review of such an analysis.

(iv) Lack of management control to ensure that approved procedures and operational limits were strictly adhered to.

(v) The apparent ease with which operating staff were able to bypass fundamental reactor protection systems, either with no constraint, or with blatant breach of the fundamental requirement that every action affecting safety should be authorised by a competent, qualified reactor specialist.

(vi) A lack of training of staff at the operating interface to recognise that many unforeseen circumstances and reactor conditions were arising, any of which should have led to serious re-appraisal of whether it was appropriate and prudent for the proposed experiment to proceed.

(vii) Inadequate training of the staff to enable them to appreciate potential dangers which the breach of safety margins and instructions might lead to, or to understand the physical conditions developing in the reactor under non-standard operational conditions.

(viii) Lack of any additional specialist supervision for the non-standard procedures, either with direct line responsibility, or as advisers to the line management in charge of the experiment.

In the event, determination and haste to carry out an experiment at all costs led to the experiment starting from an unstable and improperly known state of the reactor. There seems no doubt that an inherent fundamental aspect of the experiment was that the reactor would be automatically shut down by the closure of the turbo-generator valve which would initiate the planned test.

A vital question is: Who made the crucial and fatal decision to bypass the turbo-generator trip "in order that the experiment could be repeated" (to get further data, if necessary, prior to full shutdown for scheduled maintenance and before "poisoning" out by xenon prevented reactor re-start)? Such a decision can only have been made either in ignorance of the importance of its implications on plant safety, or with a total disregard for safety. It is inconceivable that it could have occurred in any organisation where:

(i) Any proposed non-standard operation must be fully documented in detail, and analysed for safety impact.

(ii) The proposal and analysis is reviewed in detail by independent experts on reactor safety, and

(iii) Approval to proceed is subject to clearly defined conditions and authorities which are rigorously adhered to by a diligent and technically competent management/supervisory team.

The implications for a thorough reappraisal of training requirements for operating staff and management with responsibility for nuclear reactors are self-evident. So is the requirement for review of the adequacy of safety approval procedures and audits of compliance. The events further highlight the importance of simulator training of operators. Simulators enable unusual and emergency situations, far too hazardous to be deliberately created on the actual plant, to be realistically modelled. By exposure to such simulated conditions, the probability that appropriate and effective operator intervention will be available in actual emergency situations is likely to be considerably enhanced.

Intervention Levels

As noted earlier, considerable uncertainty and confusion arose in some countries as to the action required to protect their citizens from the radiation and contamination resulting from the accident. Action was taken to prevent the consumption of water, milk and foodstuffs (as shown in Table 3) but there was little consistency in the levels of contamination at which these intervention measures were set. As a result, some countries in Europe had the anomalous situation of different standards being applied to communities less than a kilometre apart. On a larger scale, the lack of consistent action caused disruption to trade.

The IAEA and WHO had already examined the problem of setting consistent intervention levels and published the general principles which should apply. The problem is not simple, however, and it is unlikely that world-wide intervention levels

will be agreed in the short term. Some of the issues that need to be addressed are:

- the different pattern of food consumption in regions which determines the intake of contamination likely to arise from each food group;

- the different radiation protection philosophies in countries;

- the complexity of radiation emissions which may occur in an accident; and

- the relative risks of short and long term health effects.

In spite of these difficulties, action is urgently needed to reach some agreement on intervention levels, if only on a regional basis. Unless this is done, the potential for confusion and for disruption of trade will remain.

Operation of Lucas Heights Reactors

Neither of the reactors at the Lucas Heights Research Laboratories (LHRL) resembles the RBMK reactor in any aspect which is significant in the context of safety. Both HIFAR (10 MW) and Moata (100 kW) are research reactors, not power reactors for electricity generation. The Chernobyl reactor was a power reactor operated at 3200 MW.

Although both HIFAR and Moata have water (or heavy water) coolant, the coolant circuits operate at close to normal atmospheric pressure, temperatures are well below 100°C, and the coolant is not required to boil. Furthermore, in direct contrast with the situation for the RBMK reactors, if the power of HIFAR or Moata were to increase sufficiently for steam to form, displacement of cooling water from the reactor core by the steam would, by the inherent physical properties of the designs, reduce the system reactivity and power, so moving the reactor towards a safer

condition; that is, the coolant void coefficients of reactivity are negative, unlike in RBMK reactors.

These considerations alone establish that the control and safety systems for HIFAR and Moata can be, and are, much less complicated than those for the Chernobyl reactors. Furthermore, because the cores of HIFAR and Moata are small, spatial instabilities in neutron flux are absent and there is consequently no requirement for their control; spatial instability effects appear to have made a major contribution to the conditions which allowed the Chernobyl accident to take place.

Because of its much greater simplicity and inherently stable, self-limiting physical behaviour, HIFAR is less reliant for its safety on administrative controls than appears to have been the case for the reactor at Chernobyl. The complexity of operational procedures is also far less. Although research reactors are generally used for "non-standard" operations far more frequently than a power reactor would be, their design allows for these requirements, and the potential for operator error to impact significantly on safety, and the potential consequences of such error, are low.

For Moata, the operating power level is so low, its available excess reactivity is so small, and its inherent self-regulating properties so strong, that it is inconceivable that an accident could occur which would result in a significant release of fission products to the environment.

For HIFAR, extensive analyses have been made of the effects of plant failures and operator error on safety. These analyses have shown that some extremely unlikely, but perhaps still credible, reactivity addition accidents could, in conjunction with some protection system failures, lead to melting of fuel and failure of the primary circuit. However, no credible combination of a reactivity addition and protection system failure has been identified which, on the basis of conservative but realistic evaluation of the consequences, would lead also to breach of the reactor containment building. The worst conse-

quences of a reactivity accident in HIFAR, accompanied by protection system failure, are therefore comparable with those for a loss of coolant accident accompanied by failure of the emergency core cooling system. The likelihood of their occurrence is, however, even lower.

To limit the public consequences of these very unlikely accidents, HIFAR is designed so that a considerable proportion of any fission products released from the fuel would be retained within the boundary of the reactor biological shielding block. Still further attenuation of any fission product release is provided by the steel containment building. Analyses have consistently shown that, even in unfavourable circumstances, it is extremely unlikely that the resulting radiation levels in any neighbouring population zone could reach the threshold at which health authorities recommend that limited evacuation procedures should be considered.

An accident of the nature and consequences of those arising from the Chernobyl RBMK reactor is not conceivable for the LHRL research reactors.

Response in Australia

Immediately following the announcement of the accident, the AAEC established a Task Group to monitor and assess all information coming to hand, and to advise on any action required. The Task Group produced a first report on 9 May, 12 days after the accident.

The Task Group noted that contamination from the accident in the Northern Hemisphere was unlikely to reach Australia by wind movement for at least some months and by that time, dispersion and decay of fission products would reduce risks to a very low level. There was however a risk that contamination could be directly imported from the Northern Hemisphere (and particularly from the region near the accident) through foodstuffs, and other goods, exposed persons or aircraft. In response, the Department

of Health established a monitoring system for imported foodstuffs which is still operating. There have been no cases of contamination at significant levels detected to date.

The Australian Radiation Laboratory continues to monitor for atmospheric fallout from the accident but as yet none has been detected.

A further immediate response was required to answer the many concerns from the general public regarding the accident, and particularly the possible effects of the accident on travel plans. The AAEC and Department of Health handled many of these enquiries, and those relating to specific travel advice were referred to the Department of Foreign Affairs. These arrangements worked satisfactorily although there may be arguments for nominating a specific contact point for public enquiries in any future situation.

The overall impact of the Chernobyl accident on Australia has been negligible, mainly because it happened in the Northern Hemisphere. An accident of similar magnitude in a nuclear power plant in the Southern Hemisphere (such as in South Africa, Argentina or Brazil) would have more impact, but dilution and decay in the transport of contamination over a large distance would greatly reduce this impact, compared with that of the Chernobyl accident on Europe.

CONCLUSIONS

1. The accident at the Chernobyl Nuclear Power Plant was caused by violation of safety procedures by the operators of the plant, compounded by certain aspects of design (notably the existence of a positive void coefficient of reactivity, and reliance upon non-engineered safety controls) which are largely unique to this type of reactor.

2. The statement by the USSR on the causes of the accident and its progression, appears to be consistent with the available

facts and the technical features of the reactor. However, a number of details and apparent anomalies need to be resolved.

3. The USSR response to the accident and the countermeasures introduced appear to have been both rapid and effective. The glaring omission in this response, however, was the lack of notification to other countries likely to be affected by the accident.

4. The accident killed 31 people and 203 were affected by acute radiation sickness. It is possible that the number of deaths in this group will increase in coming months. Some 135,000 people were evacuated from around the Chernobyl site and social and economic activities were severely disrupted. An area will remain uninhabitable on a normal basis for some time.

5. The impact of the accident on affected populations (notably in European USSR and Europe) is still being assessed. An estimate at this stage is that there may be some 10,000 additional deaths from cancers induced by radiation effects from the accident together with a similar number arising from the long term ingestion of radionuclides, over and above the normal occurrence of cancer in these populations of some 100 million over the next 50 - 70 years.

6. The USSR has firmly re-stated its intention to proceed with its nuclear power program. Some countries in the West are likely to review their programs but the accident is unlikely to affect the long term development of nuclear power.

7. The accident has emphasised the need for international agreements covering the notification of accidents likely to have trans-boundary consequences, and for cooperation in the provision of emergency assistance. Action is also required to define consistent intervention levels including those for control of contaminated water, milk and other foodstuffs.

8. Although there is no evidence that the RBMK reactor was poorly designed or constructed, the design philosophy, particu-

larly the reliance upon procedural rather than engineered safety systems makes questionable its licensing in the West.

9. The impact of the accident on Australia has been, and will continue to be negligible because of distance, the slow exchange of air between the Northern and Southern Hemispheres, and the dilution and decay of contamination which occurs during this process.

10. An accident of the type which occurred at Chernobyl could not occur in either of the reactors located at Lucas Heights.

TABLE 1

MAIN REACTOR PARAMETERS

Electrical power	1000 MW
Thermal power	3200 MW
Steam output	5800 t/h
Steam parameters before turbines:	
pressure	65 kgf/cm^2
temperature	280°C
Fuel enrichment	2.0%
Uranium mass in a fuel assembly	114.7 kg
Number/diameter of fuel elements in the assembly	18/13.6 mm
Fuel burnup	20 MW d/kg
Radial power form factor	1.48
Axial power form factor	1.4
Max. design channel power	3250 kW
Isotope composition of discharged fuel:	
^{235}U	4.5 kg/t
^{236}U	2.4 kg/t
^{239}Pu	2.6 kg/t
^{240}Pu	1.8 kg/t
^{241}Pu	0.5 kg/t
Void reactivity coefficient	2×10^{-4}/vol. % steam
Prompt power reactivity coefficient	-0.5×10^{-6}/MW
Fuel temperature (Doppler) coefficient	-1.2×10^{-5}/°C
Graphite temperature coefficient	6×10^{-5}/°C
Minimum reactivity invested in control rods	10.5%
Reactivity in manual control rods	7.5%
Reactivity effect of the replacement of a spent fuel assembly by a fresh one	0.02%

TABLE 2 INDICATIVE LEVELS OF RADIATION AND CONTAMINATION IN COUNTRIES OUTSIDE THE USSR DURING EARLY MAY 1986

(For explanation of units see Appendix 3)

Country	External exposure rate above background (μR/h)	Deposition of iodine-131 (kBq/m^2)	Iodine-131 concentration in milk (Bq/L)	
			Dairy milk (blended)	Peak values, usually for raw farm milk
Austria	2 - 230	33	0 - 450	1 500*
Czechoslovakia	20 - 200		50 - 500	1 000*
Denmark	1 - 2	0 - 3	0 - 3	30
Fed Rep Germany	0 - 250	0 - 120		1 200*
Finland	0 - 370	0.6 - 120	20 - 40	
Hungary	24 - 43	80 - 500	50 - 200	2 600*
Iceland	0	0	0	0
Israel	1 - 2	0	0	0
Luxembourg	7			
Malta		1	13	140
The Netherlands	1 - 12	0.5 - 3	40	175
Norway	6 - 22	20 - 80	15	57
Poland	10 - 500	0.1 - 200	0 - 600	1 700*
Portugal	0	0	0	
Sweden	2 - 500	0.1 - 170	2 - 56	2 900*
Switzerland	5 - 130	1.6 - 7	7 - 110	440
United Kingdom	1 - 50	0.7 - 3	2 - 15	190
Yugoslavia	0 - 150	3 - 5	50 - 150	1 000*

* The peak values are local and apply only to small groups of people.

TABLE 3 LIST OF EMERGENCY ACTIONS IN VARIOUS OECD MEMBER COUNTRIES FOLLOWING THE ACCIDENT AT CHERNOBYL

Country Code

A	Austria	J	Japan
B	Belgium	N	Norway
CH	Switzerland	NL	Netherlands
DK	Denmark	S	Sweden
FRG	West Germany	SF	Finland
GR	Greece	UK	United Kingdom
I	Italy	T	Turkey

Action	Country (Duration)	Remarks
* Use of water:		
- Advice not to drink rainwater	A, SF, I, J, N, CH, UK, T, (a few days)	
- Advice not to use rainwater for watering cows	SF	
- Advice not to use rainwater in the sauna	SF	
- Advice to filter rainwater through charcoal-filter before drinking	J	
* Use of milk:		
- Milk-producing cattle kept from grazing	B, DK, FRG, SF, I, NL, S, CH, T (a few days - weeks)	Recommendations on regional basis
- Restrictions in use of milk (cow and others)	A, GR, I, S, CH	I: No milk to children and pregnant women
- Advice to avoid use of milk from sheep and goats	NL, CH	
- Sheep cheese forbidden for consumption (within 5 weeks from production)	NL, I	
- Import restriction	Practically all countries	

Table 3 cont'd

Action	Country (Duration)	Remarks
* Use of vegetables:		
- Advice not to eat fresh surface vegetables	A, (F), NL, S, FRG, CH I: restriction (several days-weeks)	NL, F: Spinach for a short time CH: For children < 2 y, pregnant women (13-16 May) NL: Fresh spinach destroyed (4-10 May)
- Advice to wash fresh vegetables before they are eaten	Several countries	
- Restrictions on the use of plants and mushrooms gathered in the wild	SF (7-16 May)	
- All green vegetables confiscated if grown in the open	A (6 May -)	
- Ban on human consumption of large leaf vegetables	FRG (?-23 May) I (2-17 May)	
- Import restrictions	Practically all countries	
* Use of meat		
- Restrictions in sale of animal thyroids	NL, GR	Recommendations to slaughterhouses to destroy thyroid glands from slaughtered animals
- Restrictions in sale of lamb meat	UK, CH	CH: "Do not bring sheep to butcher" (23 May .....)
- Restrictions in use of fish from small lakes	SF, S	S: Advice on not eating fish from some areas or on the frequency of such consumption
- Restrictions in sale of reindeer meat	S	Limit 0.3 KBq/kg is largely exceeded in certain areas. The problem will become acute at the slaughter this fall.

Table 3 cont'd

Action	Country (Duration)	Remarks
* Others		
- Advice to stay indoors or to avoid outdoor life	A (5 May .....)	A: BMFGU recommend avoid playing in sand, dust-generation, close contact with soil/lawn/fields (picnic, ball games, etc.). Also avoid possible contact with animals because of possible dust in fur.
- Advice to wear breathing filters and protective gloves when exchanging air filters in big industries	SF, S, CH	SF: Recommendation to replace air-conditioning filter earlier than usual (13-26 May)
- Advice not to take iodine pills	A, FRG, F, S, CH	
- Advice to take a one time dose of 200 mg of potassium iodine if going within 500 km of Chernobyl	SF	
- Advice to tourists not to go to some areas	Several countries	
- Checking of people and cars coming from potentially contaminated areas	Several countries	
- Development of special harvesting methods to avoid contamination with active soil	S	
- Restrictions in the use of sewage-sludge for soil improvement.	S	Limit: 4 kBq/kg wet weight 20 kBq/kg dry weight

TABLE 4 LIST OF INTERVENTION LEVELS USED IN VARIOUS OECD MEMBER COUNTRIES

(For explanation of units see Appendix 3)

Country	Iodine-131 (Bq/kg or Bq/L)			Caesium-137 and Caesium-134 (Bq/kg or Bq/L)			Remarks
	Milk	Veg	Meat	Milk	Veg	Meat	
Austria	185						370 if shortage on the market
Belgium							
Canada	10	70					Limit for imports
Denmark							
Finland	2000			1000			
France	2000	2000					
FRG	500	250		370*	1000	600*	*Import limit 1 June to 30 September
Greece		250		300			Rejection limit 500 Bq/kg
Iceland							
Ireland							
Italy	500-5000 (1) (2)	500-5000 (1) (2)					(1) = Attention level (2) = Emergency level
Japan							
Luxembourg							
Netherlands							
Norway	1000	1000		300	300		
Portugal							
Spain							
Sweden	2000	5000* 300**	300**	1000 300**	10 000* 300**	300**	*Imports limits **Finally decided intervention levels for consumption
Switzerland	370(?)			370(?)			
Turkey							
United Kingdom	2000	100 000*	3600*	200 000	*1000		*Dept of Environment Reference Level
USA	560		8880				FDA Protection action guide. Protective guidance for import admission: Cs: 370 Bq/kg I-131, infants food: 56 Bq/kg
Commission of the European Community	500*	350*	370**	600**	600**		*Recommendation **Regulation 31 May to 30 September 1986

TABLE 5 CURRENTLY AVAILABLE INFORMATION ON RADIOLOGICAL IMPACT OF THE CHERNOBYL ACCIDENT IN OECD COUNTRIES

(For explanation of units, see Appendix 3)

Country	Total Deposition (TBq)		Average Deposition (kBq/m^2)		Collective Effective Dose Equivalent (Person - Sv)		Population $\times 10^6$	Average Dose (mSv)	Doses* to Critical Group - Adults (*Effective Dose Equivalent) (mSv)	
	I	Cs	I	Cs	With Countermeasures	Without Countermeasures			With Countermeasures	Without Countermeasures
Netherlands	840	110	11	2.7	950	1120	14.5	0.06	0.06(0.19 child)	0.08(0.25 child)
France		250						0.10		
Denmark	73	72	1.7	1.7		311	5.2	0.06		0.05
Italy	9700	1950			5200 (95,000)(a)			0.04		
Germany	4000	2000	16	8	34,000		61	0.6	0.5 - 1.1	
Belgium	120	40	4.0	1.3		400	10	0.04		0.12
Iceland				< 0.1				< 0.001		
Switzerland	1500	500	37	12	1330	1350	6.4	0.21		1.8
Finland	17,100	3030	50	9	2500	2500	4.9	0.5	0.65	0.7
Sweden	53,700	6200	120	14	3160	3160	8.3	0.3	2.0	3.4
Canada	953	415	0.1	0.04		63	25.5	0.003		0.007
Spain	4.4	1.9						0.002		
Japan	440	48			780(8200)			0.007		
Luxembourg			40	10	46(180)					
Norway	2500	4800			1600			0.4		
Austria	6000	800			4000	33,000			2	
UK	300	300			2400(11,000)		55	0.04		
Turkey	130	39			9100(43,000)		51	3 - 11		

(a) Figures in parenthesis under collective effective dose equivalent are collective thyroid dose equivalent, not effective dose equivalent.

(b) Total collective effective dose equivalent = 65,066 person - Sv

TABLE 6 REACTIONS OF SOME COUNTRIES TO THE CHERNOBYL ACCIDENT

COUNTRY	ACTION	COMMENT
Austria	Reactor to be disassembled.	The reactor at Zwentendorf was constructed but mothballed following a vote in a referendum in 1978 against its start-up.
Egypt	Accident to be reviewed and plans postponed.	Plans for the first two reactors have previously been postponed several times owing to economic difficulties. Bids for construction were first sought in 1982.
Netherlands	Accident to be reviewed and plans postponed.	A decision had been made to plan the construction of additional reactors after a two year debate and overwhelming public opinion against nuclear power.
Switzerland	Reconsideration of plans to construct Kaiseraugst.	This reactor project has been the focus of controversy since it first received government approval in 1969.
Finland	Plans postponed until review of the accident.	Plans for the fifth reactor, possibly Russian, were being considered.
Yugoslavia	Possible delay in reactor order.	Bids for construction of a second reactor had been received including a bid from the USSR.
Philippines	Reactor to be mothballed.	Cabinet has voted against commissioning Bataan, the recently constructed first reactor. Seismic safety of the reactor was being argued prior to the Chernobyl accident.
Sweden	Phased closure of operating reactors could be advanced.	Following a 1980 referendum the government decided to phase out the 12 operating reactors by 2010.

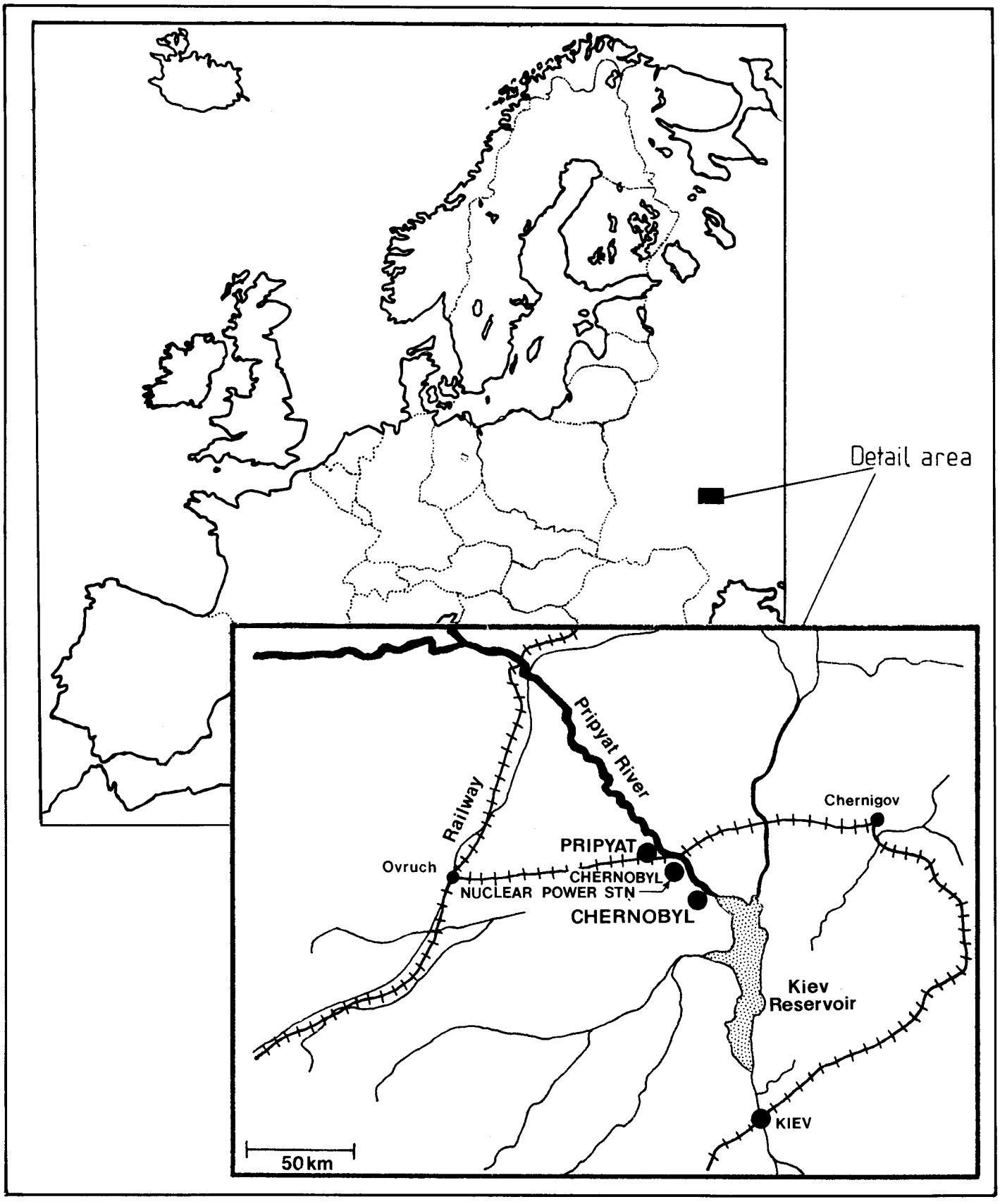

Figure 1 The Chernobyl Area

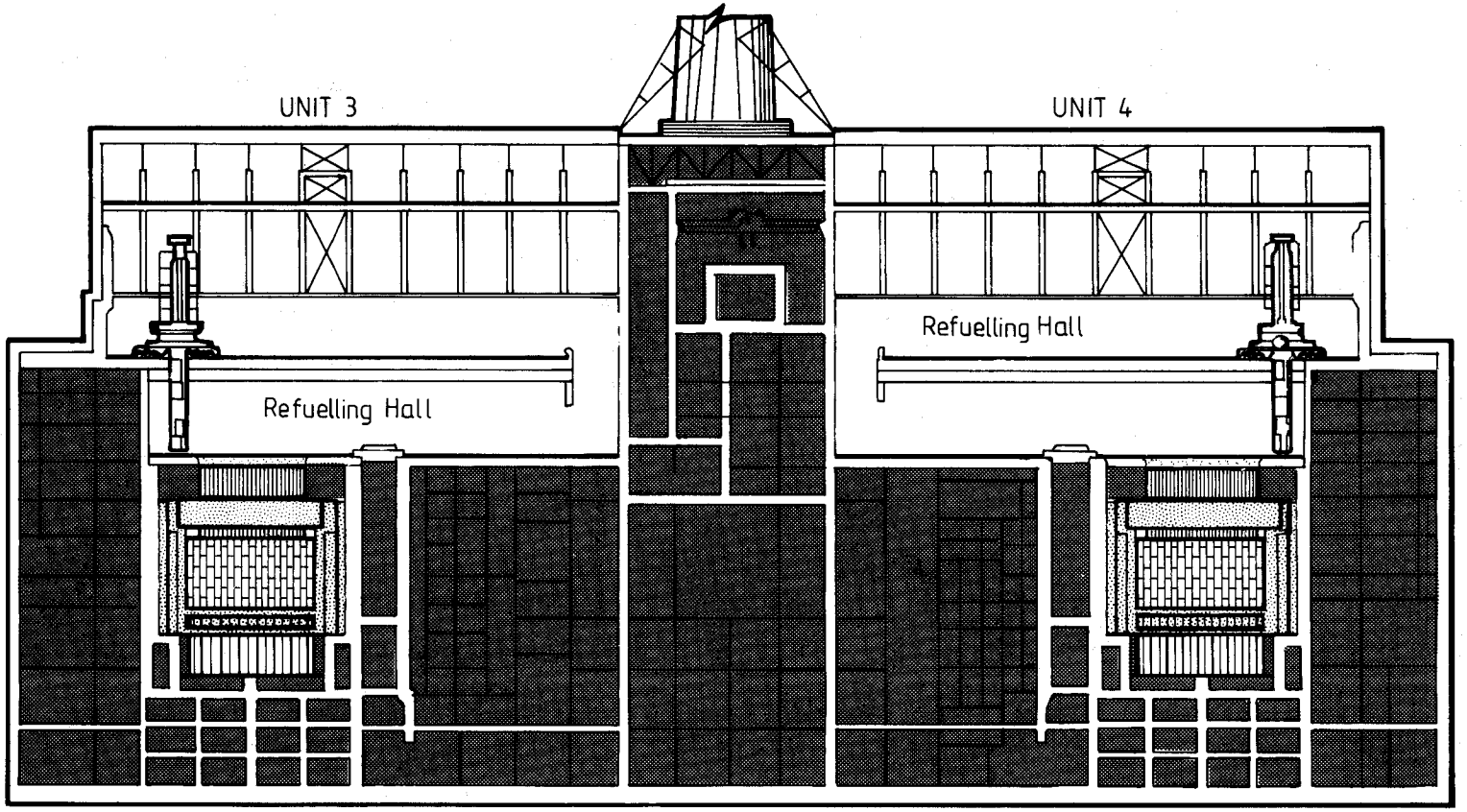

Figure 2 VERTICAL CROSS SECTION OF THE REACTOR PART OF CHERNOBYL NUCLEAR POWER PLANT (UNITS 3 AND 4)

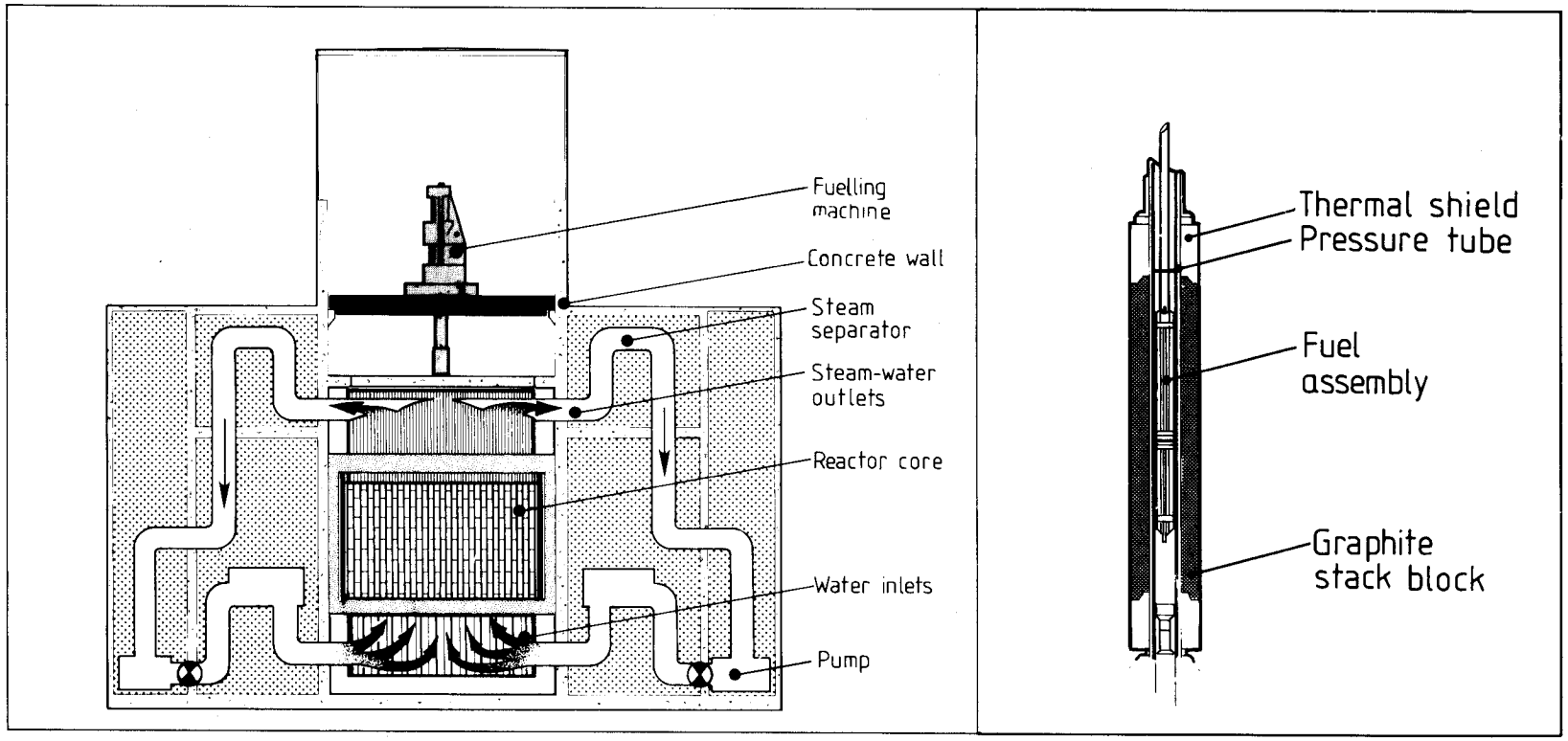

Figure 3 General features of RBMK type reactors and a fuel channel.

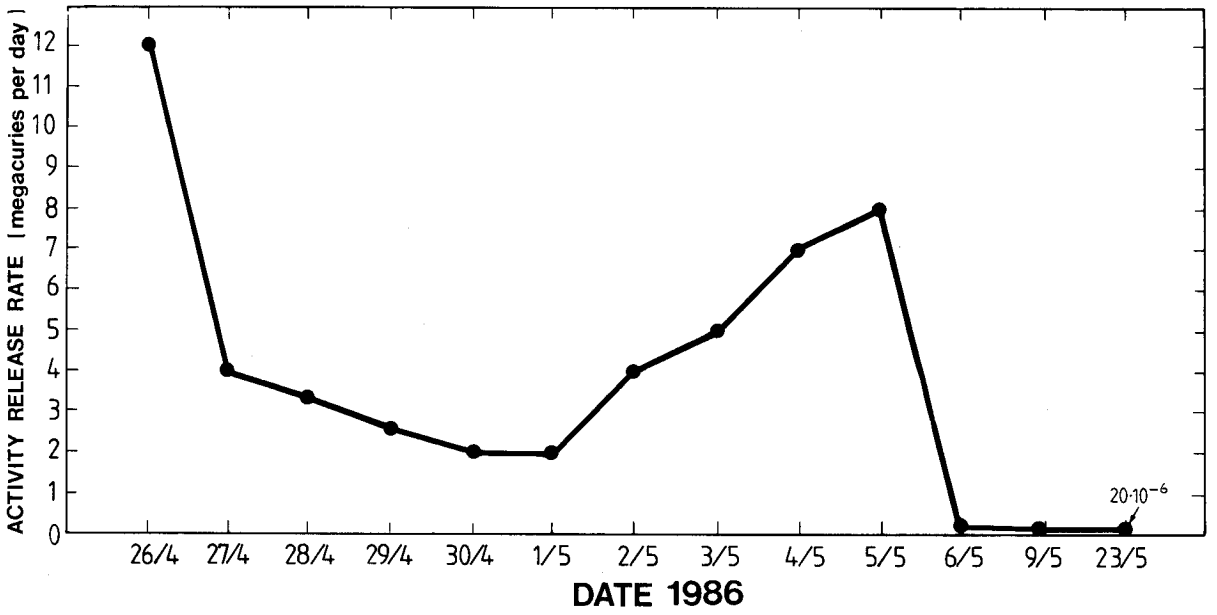

Figure 4 Daily rates of release of activity from Chernobyl Unit 4

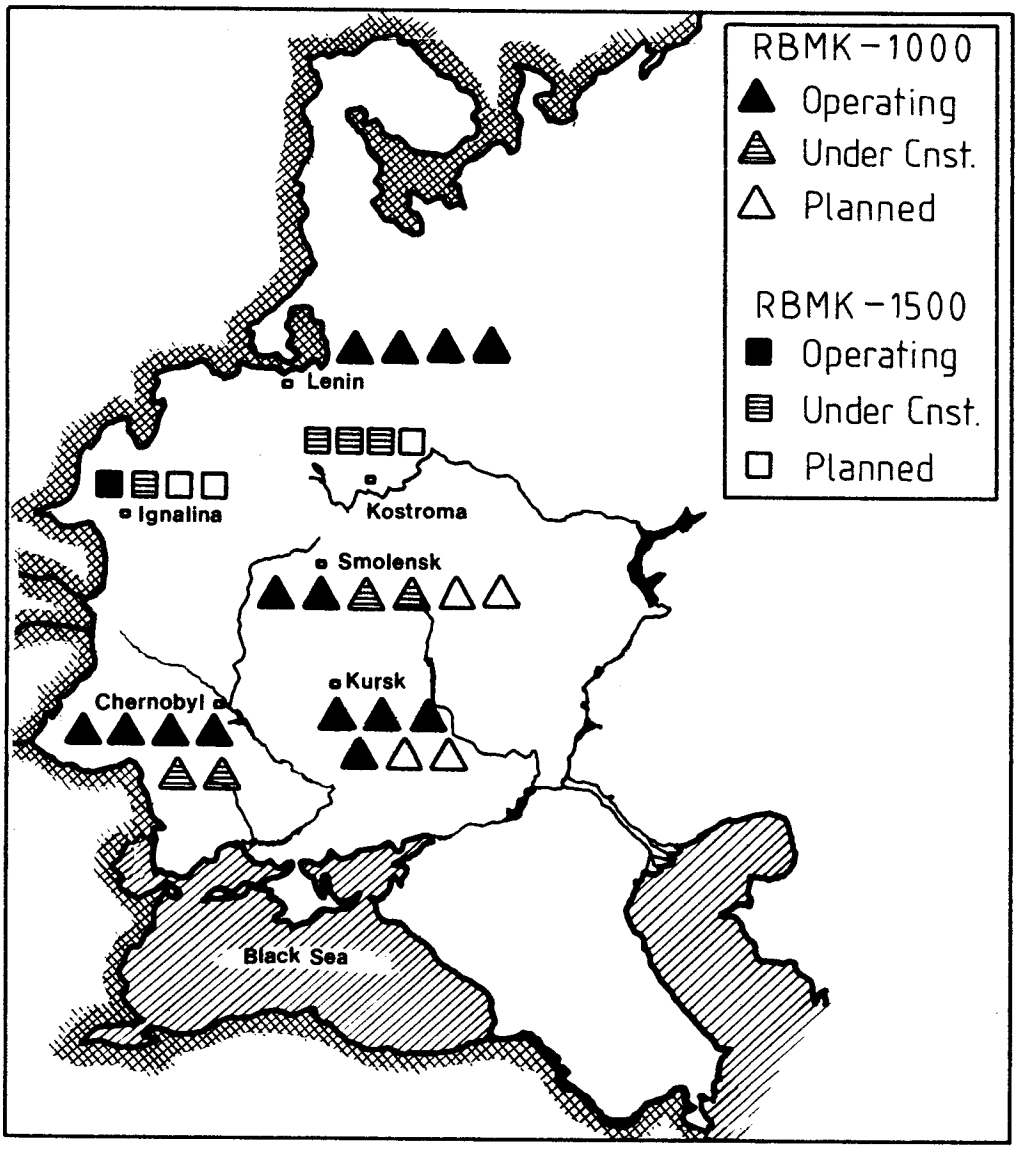

Figure 5 RBMK Reactor sites in the USSR

APPENDIX 1

THE USSR NUCLEAR POWER PROGRAM AND ITS MANAGEMENT

USSR energy planners foresee the rapid development of nuclear power in the European part of the country and the Urals in accordance with "The Main Lines of Economic and Social Development of the USSR for 1986-1990 and until the year 2000". In 1985, power generation at nuclear plants reached nearly 170 TWh (Terawatt hours) and is expected to increase to 5-7 times that amount by the end of the century. There are also plans for the maximum possible use of nuclear energy for centralised heating and industrial heat supply.

The Russian nuclear power program is based on two types of light water reactor. One is the Chernobyl type, designated RBMK, which is a boiling light water-cooled, graphite moderated, pressure tube, reactor. The other type is a pressurised water reactor designated VVER.

The RBMK design has been built only in the USSR. Reactors exported to Eastern Bloc countries and Cuba are of the VVER type. Although additional RBMK units are to be constructed within the USSR, it is intended that expansion of nuclear power will come mainly from the deployment of VVER reactors.

An advantage of the RBMK design is that the units can be built without the need for special manufacturing facilities for heavy pressure components. This requirement has delayed the VVER construction program in the past. For example, the purpose-built Atommash factory which makes pressure vessels and components for the VVER reactor primary circuit has experienced severe manufacturing problems. It should have been producing eight vessels a year by 1980 but only managed to deliver its fourth vessel by August 1985.

The first power reactor in the USSR was a graphite moderated, channel-type reactor which started operating in June 1954 at Obninsk, near Moscow. Six 100 MWe units at Troitsk, and Unit 1 at Beloyarsk, followed from 1958 to 1964. Beloyarsk-2, a 200 MWe unit, was linked to the grid in 1967.

The next step in the development of the water-graphite reactor concept was the construction in 1973 of the RBMK-1000, a high power channel-type boiling water reactor with a unit capacity of 1000 MWe at the Leningrad Nuclear Power Plant. The RBMK-1000 reactor and the VVER-1000 reactor have become the basic reactors for large-scale nuclear power production in the USSR.

Further development has led to a unit capacity of 1500 MWe, the RBMK-1500. (The modular concept of the RBMK design allows the total power of the unit to be increased by increasing the number of fuel channels and improving flow conditions). The first units of this size were at Ignalina in Lithuania. Ignalina-1 entered commercial operation in 1984 and Ignalina-2 is nearing completion. Another four-unit RBMK-1500 plant is being constructed at Kostroma on the Volga. Even larger RBMK reactors may be built. Design work is said to be in hand for an RBMK-2400.

Before the accident, fourteen RBMK-1000 units and one RBMK-1500 reactor operated at Leningrad, Kursk, Smolensk, Chernobyl and Ignalina. These reactors represented about half of the installed nuclear generating capacity or about 5% of the total electricity generating capacity of the USSR. Eight RBMK-1000 and RBMK-1500 reactors were under construction and plans for another seven units had been announced. The locations of RBMK-1000 and RBMK-1500 units in operation, under construction and planned are shown in Figure 5.

The State Committee for the Utilisation of Atomic Energy is responsible for operating the prototype RBMK-1000 plant at Leningrad and the RBMK-1500 plant at Ignalina. The Ministry of Power and Electrification is responsible for the operation of follow-on RBMK plants, including the Chernobyl reactors.

The supervision of nuclear power plant safety is the responsibility of three bodies:

(a) The State Committee for Nuclear Industry Safety supervises compliance with regulations and standards of engineering safety in design, construction and operation of nuclear power plants.

(b) The State Nuclear Safety Inspectorate supervises compliance with rules and standards of nuclear safety in design, construction and operation of nuclear power plants.

(c) The State Sanitary Inspectorate, responsible to the Ministry of Health, supervises compliance with rules and standards of radiation safety in design, construction and operation of nuclear power plants.

The system of three supervisory bodies has largely determined the structure of a complex of regulations which is one of the main tools for ensuring the safety of nuclear power plants in the USSR. These documents are complemented by the system of state standards developed and established by the State Committee on Standards which ensures nuclear plant safety through establishing requirements for many components, materials, processes, etc.

APPENDIX 2

ENGINEERING/PHYSICS ANALYSIS OF RUSSIAN DESCRIPTION OF THE ACCIDENT

The following is a necessarily superficial analysis of the course of the accident as described by USSR experts. It is superficial because there is little numerical data relating to the time interval of five seconds before the explosions that destroyed the reactor, and because the complete understanding of the course of the accident and the consequences of the actions of the operators will require detailed study of the engineering of RBMK reactors.

The part of the accident sequence examined here is that following the closure of the steam supply valve to turbo-generator 8. This is taken as time zero. Prior to this the reactor had been at 1600MW for approximately ten hours, and about two hours before time zero, attempts were made to stabilise the reactor power in the range 700-1000MW by manual operation of the control rods. However, the xenon transient that was under way severely reduced the operational reactivity margin and the operators found it impossible to reach a steady power of more than 200MW. Although the power was stabilised at this level, this was achieved only by withdrawal of nearly all the control rods from the core, and control of the spatial power distribution in the reactor was lost.

Twenty minutes before time zero, two additional main circulating pumps were switched on, making a total of eight operating at this time. The low reactor power and the high coolant flow rate led to decreases in both steam pressure and water level in the steam separators and the value of these parameters fell below permissible levels. For the next twenty minutes, attempts were made to stabilise the system by varying the flow rate of the feedwater pumps. This caused variations in the core inlet temperature and core exit steam quality with consequent variations in excess reactivity.

Thus at time zero the reactor was in an unknown and presumably unstable state. The reactivity invested in control rods was about half that permitted, from which it may be inferred that the response time of the emergency shutdown system was longer than permissible.

At time zero the steam supply valve to turbo-generator 8 was closed. This would normally have resulted in a reactor shutdown, making the events that were to follow impossible, but the staff had bypassed the control logic to allow a second attempt at the experiment if the first was unsatisfactory. The reactor therefore stayed at power; this was the gate the operators opened on their way to the accident.

Closing the steam supply valve to turbo-generator 8 and bypassing the steam flow to the steam dump line initially resulted in an increase in system pressure and a consequent decrease in steam quality, and at +32 seconds, automatic control rod AC-2 began to drive out of the core to compensate for this, followed at +39 seconds by rod AC-3.

The rundown of turbo-generator 8 which was supplying power to four of the main circulating pumps resulted in a run-down of these pumps, a consequent decrease in core coolant flow and an increase in steam quality. Automatic control rods began to move back into the core but at +40 seconds a sharp increase in reactor power was observed and the manual reactor shutdown button was pushed.

The events that followed are subject to speculation, but, as calculated by USSR experts, there were probably two power excursions. In the first, at +40 seconds the control and safety system, aided by the Doppler effect, took five seconds to arrest the power rise and at +45 seconds it had returned to a few hundred megawatts. At about this time the check valves on the core inlet coolant lines closed, probably as a result of a sharp increase in core pressure. Coolant flow through the core decreased rapidly and a second fast power transient occurred. At

+46 seconds the power had returned to several hundred megawatts but at +48 seconds and +51 seconds explosions occurred which destroyed the core and much of the containment structure.

Comments

1. This accident can be classified as a power transient with failure to scram. The initiating event appears to have been driven by the positive void coefficient of reactivity and possibly the failure of the automatic control rod logic to respond correctly to rapidly fluctuating signals at a relatively low power.
2. The operator action that allowed the accident was essentially the bypassing of the turbine isolation trip signals. Other actions contributed to the result but would not have resulted in an accident by themselves. Isolation of the emergency core cooling system did not have any influence on the accident and points only to poor operational judgment. The most disquieting feature of events leading up to the accident was the apparent ease with which it was possible to make ad-hoc decisions to bypass the safety and control logic of the system.
3. The failure to scram during the first excursion remains an enigma. It may have resulted from too slow a response, but with 10 per cent reactivity margin invested in control absorbers and five seconds between scram action and the onset of the damaging power pulse, this does not appear likely, even given the circumstance that most of the control rods were at their upper limits. It therefore seems probable that a mechanical or electrical malfunction occurred to prevent adequate response to the scram signal.
4. The positive void coefficient was the essential cause of the second transient and became operative as rapid evolution of steam and hydrogen from the disintegrating fuel rods drove the coolant from the fuel channels. It is not known whether this expulsion of coolant was so rapid that it would have been impossible for any mechanical safety control system to terminate the transient or whether the transient was slower but the failure to scram was due to the slow response time of

the safety system. The former seems more probable.

5. Quantitative data on the rate at which the control and safety absorbers were capable of injecting negative reactivity is required in order to understand the reactor behaviour after the manual shutdown button was pushed.
6. It is not clear why the four main circulating pumps still running from the external power supply allowed the increase in steam quality that initiated the first power transient, since the reactor was at only 200MW and six pumps would normally allow operation at power up to 3200MW.
7. The description of the Chernobyl accident provided by the USSR experts is plausible and in accord with the known characteristics of the reactor. However, quantitative understanding of events will require further data and extensive analysis.

APPENDIX 3

THE BIOLOGICAL EFFECTS OF IONISING RADIATION AND DEFINITION OF RADIATION UNITS

The Acute Effects of Large Doses of Radiation

Cells which are dividing are much more readily damaged or killed by ionising radiation than cells which are not. Hence the tissues of the body that contain cells which are often dividing, such as the lining of the gut, the bone marrow producing red and white blood cells, the testes, and the skin are more readily damaged than tissues such as muscles and nerves.

Whole body doses of 10 grays or more are generally lethal. At 3 to 5 grays damage is such that about 50 per cent of those irradiated will die within weeks or at most a few months, chiefly owing to bone marrow damage.

The foetus is likewise very sensitive to acute radiation doses. Developing and differentiating tissues can be damaged at doses of only a fraction of a gray: mental retardation is an observed effect of such doses received in the 8th to 15th weeks of foetal development.

The Long Term Effects of Ionising Radiation

Cancer induction

Although whole body doses of 5 grays are lethal for many people if received in a short period, the same dose spread over a few years may lead to lesser effects such as anaemia. Many early radiologists appear to have been exposed to lifetime doses of the order of ten grays or more without incurring chronic ill health. In the 1940s it was noticed, however, that their risk of dying of leukaemia was considerably higher than that of non-radiological medical specialists and further study showed that they were also more likely to die of solid cancer as well. The total number of excess deaths from solid cancers was about four times that from leukaemia.

Although it was already known that radiation could lead to cancer and leukaemia, this was the first group of persons whose histories demonstrated unequivocally that chronic exposure to gamma radiation increased risk. There were already two groups of workers (uranium miners and radium dial painters) in which chronic exposure to radioactive materials had led to a significantly increased risk, but because their exposures were to specific tissues and not the whole body, that experience could not be translated into risks for whole body exposure.

Following the nuclear bombing of Japanese cities in 1945, data were accumulated on the health and mortality of the survivors and related to the long-term risks of whole body exposure. By 1950 some 200,000 survivors had been registered for study. Of these, some 80,000 could reasonably be assigned specific doses. It is from this group that much of the quantitative evidence on the relationship between risk of leukaemia and other cancers as a function of dose (over the range 0.1 to 5 grays) has been obtained. The average dose for the Japanese group as a whole was about 0.25 grays.

Most of the excess leukaemias in the bomb survivors appeared in the period 5 to 15 years after exposure, whereas the excess solid cancers took longer to appear, and are still appearing. The ratio of excess solid cancer deaths to excess leukaemia deaths up to 1978 was about two. Presumably, as excess deaths from solid cancers are still appearing, this ratio will continue to increase and approach the factor of four found for the early radiologists.

Much information has also been obtained from study of persons irradiated for medical reasons. Most of these have only had partial body irradiation, but the observed cancer risks and doses serve to correlate or supplement the information from the bomb survivors.

Thyroid cancers observed in the medically irradiated groups, particularly amongst children irradiated about the head and neck for various reasons, provide the basis for concern with radio-

iodines released in reactor accidents, because iodine concentrates in the thyroid. Fortunately, unlike many cancers, thyroid cancers are treatable and the mortality rate is low.

Most radiation-induced thyroid cancers have followed irradiation with X-rays, with thyroid doses from 0.1 to 5 or more grays. Many people have received iodine-131 for diagnostic purposes, with thyroid doses of 0.5 to 1 gray. No excess cancers have been seen in such people, in contrast to excess cancers observed from X-rays at the same dose level. This observation suggests that irradiation by iodine-131 may be less effective, per unit dose, than X-rays in initiating these cancers. However, Marshall Islanders who were inadvertently exposed to fallout in a weapon test and received thyroid doses up to 10 grays or so and whole body doses of the order of 1 gray, have developed thyroid abnormalities and cancers, particularly those who were children at the time of exposure.

Where sufficient data are available, excess cancer risk has been examined as a function of dose. In some cases risk is proportional to dose (solid cancers in bomb survivors, thyroid cancers and X-rays, lung cancer in uranium miners). In other cases proportionality is not observed (leukaemia in bomb survivors, bone cancers in dial painters) and the data might be interpreted as showing little or no risk at low doses (less than 0.1 gray). However, the statistical uncertainties are such that this non-linearity cannot be substantiated.

To protect populations it is therefore assumed that risk is proportional to dose: risk at large doses is high, risk at low doses is low, but not zero. The risk factors used by the International Commission on Radiological Protection (ICRP) for assessing the impact of chronic low level exposures are:

For all cancers, whole body dose	1.25×10^{-2}	deaths per sievert
Leukaemia, bone marrow dose	0.25×10^{-2}	" " "
Thyroid cancer, thyroid dose	0.05×10^{-2}	" " "

Genetic effects

Experiments in the 1920s with fruit flies showed that irradiated parents produced more offspring with genetic mutations than unirradiated parents. Radiation induced mutations in fruit flies were extensively studied and formed the basis for concern for effects in irradiated human populations.

In the 1950s, long term experiments in mice began. From the results of these experiments, the ICRP and other bodies concluded that the risk of adverse genetic effects in the offspring of irradiated parents might be of the order of 10^{-2} cases per parental-sievert, with half the cases appearing in the first and second generations, the remainder over subsequent generations.

Studies of the children of survivors of the bombing of Japanese cities show that the risks are less than those derived from experiments with mice. The bomb survivor studies do not show a statistically significant increase in risk for the offspring of the irradiated parents, although for four indicators of genetic mutation studies, the slight differences in incidence in the children of irradiated and non-irradiated parents tended to support some effect of exposure. For the present, however, the ICRP risk factors above continue to be used for assessment of protection of the population.

Radiation Units

Units used in radiation protection can be put into two major categories:

- units specifying how radioactive something is, that is, how many nuclear transformations, producing ionising radiation, occur in a given time; and
- units specifying something about the consequences of the interactions of ionising radiations as they pass through matter.

The former are units of activity, the latter units of dose.

A present source of confusion is a fairly recent international decision to abandon a well-used system of units which had grown up in an ad hoc fashion over the past 90 years in favour of a system, for the same quantities, consistent with the Systeme International (S.I.) convention. It is therefore necessary to explain both the old units and the new.

Units of Activity

Old: The curie (Ci) is 3.7×10^{10} nuclear transformations per second.

New: The becquerel (Bq) is one nuclear transformation per second.
i.e. 1 curie is 3.7×10^{10} becquerels.

Because of the very wide range of magnitudes of interest, multiples and submultiples are in common use, e.g.

10^{-12} Ci	=	1 picocurie (pCi)	=	37 millibecquerels (mBq)
10^{-6} Ci	=	1 microcurie (Ci)	=	37 kilobecquerels (kBq)
10^{6} Ci	=	1 megacurie (MCi)	=	37 exabecquerels (EBq).

Concentrations of activity
in air are often quoted in Bq/m^3 or pCi/m^3
in water or milk in Bq/L or pCi/L
in soil, vegetation in Bq/kg or pCi/kg.

Units of Dose

Dose can be quoted either in physical terms or biological terms. The physical quantity of interest is the energy absorbed in a substance when it is exposed to ionising radiation. Energy absorbed per unit mass is known as absorbed dose.

The old unit is the rad (no abbreviation)
1 rad is equivalent to the energy absorption of 0.01 joules per kilogram of irradiated material.

The new unit is the gray (Gy)

1 gray is an energy absorption of 1 joule per kilogram of irradiated material.

Thus, 1 gray is equal to 100 rads.

Observation of the effects of ionising radiation on living cells shows that the magnitudes of specific biological effects per unit of absorbed dose vary with the nature of the radiation. In general, a unit absorbed dose of neutrons or alpha particles produces significantly more damage than a unit absorbed dose of beta particles or X- or gamma rays.

For radiation purposes therefore, the quantity dose equivalent is defined, to take account of this dependence. Dose equivalent is the product of absorbed dose and quality factor.

For occupational and environmental protection the quality factor for beta particles, X- and gamma rays is taken as unity and that for neutrons and alpha particles is taken as 20.

The old unit was the rem (no abbreviation):

1 rem = 1 rad from X, gamma and beta radiation,

1 rem = 0.05 rads from neutrons or alpha particles.

The new unit is the sievert (Sv):

1 sievert = 100 rem.

Often submultiples are used: millisieverts (mSv), millirem (mrem) etc.

A further modification takes account of the fact that the risk of cancer per unit dose varies from one tissue of the body to another. This modification consists of multiplying the dose equivalents received by different organs by appropriately chosen weighting factors and summing the resulting contributions to give a quantity called effective dose equivalent.

Effective dose equivalent is quoted in rems or sieverts. It is important therefore to look at the context of a statement to

determine whether doses are quoted as organ doses in terms of dose equivalent, or as effective dose equivalent.

Exposure to X- or Gamma Rays

There is an old unit of exposure to X- or gamma rays, the roentgen (R), which has no new counterpart. Many instruments are calibrated to read exposure rates in milli- or micro-roentgens per hour.

An exposure of 1 roentgen from penetrating X- or gamma rays gives a whole body absorbed dose of a little less than 1 rad. As a whole body absorbed dose of 1 rad is also a whole body dose equivalent of 1 rem, and as the weighting factors for dose equivalent are chosen such that a whole body dose equivalent of 1 rem is also an effective dose of 1 rem, an exposure to 1 roentgen of X- or gamma rays gives an effective dose, approximately, of 1 rem, or 0.01 sieverts.

Summary

Quantity	New Unit	Old Unit	Relationship
Activity	becquerel (Bq)	curie (Ci)	1 Ci = 3.7×10^{10} Bq
Absorbed dose	gray (Gy)	rad	1 rad = 0.01 Gy
Dose equivalent	sievert (Sv)	rem	1 rem = 0.01 Sv
Effective dose equivalent	sievert (Sv)	rem	1 rem = 0.01 Sv
Exposure (X or gamma rays)	none	roentgen (R)	1 roentgen gives approx. 0.01 Gy or 0.01 Sv

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GLOSSARY

Absorber — A material whose constituent atoms will combine with neutrons, forming a different atom and thus resulting in the removal of free neutrons.

Beta radiation — Free, energetic particles carrying either unit positive or unit negative electric charge and having low mass. Emitted during some transformations of nuclei of one species to those of another.

Cladding — A material, usually metal, totally enclosing nuclear fuel and serving to protect the fuel from chemical attack by the coolant and prevent the escape of **fission products.**

Containment — The final barrier preventing escape of fission products to the external environment and thus totally enclosing the volume in which **fission products** may be released. Total containment encloses the complete reactor.

Control rod — A solid, movable part of a reactor that absorbs neutrons and hence when inserted into the core makes the **multiplication constant** smaller, i.e. decreases **reactivity,** producing a decrease in power.

Doppler coefficient	The amount of **reactivity** change associated with a one degree Celsius change in the fuel temperature.
Emergency Core Cooling System	A separate cooling circuit designed to maintain core cooling in a shutdown reactor, following an accident that has disabled the normal cooling arrangements.
Fission products	The nuclei resulting from the division of a heavy nucleus such as uranium-235. Fission products may be radioactive or stable; in the former case they emit **beta** and **gamma radiation.**
Gamma radiation	Electromagnetic radiation emitted in the process of high energy nuclear transition.
Half-life	For a single radioactive decay process, the time required for the activity to decrease to half its value by that process.
Intervention level	The level of contamination at which authorities restrict social or economic activity, including for example the intake of some foodstuffs.
Ionising Radiation	Radiation which causes an atom, molecule or ion to gain or lose electrons.

Multiplication constant	The ratio of the number of neutrons being produced by fission to the number of neutrons disappearing by absorption at a given time. Usually denoted by k and if k = 1 the number of neutrons, and therefore power, is constant.
Plume	The trail of airborne contamination from a smokestack or fire.
Power excursion	A very rapid increase of reactor power above the normal operating level.
Reactivity (In a nuclear reactor)	A measure of whether the number of neutrons and thus number of fissions is increasing or decreasing with time and given by $\frac{k-1}{k}$. If k is greater than 1 the reactivity is positive and reactor power will increase; if k is less than one the reactivity is negative and power will decrease.
Stable iodine	A prophylactic dose of iodine, usually as potassium iodide, to protect the thyroid gland from uptake of radioiodine.
Transient	A sharp variation from normal condition of a reactor operating characteristic, e.g. power transient.
Trip	Operation of an engineered control to protect an operating system.

Void coefficient The change in **reactivity** with decrease in the material density of a reactor constituent. Usually applied to a liquid coolant which may change phase to a vapour of much lower density than the liquid. Void coefficients may be positive or negative but since increasing reactor power leads to decreasing density of liquid coolants,negative void coefficients are highly desirable.

Xenon poisoning Xenon will absorb neutrons very readily. Thus an increase in the number of xenon atoms will reduce the **multiplication constant** of the reactor and thus the **reactivity;** such an increase in xenon concentration is referred to as xenon poisoning.

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