The Chernobyl Accident – A Retrospective

"The past is a foreign country: they do things differently there." LP Hartley

"It is a riddle, wrapped in a mystery, inside an enigma." Winston Churchill

TOURISM BEHIND THE IRON CURTAIN, 1984

In April 1984, two years before the Chernobyl accident, Jane and I visited Beijing and Moscow on a package tour holiday. This was an unusual thing to do at that time; the Cold War with the Soviet Union was still going very strongly, and I worked for the UK Atomic Energy Authority! President Reagan was in the process of bankrupting the Soviets by out-spending them in an arms race. Meanwhile, China was still poor and recovering from the Cultural Revolution.

The Head of Security at Dounreay had to brief me before I left. "Don't talk to strangers", he said, like I was a child about to go to school unescorted for the first time.

He then had to de-brief me when I returned. "Did any strangers approach you?" he asked, so I told him about our bizarre holiday while he earnestly took notes.

Beijing was mostly friendly and keen to impress, but the Cultural Revolution was far too recent for people to have got over it. Conditions for the Chinese were still fairly primitive – at that time, apart from the occasional official car, the roads were empty except for buses and bicycles. There were no high-rise buildings. There were no advertisement billboards.

In Beijing, our small party of fifteen was followed everywhere by a comic-book secret policeman who wore sunglasses, a hat, and an overcoat with a turned-up collar. I tried to speak to him more than once but he looked away – he seemed to think he was invisible.

Our Chinese tour guide, Miss Chang, was absolutely delightful, however. She was polite and cheerful throughout, although she would not come into our hotel to join us for a drink - she seemed concerned about being seen to fraternise with decadent westerners.

The only time Miss Chang became anxious and assertive was when we went to see Chairman Mao, who frankly looked a bit green in a glass case inside his mausoleum on Tiananmen Square. He was the first dead body I had ever seen, kept in a room that was maintained just above freezing point, with armed guards wearing fur coats. Before we went in, Miss Chang shouted at us that we must not laugh or smile. We must not jostle or hurry. We must not carry any bags. Definitely, definitely, there was no photography allowed. We must behave respectfully. It was as if we were a party of rowdy schoolchildren visiting a cathedral.

On the way back from Beijing, our strange party of fifteen assorted people – what sort of person took a holiday behind the Iron Curtain in 1984? – stayed for two days in Moscow.

Jane and I are children of the Cold War, both born in 1955. Some of my earliest memories relate to the Soviet Union and the Cold War: the Berlin Wall, Yuri Gagarin. During the Cuban Missile Crisis in 1962 it seemed the world was about to end. I remember the fear of my parents and grandparents, two generations that had known world war. Communism was considered a threat by most people apart from the few innocents and ideologues who really seemed to believe, despite the evidence, that there actually was a workers' paradise on the other side of the Iron Curtain.

In April 1984, seventy-two year old Konstantin Chernenko was briefly the leader of the increasingly gerontocratic Soviet Union. Chernenko was dying of emphysema even before he had become General Secretary, two months before our visit. He was a metaphor for the Soviet Union itself – frail, ageing, devoid of energy, unable to recognise the need for change. He died in office after only thirteen months. Much of that time he was wheelchair-bound, or in hospital, with Mikhail Gorbachev deputising but not yet in power.

Moscow had opened up a little to Westerners since the Moscow Olympics in 1980. Our visit to Moscow in April 1984 was brief but it was memorable, albeit mostly for strange reasons. The memories are still like snapshots in my head, quite vivid after all the intervening years.

Fig 1: Moscow April 1984 – The Monument to the Conquerors of Space, and the Hotel Cosmos

Our room on the sixteenth floor of the Hotel Cosmos had an enormous television that didn't work. I left it switched on for ten minutes but nothing happened. Later, another member of our party told me if you left it switched on for fifteen minutes, the vacuum tubes eventually got hot enough and it suddenly sprang to life.

The big department store, GUM, on Red Square – their showplace store – seemed almost empty of any worthwhile products, yet the tourist 'Berioska' shops (which only accepted hard currencies such as dollars and pounds, so normal Russians could not shop in them) had a good range of consumer luxury goods.

All shops were grossly over-staffed: One person would help with selection of the required product, another would wrap it, and a third would take the money.

Western clothes were considered cool. Teenagers in the streets, when they thought no-one was looking, offered in poor English to buy my clothes from me. However, they could only offer to pay in roubles, which were useless to me since it was impossible to buy anything with them.

Our tour guide in Moscow was called Rosa, from Intourist, the Soviet travel agency. In the bus we got a running commentary delivered in a loud, intimidating monotone which also seemed strangely bored and indifferent: "On your left.......on your right......great Soviet technology.......Great Patriotic War......." The Soviet efforts at propaganda were, frankly, cack-handed and quite unconvincing. It was as if we were expected to be completely overawed by everything when actually it all seemed, well, a bit shabby. Their arrogance seemed misplaced.

Stalin's purges, the slaughter of the Great Patriotic War, the Gulag, and the KGB and finally the mindless bureaucracy of the State seemed to have removed most of their humanity. It was as if the entire population of the country had been schooled into not thinking for themselves. There was a widespread cynical indifference. It was the Orwellian dystopia made real. The only spark of real humanity was the teenagers wanting to buy my clothes.

It is difficult to explain the Cold War to my children's generation. It just sounds so crazy. It seemed like half the world was imprisoned.

GENERIC TECHNICAL SAFETY REQUIREMENTS FOR ALL NUCLEAR REACTORS

The generic technical requirements for any safe design of nuclear reactor can be stated quite concisely:

The *first requirement* for any nuclear power reactor is that the reactor should behave predictably during operation. The reactor output power should not change unless the operators want it to change, and when the operators do want the power to change, it should do so in a smooth, predictable manner. This is discussed further in the section below.

The *second requirement* is that the reactor must have reliable and quick shutdown systems that will operate under all foreseeable design-basis conditions.

Operating nuclear reactors have within their fuel pins a large amount of highly radioactive and radiotoxic fission products, some of which are volatile at low temperatures. These include in particular iodine-131, and caesium-137. There are also non-volatile but radiotoxic alpha-emitters such as plutonium-239. Hence the *third requirement* is that there must be robust containment of all the fission products under all foreseeable design-basis conditions.

Because of short-lived radioactive isotopes, a recently-shutdown reactor continues to generate a lot of 'decay heat', the heat produced by the decay of the fission products. The amount of decay heat falls from about ten per cent of the pre-shutdown power immediately after shutdown, to 0.1 per cent of the pre-shutdown power after about 50 days. The value after 50 days may not sound much, but it still corresponds to about 3 megawatts of heat for a typical large power reactor. Hence the *fourth requirement* is that reactors must have reliable means of removing the decay heat from recently-shutdown reactors under all foreseeable design-basis conditions.

Predictable behaviour, reliable shutdown, robust containment and reliable decay heat removal: these four requirements are unambiguously applicable to all reactor designs. All four are necessary for a safe design.

STABILITY AND PREDICTABILITY OF NUCLEAR REACTOR BEHAVIOUR

Nuclear engineers talk about *reactivity*, which means, in essence, the instantaneous rate at which the reactor power is increasing (or decreasing). For a reactor to behave predictably and with stability there must be fast-acting negative feedback processes which cause the reactivity to fall if the fuel becomes hotter. This is called *negative thermal feedback*.

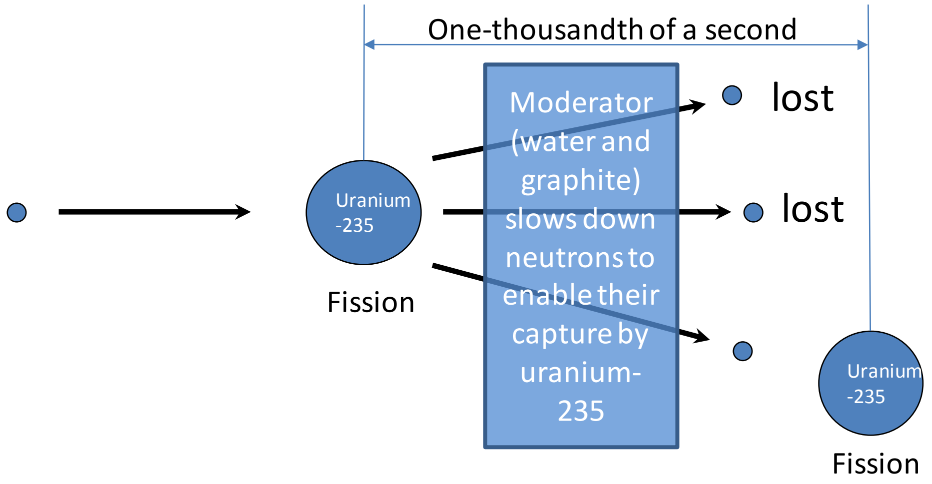
There are a number of processes which affect thermal feedback, the most important of which are the *Doppler* coefficient and the *steam voidage* coefficient.

The Doppler Effect[1] is a key process in reactor stability, which takes place at the level of the atomic nucleus.

Nuclear reactor fuel is normally only 2 to 3 per cent fissile (heat-producing) uranium-235. (We say it is "2 to 3 per cent enriched". Such changes to isotopic content are carried out in large energy-intensive enrichment plants.) The other 97 to 98 per cent is uranium-238, which is non-fissile – that is, it doesn't fission easily to produce heat. Instead, uranium-238 captures neutrons and becomes uranium-239, which with a half-life of just over two days becomes plutonium-239 (which is again fissile). The key point is that the immediate effect of uranium-238 is to mop up neutrons within the reactor core without producing more heat.

The Doppler Effect in nuclear reactors is this: As the reactor fuel becomes hotter, the uranium-238 absorbs *more* neutrons. This means that, if the reactor fuel becomes hotter, the reactivity reduces. Also, because uranium-235 (which generates the heat of fission) and uranium-238 are mixed at the atomic level, the Doppler Effect is very fast-acting. In essence, the Doppler Effect is the reason we have nuclear reactors – it is a fundamental physical process that makes them stable.

[1] The 'Doppler Effect' in nuclear reactors is different from the normal sense of this term, where it refers to the change in tone of a rapidly-moving object as it passes by the listener, such as a car or a train. In nuclear reactors, the Doppler Effect is due to thermal vibration of uranium-238 nuclei making them appear bigger to passing neutrons. Hence neutrons are more readily captured when the temperature is higher.



Reactivity is a measure of the instantaneous rate at which the reactor power is increasing (or decreasing), which is proportional to 'how many more (or less) neutrons there are in any generation than there were in the previous generation'.

The ***'lost'*** neutrons are absorbed by non-fissionable materials. These include:

- Shielding,
- Structural steel,
- Moderator,
- Uranium-238 – this is most important because of the ***Doppler Effect –*** higher fuel temperature means that uranium-238 absorbs more neutrons

Fig 2 Neutrons and fission in a nuclear reactor

The second fundamental physical process that affects the behaviour of water-cooled nuclear reactors is steam voidage. The water in nuclear reactors carries out two functions: First it acts as a coolant, and second, it acts as a neutron moderator – that is, it slows down the neutrons to enable their capture by uranium-235 nuclei. Water boils inside the reactor of the RBMK, so that means that there is an 'absence of water' where steam forms, since steam is much less dense than liquid water. Where steam bubbles form, the neutrons may not (on average) be slowed down so much – and faster neutrons are less likely to cause fission. Also, where steam bubbles form, this means (on average) the neutrons will travel further – so more neutrons may escape the reactor into the shielding and be 'lost'. These effects due to steam voidage are beneficial – they lead to a reduction in reactivity as more steam bubbles form because of rising reactor temperature. This is called a *negative steam voidage coefficient*.

However, steam voidage can also have another effect, because water also absorbs some neutrons. Hence, if the neutrons are already fully moderated (for example, by the graphite in the RBMK reactor core) then increased steam voidage will just mean that fewer neutrons are absorbed in the water; this means that increased steam voidage can lead to an increase in reactivity – exactly the effect that we do not want. This is called a *positive steam voidage coefficient*.

NUCLEAR TECHNOLOGY IN THE SOVIET UNION

Right up until the time of the Chernobyl accident, almost nothing was known about Soviet nuclear activities. Their nuclear weapons programme was of course extremely secret, but even their nuclear electricity generation programme was veiled in secrecy. Visitors to the Soviet Union were not allowed to travel freely; generally, they were never allowed to go anywhere except a few major cities like Moscow.

In the early 1970's the Soviet Union embarked on an ambitious nuclear power programme aimed at commissioning some 15000 megawatts of generating capacity by the end of 1980. There were two main designs employed, the VVER and the RBMK. The VVER was a Russian version of the western Pressurised Water Reactor (PWR); several were built in the Soviet Union, and the design was also built in other Eastern European countries. The other design, the RBMK, was only ever built within the Soviet Union, where it provided the larger share of the nuclear programme. The RBMK[2] design was unique to the Soviet Union; there was nothing like it in the West. It combined vertical water-cooled fuel channels with graphite moderator. The water boiled in the fuel channels and then was delivered, via steam separator drums, direct to steam turbines. The fuel channels could be refuelled on-load. It can therefore be thought of as a bit like a combination of the UK's Advanced Gas-cooled Reactors (AGRs) and American Boiling Water Reactors (BWRs).

One reason this design was adopted was due to reasons of transport. The Soviet Union was a vast country, and their preference was for a design where the components could be readily transported by rail. The RBMK did not have a massive reactor pressure vessel like the BWR or PWR designs. Hence, the RBMK could be built wherever there was a railway line.

Almost all that was known outside the Soviet Union about the RBMK prior to the accident was from a visit by British engineers to an RBMK plant in Leningrad (now St Petersburg) in 1975. At the time, the UK was considering building a design called the Steam Generating Heavy Water Reactor (SGHWR) which was vaguely similar to the RBMK except it used heavy water as a moderator instead of graphite. Hence a knowledge exchange visit was arranged, and a report with the findings of the UK team was issued[3]. The report was highly technical and no-one in the West was really too concerned about the safety of the RBMK design at that time – the report was a comparison between the SGHWR and the RBMK - but some of the information buried in the details was prescient:

- The reactivity worth of the control rods – that is, how much neutron absorption capacity there was in the control rods – was inadequate to meet all possible shutdown requirements. It was possible to conceive of situations where the control rods might not be able to shut down the reactor.
- The reactor had a positive steam void coefficient at low powers.
- The graphite moderator was blanketed with nitrogen in normal operation, because it operated at temperatures in excess of 700 degrees Centigrade. At this temperature, when exposed to air, the graphite ignites spontaneously. The report said that graphite operating temperatures were "unacceptable".

[2]Reaktor Bolshoy Moshchnosti Kanalniy (High Power Channel-type Reactor)
[3] The Russian Graphite Moderated Channel Tube Reactor, NPC(R) 1275, Nuclear Power Company Ltd, March 1976. This report does not appear to be available on-line.

- The containment structure was less robust than would normally be considered adequate in Western designs. Pressure tube failure could be disruptive

Why did the RBMK design have a positive void coefficient? This had been a design decision. The RBMK design deliberately used too much graphite – the UK engineers reported that moderation was "beyond the optimum in terms of fuel enrichment and seems to give a positive void coefficient". The explanation for this decision would have been unseen to the UK team at the time, but it appears the Soviet Union was short of uranium enrichment capacity. An over-moderated design enabled the reactor to use only 2 per cent enriched uranium (that is, 2 per cent uranium-235) instead of a more typical 2.5 to 3 per cent. The penalty of over-moderating with graphite is that there was a positive void coefficient at low power. Under particular circumstances, the reactor could be unstable and suffer runaway power increases.

In addition to the weaknesses in the RBMK design described above, the detailed implementation of the design also allowed greater freedom of action for the operators than would be normal in a reactor design elsewhere. For example, the operators could override reactor trip systems at the flick of a switch; in 'normal' designs, key interlock systems would have prevented this. Also it was essential for the safe operation of the plant that the control rods should never be withdrawn beyond the point at which the control rod 'reactivity margin' became dangerously low, yet this vital aspect was left entirely to the operators, with no automatic trip system.

Also, reactor emergency shutdowns were normally carried out by motoring the control rods into the core, and not (as is common in some other designs) by disconnecting electromagnetic clutches and allowing them to fall quickly into the reactor core under gravity. Because the rods were driven-in instead of being allowed to drop, shutdown could take 20 seconds to occur.

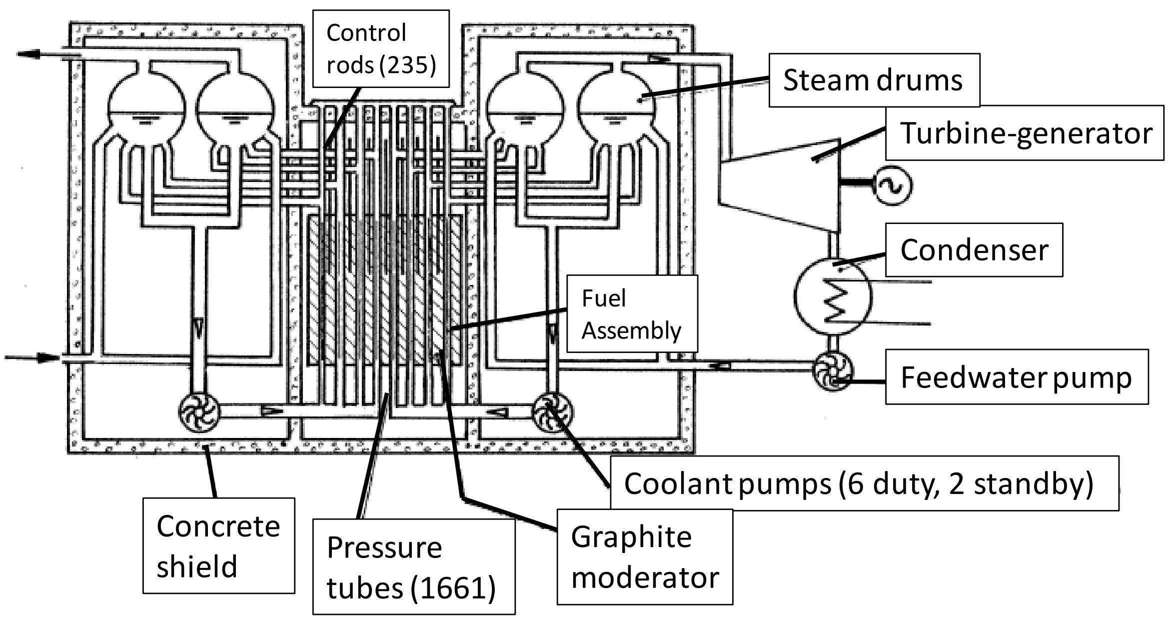


Fig 3 A simplified schematic of an RBMK power station

THE CHERNOBYL ACCIDENT

At the time of the accident, Mikhail Gorbachev was General Secretary of the Communist Party of the Soviet Union. In the West, he seemed like a breath of fresh air: he was relatively young, pragmatic and seemingly less restricted by Communist dogma. He wanted to improve the Soviet centrally-planned economy which was struggling under its inflexible bureaucracy, political dogma, *apparatchiks*, and over-manning. He sacked Andrei Gromyko, the long-standing Minister of Foreign Affairs, in an effort to control old-style thinking in the Politburo. He forced up the price of alcohol to try to reduce alcoholism and its effects on the country.

Just prior to the Chernobyl accident, at the Communist Party Congress in February and March 1986, he announced plans for *perestroika* (restructuring), and he subsequently used the Chernobyl accident as one of his first efforts at *glasnost* (openness). *Perestroika* and *glasnost* were to be Gorbachev's two watchwords in his attempts to salvage the sclerotic Soviet economy but, ultimately, it was too little, too late - for both the Soviet economy and the RBMK reactor design.

The accident at Chernobyl happened shortly after midnight on Saturday 26th April 1986, although no announcement was made by the secretive Soviet authorities. The following Monday morning, airborne radioactivity was detected at a nuclear power station in Sweden, but the Soviet authorities would not initially admit anything had happened. At 9pm on Monday 28th, after the Swedish authorities had threatened to notify the International Atomic Energy Agency based in Vienna, the Soviet news agency TASS released a brief message:

> "An accident has occurred at Chernobyl nuclear power station. One of the atomic reactors has been damaged. Measures are being taken to eliminate the consequences of the accident. Aid is being given to the victims. A government commission has been set up."

For the next few weeks the world watched as, gradually, more details came out of the Soviet Union about the accident. Television cameras on board Soviet military helicopters looked straight down into the core of reactor 4, where the burning graphite could be seen. Other helicopters dropped sand and boron into the reactor. The world saw Soviet soldiers receiving large radiation exposures as they tried to mitigate the consequences.

All of this was previously almost unimaginable for two completely different reasons. First, the rest of the world was actually seeing events as they occurred inside the Soviet Union in a way that had never happened throughout its history. The Soviet Union had always been pathologically secretive. Churchill's description of the Soviet Union in 1939 as "a riddle, wrapped in a mystery, inside an enigma" had remained true, yet now, suddenly and for the very first time, we seemed to be seeing through the layers.

The second reason that this seemed unimaginable was that, for years, the nuclear industry around the world had said that such an accident was extremely unlikely. Nuclear reactors were stable, and there were multiple layers of defences. No-one knew for certain the radiological consequences of a severe reactor accident, but hypothetical studies had been carried out. Few in the nuclear industry expected to see an 'experiment' done for real in which the consequences of a reactor accident would be measurable.

During the week beginning 25th August 1986, Soviet scientists presented information about the accident, in an unprecedentedly candid way, at a Post-Accident Review Meeting held at the International Atomic Energy Agency in Vienna. Following that IAEA meeting, in October 1986 a nuclear industry seminar was held in London where explanations were presented of what had happened, and preliminary estimates of the radiological consequences were given[4].

Ironically, the accident had occurred during a test to check whether the emergency core cooling systems were adequate. The test was to be performed during a planned shutdown for routine maintenance. The main events were as follows:

1. Thermal power was to be reduced in stages from 3200 megawatts to 700 megawatts. Operator error caused the power to undershoot to 30 MW, and the consequent increase in xenon poisoning[5] meant that the operators could only manage to raise the power back to 200 MW. This power level was lower than stipulated in the test instructions. The operators should have abandoned the test at this point.

2. **In** violation of the test procedure, the operators started up the standby coolant pumps. This meant that core power was only 7 per cent normal but coolant flow was 120 per cent normal, which made the whole core virtually isothermal.

3. Difficulties in steam drum water level control at this juncture led the operators to override the reactor trip signals generated by low drum level. They then topped up the drum water level under manual control, with relatively cold feedwater. This caused a fall in reactor temperature and therefore a reduction in the amount of steam voidage inside the reactor core; hence (via the positive steam voidage coefficient) the control rods had to be withdrawn yet further to maintain reactor power level at 200 megawatts.

4. The operators noticed that the "control rod reactivity margin" was too low – the control rods had been raised so far that they would be unable to have any significant and immediate effect to reduce reactor power when required. Indeed, the reactivity margin was at a level where operating rules stipulated that the reactor should have been shut down. No such action was taken.

5. The test was to be initiated by tripping the turbine. Normally, this would have tripped the reactor also. However, it would appear that the operators wanted to reserve their options in case the test of the emergency core cooling system was unsatisfactory; hence they overrode the reactor trip. This meant (they thought) that they would be able to repeat the test if necessary.

6. At 0123.10 hours on the 26th April 1986, the turbine was tripped. The operators had contrived, unwittingly, to put an already unstable reactor design into a highly dangerous condition. The reactor was operating at fairly low power (200 megawatts), and was almost isothermal due to the high coolant flow-rate. By tripping the turbine the only significant heat sink had been removed. **In**

[4] Chernobyl, A Technical Appraisal: Proceedings of the seminar organised by the British Nuclear Energy Society held in London on 3 October 1986, BNES, 1987.

[5] 'Xenon poisoning' is a transient behaviour of nuclear reactors during power reductions. Xenon-135 is a fission product that absorbs neutrons, and which decays with a half-life of about 9 hours. When power is reduced, xenon-135 levels increase, which makes it difficult to increase power until the xenon-135 has decayed.

addition, the control rods were too far out of the core to have any significant immediate effect in the event of a reactor trip.

7. The water coolant temperature now began to rise steadily (because of the heat being generated in the reactor) until it approached the saturation temperature, at which point bulk boiling occurs. Because of the virtually isothermal state of the reactor, the value of the positive void coefficient had been maximized, i.e. bulk boiling would begin throughout the core more-or-less simultaneously.

8. At 0123.40 hours, a rise in power was noted and a reactor trip was initiated manually, by starting to drive the control rods into the core. Because the rods were so far out of the core, however, they had no significant immediate effect on reactivity, which continued to rise.

9. Coolant bulk boiling led to a rapid rise in power, which Doppler Effect could not counteract.

10. The power rose to 530 megawatts at 0123.43 hours, and thereafter extremely rapidly, doubling each fraction of a second; the reactor went ‘prompt critical’, and the fuel (uranium oxide ceramic) shattered due to the thermal shock of the sudden power rise; the fuel cladding melted and the white hot fuel fragments came into contact with the cooling water, causing a steam explosion at 01.23.48 h. This was followed a few seconds later by a hydrogen explosion; the hydrogen was generated by zirconium-water and graphite-water reactions. (There was no nuclear explosion.) The explosions ruptured the containment.

11. The hot graphite moderator caught fire upon exposure to air.

12. Truly heroic efforts by firemen, helicopter pilots and engineers led to the fire being extinguished, and the radioactive release being stopped by 5th May, ten days after the accident began. In the interim, it is estimated that 20 per cent of the iodine inventory and 12 per cent of the caesium inventory was released to the atmosphere, together with practically all of the noble gas fission products.

The Chernobyl accident was about as bad a nuclear reactor accident as it is possible to imagine. The reactor core burned without any containment for ten days. It is difficult to postulate any accident which could lead to a greater release of radioactivity to the environment. A total of 31 people died either at the time of the accident or within a few weeks from radiation sickness. The nearby town of Pripyat, with a population of 49000, was evacuated within a few days and an exclusion zone of 30 kilometer radius around the Chernobyl plant was declared.

The RBMK design violated at least three of the four generic technical safety requirements described previously: The reactor power was unstable, the reactor shutdown systems were slow and inadequate, and the containment systems were insufficiently robust.

Also, the operators showed complete disregard for their operating instructions: the initial conditions for the test were not as stipulated, protection systems were overridden, and the control rods were raised too high to retain control of the reactor.

By the time the operators realised that the reactor power was increasing uncontrollably, it was too late.

AFTERMATH – RADIOLOGICAL AND HEALTH CONSEQUENCES

In the days and weeks following the accident, radiation spread across Western Europe, with some unlikely places being worst affected. The contamination happened in discrete locations, according to the vagaries of the weather, with other nearby places sometimes being unaffected. Inside the Soviet Union, there was significant contamination within a thirty mile radius of Chernobyl, straddling the Ukraine/Belarus boundary. There was also significant contamination one hundred miles to the north-east, on the Belarus/Russia boundary. Some three hundred miles further east, there was significant contamination in Russia between the towns of Bryansk and Tula[6].

Further afield, wherever rain fell it caused local contamination. Finland, Sweden, Norway and Austria all acquired large areas of land contaminated with significant amounts of caesium-137. Some hill farms in Scotland, Wales and Cumbria also became contaminated. Controls were placed across the European Union on the sale of meat with contamination levels more than 1000 Becquerels per kilogram. This figure was of course arbitrary, a sop to public opinion, but politics demanded that action had to be taken and some limit had to be imposed.

Few technical subjects are so prone to misrepresentation, distortion or exaggeration as the health effects of low-level nuclear radiation. Journalists can always find a knowledgeable-sounding, self-appointed expert who is prepared to make unreasonable assertions about the consequences of nuclear accidents. Also, in the months following the accident there were new daily revelations from inside the Soviet Union, which had hitherto been mostly *terra incognita*. The combined effect was to put the news media into a feeding frenzy that was probably not matched until the Macondo/*Deepwater Horizon* accident in 2010.

My wife Jane was two months pregnant at the time of the accident, so we had a very personal interest in the levels of radiation. I researched the topic and concluded the risk in the UK was miniscule. (I even published my findings[7]. I am glad to say Jennifer is now a very healthy postgraduate student at the University of London.) However, the subject of health effects of radiation was controversial, and remains so; hence, I will tread carefully.

The principal isotopes of concern from the accident were iodine-131 and caesium-137. Iodine-131 is of concern because it concentrates in the thyroid gland and can lead to thyroid cancer, although this is treatable with survivability of about 95 per cent. Iodine-131 has a short half-life of about 8 days, so after two months it has effectively disappeared. Thyroid cancers may then develop within a few years of the exposure. In Pripyat and some other areas, people were given potassium iodate tablets to swamp their thyroids with non-radioactive iodine, thereby preventing uptake of iodine-131.

Caesium-137 has a half-life of about 30 years, so caesium-137 from Chernobyl will remain detectable for more than two hundred years[8]. It behaves in the human body like common salt, so it spreads evenly throughout the body, without concentrating in any particular organ. Hence its biological effects are similar to those of external gamma or X radiation.

[6] At the time of the accident, Belarus, Ukraine and Russia were all part of the Soviet Union.
[7] *Sample calculations of risk from Chernobyl fall-out in the UK*, The Nuclear Engineer, vol 27, no 5, 1986
[8] An interval of eight half-lives (240 years) corresponds to a reduction factor of 2 to the power 8, which equals 1024.

The difficulty in discussions about low-level radiation is that a lot of people die from cancer anyway – typically some 30 per cent of the population, although the exact figure depends on regional variations in life expectancy (if you die young, you are less likely to die of cancer), together with diet, smoking and alcohol consumption. Also, we all receive doses of natural background radiation – typically one or two milliSieverts (mSv) per year. Hence it becomes problematic to separate the 'noise' (normal background levels of cancer) from the 'signal' (artificial-radiation-caused cancer).

Lots of people have axes to grind on this topic, so I am going to quote directly from reports about health effects produced by bodies funded by the United Nations – one from the International Atomic Energy Agency (IAEA), and one from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)[9][10]. I think these reports are neutral, unbiased and honest.

The socio-economic impact of Chernobyl has been enormous, but it was made worse by the collapse of the Soviet Union in 1991. It becomes difficult to separate these two issues, as the 2005 IAEA report made clear. It painted a disturbing and depressing picture of the overall effects:

> "(Radiation) Doses that could only be estimated some time after they occurred by careful evaluation of all available information were 17 mSv on average to Ukrainian evacuees, with doses to individuals ranging from 0.1 to 380 mSv. The average dose to Belarusian evacuees was 31 mSv, with the highest average dose in two villages being about 300 mSv......
>
> "The number of deaths attributable to the Chernobyl accident has been of paramount interest to the general public, scientists, the mass media, and politicians. Claims have been made that tens or even hundreds of thousands of persons have died as a result of the accident. These claims are exaggerated: the total number of people that could have died or could die in the future due to Chernobyl originated exposure over the lifetime of emergency workers and residents of most contaminated areas is estimated to be around 4 000. This total includes some 50 emergency workers who died of acute radiation syndrome (ARS) in 1986 and other causes in later years; 9 children who died of thyroid cancer; and an estimated 3 940 people that could die from cancer contracted as a result of radiation exposure.......
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> "Because of the relatively low dose levels to which the population of the Chernobyl-affected regions was exposed, there is no evidence nor any likelihood of observing decreased fertility among males or females in the general population as a direct result of radiation exposure. These doses are also unlikely to have any effect on the number of stillbirths, adverse pregnancy outcomes, delivery complications or the overall health of children......
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> "The Chernobyl nuclear accident, and government policies adopted to cope with its consequences, imposed huge costs on the Soviet Union and three successor countries, Belarus, the Russian Federation and the Ukraine. These costs are impossible to calculate precisely, owing to the non-market conditions prevailing at the time of the disaster and the high inflation and volatile exchange rates of the transition period that followed the break-up of the Soviet Union in 1991. However, the magnitude of the impact is clear from a variety of

[9] Chernobyl's Legacy: Health, Environmental and Socio-economic Impacts, IAEA, Vienna, 2005
[10] Sources and Effects of Ionizing Radiation, Volume II, Annex D, Health effects due to radiation from the Chernobyl accident, UNSCEAR, New York, 2008

> government estimates from the 1990s, which put the cost of the accident, over two decades, at hundreds of billions of dollars...........
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> “Since the Chernobyl accident, some 350 000 people have been relocated away from the most severely contaminated areas. 116 000 of them were evacuated immediately after the accident, whereas a larger number were resettled several years later, when the benefits of relocation were less evident..........
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> “Life expectancy has declined precipitously, particularly for men, and in the Russian Federation stood at an average of 65 in 2003 (just 59 years for men). The main causes of death in the Chernobyl-affected region are the same as those nationwide — cardiovascular diseases, injuries and poisonings — rather than any radiation-related illnesses. The most pressing health concerns for the affected areas thus lie in poor diet and lifestyle factors such as alcohol and tobacco use, as well as poverty and limited access to primary health care.
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> “Added to exaggerated or misplaced health fears, a sense of victimization and dependency created by government social protection policies is widespread in the affected areas. The extensive system of Chernobyl-related benefits ....has created expectations of long term direct financial support and entitlement to privileges, and has undermined the capacity of the individuals and communities concerned to tackle their own economic and social problems. The dependency culture that has developed over the past two decades is a major barrier to the region’s recovery.”(IAEA)

The 2008 UNSCEAR report, which is more tightly focussed on the direct health impact of the accident, declines even to offer an estimate of the number of radiation-related deaths attributed to the accident.

> “.....there is a limit to the epidemiological knowledge that can be used to attribute conclusively an increased incidence to radiation exposure. Therefore, any radiation risk projections in the low dose area should be considered as extremely uncertain, especially when the projection of numbers of cancer deaths is based on trivial individual exposures to large populations experienced over many years.” (UNSCEAR)

In other words: We don’t know how many people have died or will die because of low-level radiation from the accident. Furthermore, we can’t ever know because the data we want to measure are completely overwhelmed by other factors. The answer could be anywhere between zero and 4000, over many decades, spread across the entire population of Europe, which was 740 million in 2011. *We don’t know and we never will.*

CHERNOBYL: INDIRECT CAUSES OF THE ACCIDENT

The accident at Chernobyl was directly attributable to an unsafe design and a complete disregard of operating procedures. Indirectly, however, the accident can be attributed to other factors. The design was compromised by political expediency – shortage of uranium enrichment capacity led to the design being ‘over-moderated’, which led to the positive steam void coefficient. The whole RBMK programme, which was considered in the 1976 UK report to have a variety of serious shortcomings, was at least partially constrained by the need to transport all parts through railway tunnels. This need not necessarily have compromised safety but, in the absence of any free and open discussion about nuclear safety in the Soviet Union, it apparently did so.

The Soviet Union undoubtedly produced some very good science. Between 1958 and 2003, ten Nobel Prizes for Physics were awarded for work done in the Soviet Union prior to its collapse. However, the translation from science to engineering did not have a good record.

During the period between 1969 and 1973, the Soviet Union had an especially bad time regarding the safety of its advanced technologies:

> The Tupolev 144 supersonic airliner, dubbed ‘Concordski’, broke up in mid-air in front of the world’s TV cameras at the Paris Air Show on 3rd June 1973. Six people on board and eight people on the ground were killed.
>
> The giant N-1 moon rocket, the Soviet equivalent of the American Saturn 5, had four unmanned development launches between February 1969 and November 1972. In each case the rocket launcher blew up shortly after lift-off. The programme was cancelled in 1974, although the accidents and indeed the whole programme remained secret for decades.
>
> On 30th June 1971, the crew of Soyuz 11 was returning from a 22-day, first-ever trip to a manned space station, Salyut 1. Their re-entry capsule depressurised during descent and all three crew asphyxiated.

Throughout the Cold War, the Soviet Union generally tried at least to match US developments in the nuclear arms race – missiles, warheads and nuclear submarines. However, the Soviet record of nuclear submarine safety was not impressive:

> An explosion on board the K-19 submarine 4th July 1961 caused 8 deaths.
>
> On 24th May 1968 a reactor accident on board the submarine K-27 caused 9 fatalities.
>
> On 23rd June 1983, the K-429 sank in shallow water, killing 16.
>
> A reactor accident on board the K-431 on 10th August 1985 caused 10 fatalities.
>
> The K-219 had an explosion and fire in a missile tube on 3rd October 1986, causing 4 fatalities and sinking shortly after.
>
> The K-278 suffered a fire and sank on 7th April 1989. 42 died.

Finally, it is worth recalling that the Soviet Union had previously had a nuclear accident that was even worse than Chernobyl – the 1957 Kyshtym accident. This accident was not publicly known in the West until 1976, when the dissident Soviet scientist Zhores Medvedev published some initial details which were later confirmed as more information became available. The accident occurred at a plant storing liquid radioactive waste in a fuel reprocessing plant for the Soviet nuclear weapons programme. The cooling system of a storage tank, containing some 70 tonnes of liquid waste, had failed and gone unrepaired; the liquid gradually evaporated until only a solid residue was left. The residue was highly radioactive and it also contained explosive ammonium nitrate. A massive chemical explosion blew large quantities of mostly long-lived radioactivity into the air, which remains detectable to the present day and is known as the East Ural Radioactive Trace. It spreads for some 300 kilometres.

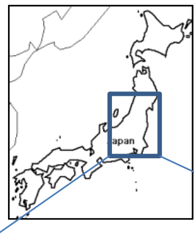
It seems reasonable to conclude that the Soviets were trying to do too many high-technology military and prestige projects, with too few resources, and with too many politically-driven targets. There was also a cavalier attitude to safety and too little (if any) independent safety regulation. In particular, the very concept of ‘independent safety regulation’ will always be especially difficult in top-down, centrally-planned economies. It is always the role of the independent safety regulator to ‘speak truth to power’, which can be difficult in dictatorships.

RADIOLOGICAL AND HEALTH CONSEQUENCES – CHERNOBYL vs. FUKUSHIMA

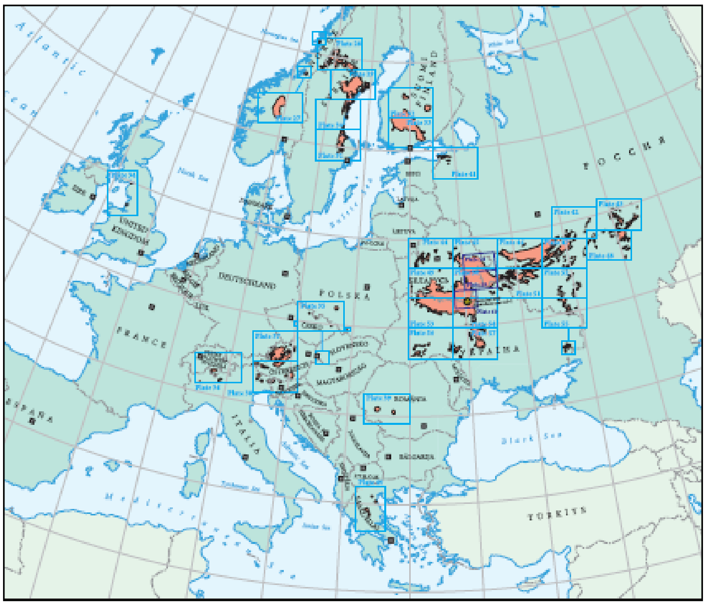
The radiological consequences from the Fukushima accidents were also serious, but a lot of the radioactivity drifted out to sea. The area of seriously contaminated land was much less than for Chernobyl - probably less than one-tenth.

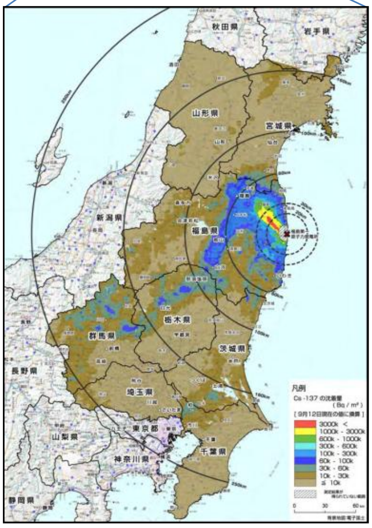
About half a million people living within 20 to 30 kilometres of Fukushima were evacuated. These were people who had survived the trauma of the earthquake and tsunami and were now required to leave their homes. The psychological impact of the accident is commonly recognised as creating the most serious health consequences. The Japanese government has announced its intention to try to decontaminate some of the worst affected areas, but this is likely to take many years. A further major effort for temporary re-housing has been necessary in addition to the effort already necessary for people made homeless by the earthquake and tsunami.

Long-term non-psychological health consequences arising from Fukushima are subject to the same uncertainties as the assessments from the Chernobyl accident. However, it seems likely that long-term additional cancer mortality from the accident will not be discernible against ‘normal’ cancer mortality, with preliminary estimates between zero and a hundred expected extra cancer deaths.



Japan to approximately the same scale as Europe.





12-7 Maps showing caesium-137 contamination from Chernobyl and Fukushima: The bright blue areas in the Japanese map (60-100 kBq/m^2) can be compared with the pink areas in the European map (>40 kBq/m^2). Hence the area affected by the Fukushima accidents appears to be less than one-tenth of that affected by Chernobyl.

Sources:

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