

THE SAFETY OF FAST BREEDER REACTORS: THE NEW THREAT OF MONJU

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SUMMARY OF REPORT ON THE SAFETY OF THE MONJU BREEDER REACTOR

Fast breeder reactors like Monju are uneconomical and will remain so for the foreseeable future; the electricity produced by them is significantly more expensive than that produced by ordinary (thermal) reactors. Obtaining the security of nuclear energy resources, the ostensible reason given for Japan's interest in breeder reactors, is not an acceptable reason for acquiring breeders. The development of fast breeder reactors, including Monju, is also a direct threat to nuclear non-proliferation, being ideal for the production of high-quality weapons usable plutonium. On these grounds alone there is no justification for the operation of Monju. This paper has focussed on an equally serious threat posed by FBR's and Monju in particular, as well as the threat of accidents leading to the contamination of the environment and human population.

Monju, presents special problems because of its use of liquid sodium and plutonium. The total amount of sodium in Monju is about 1,700 tonnes, contained in the primary and secondary coolant circuits and in the storage tank system.

The Monju reactor core contains a total of 1.4 tonnes of reactor-grade plutonium (containing 1.0 tonnes of fissile plutonium) and 4.5 tonnes of depleted uranium (containing 0.3 per cent of uranium-235). The fuel is a mixture of plutonium oxide and uranium oxide. The blanket contains a total of 17.5 tonnes of depleted uranium.

Each year, after the first year of operation, about 0.5 tonnes of plutonium and 8 tonnes of depleted uranium will be loaded into the reactor. The net production of fissile plutonium (the amount bred) is about 144 kilograms a year. But it takes about 42 years to produce enough plutonium to fuel another breeder reactor of the same size as Monju.

ACCIDENT SCENARIOS - THE SCIENCE AND TECHNOLOGY AGENCY CANNOT PREDICT RESULTS

One of a number of worrying scenarios is an accident caused

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by the failure of both the sodium pumps and the control (scram) systems in the Monju reactor. As a consequence, the sodium boils in the core. Pressure from the sodium vapour drives out the remaining coolant, and the cladding of the fuel rods melts. Within seconds the fuel itself melts and disintegrates.

The loss of coolant in the core has left large spaces in the core. This allows the fuel to compact. Fuel compaction occurs because chunks of fuel fall under gravity. Alternatively, sodium vapour explodes because of an interaction between molten fuel and sodium on the boundary of the core. The explosion drives fuel in different parts of the core together to produce a mass containing enough fissile material to be critical (able to sustain fission).

The pulse of fission energy generated by this 'recriticality' produces enough energy to breach the containment of the reactor and release plutonium, fission products and radioactive debris into the atmosphere, just as happened at Chernobyl. In fact, fast breeder reactors like Monju have a greater potential for this sort of nuclear explosion than thermal reactors because of the relatively high concentration of plutonium (the fissile material) in the fuel (the concentration of fissile uranium-235 in thermal-reactor fuel is only 3% or less).

It has been calculated that the core of a fast breeder reactor like Monju could explode with an explosion equivalent to that of up to 3,000 tonnes of TNT. This greatly exceeds the explosive energy needed to destroy the containment and release the vapourized plutonium fuel and fission products into the atmosphere.

In an accident in which no significant explosion occurred, the molten fuel may collect at the bottom of the reactor vessel and melt through it. Sodium fires may become fierce enough to breach the containment, releasing radioactivity into the atmosphere. The interaction of sodium with some materials produces hydrogen, which is also inflammable or can accumulate to a concentration which is explosive.

The designers of Monju will, of course, have chosen materials to minimise the probability of these (and less serious) accident scenarios. Or at least they will have done so within the financial limits to which they worked. And it is to a large extent a matter of money. Better containment can always be provided if there is a willingness to spend more money.

What the Power Reactor and Nuclear Fuel Development Corporation and STA cannot do is assure us that accidents will not happen or even estimate, with any precision, the probability of their occurrence. The truth is that once the cladding of the fuel melts the subsequent course of events cannot be adequately modelled by computers. The processes

are much too complex and the variables too numerous. Change a few assumptions and almost any answer can be obtained.

The basic information needed to make even a rough judgement about the safety of Monju has not been made public. The safety analysis of the Science and Technology Agency, for example, does not give this basic information. The amount of energy release (i.e., the size of the explosion) which would challenge the containment is, for instance, not publicly known. Many other examples can be given. Until more information is forthcoming it is reasonable to demand that Monju should not be operated.

"MONJU IS LIKE A NUCLEAR WEAPON WAITING TO EXPLODE"

Due to the nature of FBR's and the fuel that they use, there is a very real risk that an explosion at Monju is equivalent to a 3 kiloton nuclear weapon. In fact, in terms of radiation hazard, an FBR nuclear explosion would lead to greater contamination.

The amount of the radioactive fission products in the core of the Monju reactor will eventually build up to about 300 million curies. This is equivalent to the amount of radioactivity initially released by the explosion of a nuclear weapon with the explosive power equivalent to that of the explosion of about 3000 tonnes of TNT (3 Kt). (The explosive power of the nuclear weapon which destroyed Hiroshima was about 12.5 Kt).

Although the radioactivity produced in a reactor is of the same origin as that produced by a nuclear weapon (i.e., nuclear fission), its composition is very different. The main difference is that in a nuclear weapon only the primary fission fragments are present at the moment of explosion. These are mostly short-lived radioisotopes which subsequently decay into longer-lived ones. In a reactor, these longer-lived radioisotopes are continuously produced by the decay of the shorter-lived ones. The longer-lived radioisotopes, therefore, steadily accumulate.

This means that in a nuclear reactor the proportion of longer-lived radioisotopes is much greater than in a nuclear weapon. The decay of the radioactivity from a reactor is, therefore, much slower than that from a nuclear weapon. Thus, after one week, the radioactivity of the fission products from a nuclear weapon will have decayed to only 0.5 per cent of the initial amount whereas the radioactivity from the fission products of a nuclear reactor will have decayed to one-third of the initial amount.

It takes nearly 3 months before the radioactivity from the fission products of a nuclear reactor to decay to a tenth of the initial amount. Therefore, the radiation doses resulting from a release of fission products from a nuclear reactor would remain at unacceptably high levels for a great

deal longer than those from a nuclear weapon which initially produced the same amount of radioactivity.

The nuclear accident at the Chernobyl reactor released about 50 million curies of radioactivity, some 5% of the total in the core. If a very serious accident at Monju released about 17% of the maximum amount of radioactivity in the core it would release about the same amount as did the Chernobyl accident. In addition, a large amount of plutonium could be released.

An accident of this sort will involve an explosion and, or, a fire, which will inject radioactive materials into the air. The radioactivity will be carried by the wind. As the particles fall back to the earth they will contaminate it.

The health impact of Chernobyl inside the former Soviet Union was extremely serious and will remain so for generations. According to official Soviet government figures, an area of 25,000 square kilometres was contaminated by more than 5 curies caesium-137 per square kilometre, a serious level of contamination. The actual figure is likely to be much greater.

About 600,000 people, including those who lived in the 30-kilometre exclusion zone around Chernobyl and other heavily contaminated areas, are officially classified as having been 'significantly exposed' to radiation. It is planned that their health will be monitored for as long as they live.

Bearing in mind the great uncertainties in estimates of the health effects of radiation, it can be concluded that between 100,000 and 500,000 people may die prematurely worldwide as a result of Chernobyl, with similar numbers dying inside and outside the Soviet Union. These figures give an indication of the possible consequences of a serious accident at Monju resulting in a breach of the containment of the reactor and the release into the atmosphere of a significant fraction of the fission products and plutonium in the core.

a1. LIQUID METAL FAST BREEDER REACTORS

Characteristics of breeder reactors

Breeder reactors rely on the isotopes uranium-235, uranium-238, and plutonium-239. The isotopes uranium-235 and plutonium-239 are fissile isotopes; they are capable of nuclear fission when they capture neutrons of any energy (even neutrons at thermal energies of less than 1 eV). The isotope uranium-238 is a fertile isotope; it can be fissioned only by fast neutrons (with kinetic energies above about 1 MeV, or speeds about the speed of light). Fissile isotopes are necessary to sustain a fission (neutron) chain reaction. But only 1 in 140 atoms of naturally occurring uranium is fissile uranium-235;

virtually all of the rest (more than 99 per cent) is non-fissile uranium-238.

Breeder reactors are designed to utilize the energy potential in uranium-238. This can be achieved because uranium-238 will capture neutrons of energies less than the 1 MeV range and convert into fissile plutonium-239. Moreover, it can be arranged that more fissile atoms are produced from fertile ones than are destroyed in the chain reaction. This net increase in fissile material is called breeding.

The fissile material is contained in the core of a breeder reactor and the core is surrounded by a blanket of uranium-238 to capture neutrons escaping from the core. When uranium-238 captures a neutron it becomes uranium-239 which undergoes radioactive (beta) decay (with a half-life of 23.5 minutes) to become neptunium-239 which in turn undergoes radioactive (beta) decay (with a half-life of 2.35 days) to become plutonium-239. Plutonium-239 is also radioactive, decaying by emitting an alpha particle to become uranium-235. But the half-life of plutonium-239 is 24,360 years and so, as far as reactors are concerned, is the end product of the decay chain.

The number of neutrons emitted when a plutonium-239 nucleus fissions is higher in a fast neutron spectrum than in a thermal (slow) neutron spectrum. This means that more neutrons are available to convert uranium-238 to plutonium-239. A breeder reactor operating with fast neutrons can be made to use uranium-238 more efficiently than a reactor operating with thermal neutrons.

Although other fissile/fertile isotope combinations, such as thorium-232/uranium-233 cycles are possible, the uranium-238/plutonium-239 cycle is generally used in fast breeder reactors. Fast breeders operating on the latter cycle use the same nuclear fuel cycle as current commercial thermal nuclear-power reactors, a fact which makes them the choice of the nuclear industry.

Fission neutrons are emitted with a variety of energies. The fission neutron energy spectrum shows a peak at just under 1 MeV; the average energy of fission neutrons is about 2 MeV.

The number of neutrons emitted per fission varies from one fission to another, and depends on the isotope undergoing fission and the energy of the neutron initiating the fission. The average number of neutrons per fission, n , is a crucial parameter for breeder reactors.

For uranium-235, $n = 2.44$ at a neutron energy of 0.025 eV.

At 1 MeV, $n = 2.5$.

For plutonium-239, $n = 2.87$ at a neutron energy of

0.025eV.

At 1 MeV, $n = 3.02$ (Bennet 1981).

In thermal reactors, fuelled with either natural or enriched uranium, almost all the fission occurs in uranium-235. A moderator is used to slow down the fission neutrons so that they produce fission in uranium-235 more efficiently. Breeder reactors contain no moderator and the neutron energies are much higher than in thermal reactors. Although the fission of uranium-238 occurs to some extent in breeder reactors, it is the fission of uranium-235 which predominates and sustains the chain reaction. The importance of uranium-238 is to capture neutrons and produce fissile plutonium-239.

Clearly, the most important characteristic of a breeder reactor is the ratio of the rate at which new fissile atoms (typically plutonium-239) are produced to the rate at which the fissile (uranium-235) atoms are used up. This ratio is the breeding ratio, b , defined as: The number of new fissile atoms produced in the reactor per atom of existing fissile fuel consumed by fission and neutron capture.

If the breeding ratio is greater than 1 the amount of fissile fuel increases; if it is less than 1 the amount of fissile fuel decreases. b must be greater than 1 for an overall net increase in fissile fuel because plutonium and uranium will be lost in reprocessing (the separation of plutonium from spent reactor fuel elements) and the fabrication of reactor fuel elements.

If $n(f)$ is the average number of neutrons produced when a neutron is absorbed in an atom of fissile fuel in a reactor, one must be absorbed by a fissile atom to sustain a steady chain reaction, a number (c) will be captured in non-fuel materials, a number (l) will leak out of the reactor, and b will be captured by fertile atoms. For a steady chain reaction:

$$n(f) = 1 + b + c + l$$

$$\text{Hence, } b = n(f) - 1 - (c + l)$$

Typically, $c + l$ will be about 0.2 (Bennet, p 65).

Therefore, if b is to be greater than 1 (i.e., if breeding is to occur), $n(f)$ must exceed 2.2.

For uranium-235, $n(f) = 2.08$ for thermal neutrons (of 0.025 eV energy) and $n(f) = 2.09$ for high energy neutrons (of 0.5 MeV energy).

For plutonium-239, $n(f) = 2.12$ for thermal neutrons (of 0.025 eV energy) and $n(f) = 2.53$ for high energy neutrons (of 0.5 MeV energy) (Bennet, p 65).

This means that plutonium-239 gives a breeding ratio greater than 1 in breeder reactors. (It should be noted that the value of b in a fast reactor will be greater than that given by the above equation because of the fission of uranium-238. In a fast reactor as much as 20 per cent of the fissions may be in uranium-238. Nevertheless, a plutonium-239/uranium-238 fast reactor is a better breeder than a uranium-235/uranium-238 one.)

The doubling time, $t(d)$, of a breeder reactor is the time required for the amount of fissile material to double (i.e., the time required for a breeder reactor to produce enough new fuel to provide the first fuel load for another identical reactor). $t(d)$ is inversely proportional to $b - 1$ and the reactor rating (in watts per gramme of fissile fuel consumed). To reduce the doubling time, a breeder reactor must be designed with as high a b as possible and operated at as high a rating as possible (Waltar and Reynolds 1981). Doubling times are measured in decades rather than years.

In thermal reactors, in which uranium-235 mixed with uranium-238 is used as fuel, the best conversion ratio (the ratio between the amount of uranium-235 used and the plutonium-239 produced) achieved is about 0.7, in graphite-moderated reactors.

Reactivity

The safety of a reactor depends on the dynamics of the fission chain process, which is determined by the multiplication factor, the neutron generation time, and the emission of delayed neutrons by radioactive fission products. The multiplication factor (k) is defined as the ratio between the numbers of neutrons in two successive generations of neutrons or as the ratio between the neutron production rate by fissions and the neutron removal rate due to absorptions (fission and capture) and leakage from the reactor core (van Dam 1992, p 2030).

In practice, reactivity (ρ) is a more useful measure than the multiplication factor; ρ is defined as $k - 1/k$. If $k = 1$, the neutron population remains constant and so does the power of the reactor; the reactor is critical and the reactivity is zero. If k is less than 1, the neutron population decreases and the reactor shuts down; the reactor is sub-critical and the reactivity is negative. If k is greater than 1, the reactor power increases; the reactor is super-critical and the reactivity is positive.

The rate at which the power of the reactor increases or decreases depends on the effective generation time of the neutrons, the mean time that elapses between fissions in two successive generations of neutrons (van Dam 1992, p 2031). This time is not the same as the mean neutron lifetime because of the delayed neutrons. These neutrons are of crucial importance for the safety of a reactor.

The neutron lifetime is the mean time between the birth of a neutron and its removal. For a fast reactor it is about a millionth of a second, compared with about a thousandths of a second for a thermal reactor. This suggests that just a small positive reactivity would cause a very fast power increase. But, although the vast majority of the neutrons are emitted at the instant of fission, the prompt neutrons, a small fraction is emitted with a significant delay in the decay of fission products, the delayed neutrons. For uranium-235 the fraction is about 0.65 per cent (Ott and Neuhold 1985). Some 40 of the 500 fission products emit delayed neutrons (van Dam 1992, p 2031).

The response of a reactor to a change of reactivity depends on the prompt neutrons and the fraction (d) of the total neutrons which is delayed. If $p = d$, the reactor is critical just on prompt neutrons and the rate of increase of the neutron density equals to the rate of production of delayed neutrons (Bennet 1981, p180). This condition of a reactor is said to be prompt critical.

If p is less than d , the rate of power increase resulting from a positive step change of reactivity is relatively slow and can be controlled (by mechanical means). But if p is greater than d , the rate of power increase is rapid and almost impossible to control. This means if a reactor is to be started up and its power increased safely the reactor must not be allowed to go prompt critical. The safe operation of a reactor depends on keeping p less than d to avoid a rapid increase in power. If there were no delayed neutrons, the power of a reactor would change very rapidly as a result of changes in reactivity. It would be impossible to control a fast reactor during start-up, for example.

The units to express p are per cent and relative units are dollars (p/d) and cents (100 times p/d). The dollar value indicates how far the reactor is from prompt criticality.

The Doppler Effect

The probability that a nuclear interaction, such as nuclear fission, the capture of neutrons, and the scattering of neutrons, will occur is called the cross-section for the interaction. A graph showing how the cross-section for the fission of uranium-235 or plutonium-239 varies with neutron energy shows that there are sharp peaks below neutron energies below 100 eV. A resonance reduces the number of neutrons because a neutron of that energy interacts quickly and is removed.

When the temperature is increased, the resonance widens. The result is that, as the temperature increases, the relative frequency of the neutron interaction increases. This happens for the rate of fission in plutonium-239 and the

rate of neutron capture by uranium-238 .

An increase in the fission rate increases reactivity; an increase in neutron capture decreases reactivity. Because there is more uranium-238 in the core than plutonium-239, neutron capture dominates and there will be a net reduction in reactivity with increasing temperature.

This is called the Doppler effect because it is produced by changes in the effective energy of a neutron resulting from the relative motion of the neutron and the nucleus with which it interacts.

Breeder reactors and the proliferation of nuclear weapons

Almost all breeder reactors are initially fuelled with a mixture of uranium oxide and plutonium oxide (mixed oxides or MOX). The uranium is normally depleted uranium, in which the percentage of uranium-235 is significantly less than that in natural uranium (0.7 per cent). In the Monju LMFBR, for example, the plutonium is initially reactor-grade plutonium and the depleted uranium contains 0.3 per cent of uranium-235. The amount of fissile plutonium in the MOX used in the initial fuel load is 15 per cent by weight in the inner core of the reactor and 20 per cent in the outer core. In a fuel reload, 16 per cent will be fissile plutonium in the inner core and 21 per cent in the outer.

The amount of plutonium in the core of Monju is 1.4 tonnes (of which, 1.0 tonnes is fissile plutonium). The amount of depleted uranium is 4.5 tonnes. The blanket originally contained about 17.5 tonnes of depleted uranium; of this, about 13 tonnes are in the radial blanket and 4.5 tonnes in the axial blanket (Akebi et al 1991). It is planned that, after the first year, about 0.5 tonnes of plutonium and 8 tonnes of depleted uranium will be loaded into the reactor per year.

The operation of breeder reactors has severe consequences for nuclear-weapon proliferation of nuclear weapons because plutonium can be used to manufacture nuclear weapons. Although nuclear-weapon designers prefer weapons-grade plutonium, they could also make nuclear weapons using reactor-grade plutonium.

The preferred fuel for breeder reactors is plutonium with an isotopic composition similar to that of weapon-grade plutonium. The fuel elements are, therefore, likely to be removed from the blanket of a breeder reactor when the plutonium in them is of this composition.

The isotopic composition of the various grades of plutonium (Pu) are given by Carson Mark (Carson Mark 1990). Reactor-grade plutonium (in thermal-reactor fuel elements exposed to about 33000 MW-days per tonnes of heavy metal) contains

about: 1.4 per cent Pu-238; 56.5 per cent Pu-239; 23.4 per cent Pu-240; 13.9 per cent Pu-241; and 4.8 per cent Pu-242.

Weapons-grade plutonium contains about: 0.05 per cent Pu-238; 93 per cent Pu-239; 6.4 per cent Pu-240; 0.5 per cent Pu-241; and .05 per cent Pu-242.

Typical MOX-grade plutonium contains about: 2 per cent Pu-238; 42 per cent Pu-239; 31 per cent Pu-240; 14 per cent Pu-241; and 11 per cent Pu-242.

Typical FBR blanket plutonium contains about 96 per cent Pu-239 and 4 per cent Pu-240; it is weapons grade.

The fact that reactor-grade plutonium can be used in nuclear weapons has been confirmed in the USA by testing at least one such weapon. The bare sphere critical mass of reactor-grade plutonium metal in the alpha-phase (density = 19.0 grams per cc) 13 kilograms. For delta-phase reactor-grade plutonium (density = 15.8 grams per cc) the bare sphere critical is 20 kilograms.

For weapons-grade plutonium the bare sphere critical mass for alpha-phase metal 11 kilograms; for delta-phase it is 17 kilograms. Breeder-blanket plutonium would have about the same critical masses as weapons-grade plutonium (the bare sphere critical mass of alpha-phase Pu-239 is about 10 kilograms).

Plutonium oxide varies in density from 11.5 grams per cc in the crystal form to 2.3 grams per cc for uncompact powder. For the former the bare sphere critical mass is about 35 kilograms; for the latter it is about 875 kilograms. Plutonium oxide could be used to produce a nuclear explosive, certainly if it is in crystal form.

An important difference between the various grades of plutonium, so far as the nuclear-weapon designer is concerned, is the flux of neutrons from spontaneous fission. For weapons-grade plutonium this is 66 neutrons per second per gram; for reactor-grade plutonium it is 360 neutrons per second per gram; for MOX-grade it is 570 neutrons per second per gram (Carson Mark 1990).

The higher the number of spontaneous-fission neutrons the greater the probability that the weapon will pre-detonate. However, this can be compensated for by using faster implosion to compress a sub-critical mass to a super-critical one. The faster the implosion the more predictable the yield of the nuclear explosion.

Another difference is the amount of heat generated by the absorption of alpha particles; weapons-grade generates about 2.5 watts per kilogram; for reactor-grade plutonium generates about 11 watts per kilogram; and for MOX plutonium

it is 15 watts per kilogram.

The radiation dose on the surface of a sphere of reactor-grade plutonium is about 6 times larger than that of a sphere of weapons-grade plutonium of the same size; the dose from a sphere of MOX-grade plutonium is about 8 times larger than the equivalent sphere of weapons-grade plutonium. Ways of coping with the extra heat and radiation exposures can be devised so that the materials could be used to manufacture a nuclear explosive.

Breeder reactors require that spent reactor fuel elements are reprocessed to separate out plutonium from unused uranium and fission products. The plutonium is then used to fuel the breeders. If there were no breeders the spent fuel elements from thermal reactors could be directly disposed of without reprocessing

Plutonium in reprocessing plants and MOX fuel fabrication plants is vulnerable to theft or diversion for military purposes. Plutonium is also vulnerable to theft, diversion, and hi-jacking during transportation between reprocessing and MOX fabrication plants and breeder reactors.

According to the US National Academy of Sciences there is about 1100 tonnes of plutonium in the world (Kiernan 1994). This plutonium is in nuclear weapons, in spent reactor fuel elements, in breeder-reactor fuel cycles, in MOX fuel and fabrication plants, and in storage at civil reprocessing plants. About 700 tonnes of plutonium has been discharged from civil reactors, of which about 150 tonnes has been separated. The world's civil reactors are producing about 70 tonnes of plutonium a year (Albright et al 1993).

By the turn of the century, about 1400 tonnes of plutonium will have been discharged from civil reactors; on present plans, a total of about 310 tonnes will then have been separated in civil reprocessing plants (Dirks 1992). Planned reductions in the nuclear arsenals should result in the dismantling of about 40,000 nuclear weapons over the next ten years or so, containing roughly 100 tonnes of plutonium.

These figures for civil and military plutonium show that there is a global glut of plutonium. This state of affairs has dire consequences for the proliferation of nuclear weapons. The best solution of this problem would be to stop reprocessing civil spent reactor fuel elements and to permanently dispose of existing separated civil plutonium and military plutonium by incorporating it in silicate glass and putting in geological repositories.

The main barrier to this solution is the argument of the nuclear industry that plutonium should be used as breeder-reactor fuel. But to use nuclear-weapon-usable material in

this way is a major threat to global security. This is why Japan's breeder-reactor plans are of concern throughout the world.

Japan's Monju breeder reactor is likely to produce about 140 kilograms of fissile plutonium, about a half of it in the blanket elements (Takagi 1994). Because the burn-up of these elements is low, the plutonium produced in them is ideal for the manufacture of extremely efficient nuclear weapons. If the blanket elements are reprocessed separately, Japan will have a stock of weapons-grade material.

The 70 kilograms or so of weapon-grade plutonium produced per year by Monju is enough to produce about 20 nuclear weapons a year, with an explosive yield at least equal to that of the nuclear weapon that destroyed Nagasaki (equivalent to the explosive power of about 20,000 tons of TNT).

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a4. FAST BREEDER REACTOR SAFETY

The crucial aim of reactor safety is the prevention of the release of radiobiologically significant amounts of radioactive materials into the environment. The prevention of such a release is attempted by putting barriers between the source of the radioactivity and the environment. These barriers include: the cladding of the fuel elements; and the reactor vessel and the components of the primary system. In addition, the reactor system is typically contained in a gas-tight steel shell surrounded by a concrete structure. The cavity between the steel and the concrete is sealed and filled with an inert gas, typically argon.

Reactor safety requires that at least the outer barriers remain intact in an accident. If they do not, radioactivity will be released into the environment.

As van Dam explains, maintaining the mechanical integrity of the barriers requires that the material strength is maintained by limiting process temperatures and that loads are kept limited by limiting pressures, which also means limiting temperatures.

"Limitation of process temperatures is established if the energy content of the system remains limited, which is the case if there is a combined restriction of energy production and energy storage in the systems" (van Dam 1992). The restriction of energy production implies that the fission chain reaction should be "self-controlling to a high degree" and shut down if deviations from normal operations occur. Restriction of energy storage implies that the system should have adequate heat capacity and "inherent heat removal".

It should be noted that radioactive fission products give off energy (heat) as they decay. This means that energy continues to be produced in a reactor core after the fission chain reaction has been shut down; this radioactive-decay heat has to be removed.

The safety of liquid metal fast breeder reactors versus thermal reactors

The use of sodium as a coolant in a LMFBR creates unique safety problems. Sodium interacts exothermically (the interactions are accompanied by the evolution of heat) with air, water, and concrete. A sodium aerosol in air can explode spontaneously. An interaction between sodium and concrete can produce hydrogen which can accumulate to a concentration which explodes. Hydrogen is also inflammable.

LMBFRs contain a lot of sodium; Monju, for example, has 750 tonnes in its primary circuit. A sodium fire is obviously a significant hazard at a LMBFR. By itself, a sodium fire is not likely to affect the core of the reactor but if the primary coolant leaks to the atmosphere it will

burn and release radioactive sodium to the atmosphere.

Radioactive sodium-24 is produced in the core of a LMBFR by the neutron irradiation of the coolant. Sodium-23 captures neutrons to become sodium-24, which emits beta particles and gamma rays, with a half life of 14.7 hours.

Because of the production of radioactive sodium-24, LMFBRs usually a secondary sodium coolant circuit. The primary sodium passes through the core, cooling it but becoming radioactive. It then transfers its heat to the sodium in the secondary circuit in intermediate heat exchangers. The secondary sodium does not become radioactive. In a pool LMBFR, like Monju, the pumps which circulate the primary coolant and the intermediate heat exchangers are in the same vessel as the reactor core. In a loop LMBFR, such as the PFR, the pumps and heat exchangers are in separate vessels. The sodium is covered with a layer of the inert gas argon, at slightly above atmospheric pressure to prevent air getting in.

Some other characteristics of LMFBRs make them inherently less safe than thermal (water-cooled) reactors (LWRs). For example, the very high temperature in the centre of a LMFBR fuel element (in Monju, up to 2350 degrees Centigrade) is significantly above the boiling point of sodium (883 degrees Centigrade). If fuel elements fracture, therefore, molten fuel and liquid sodium are likely to come into contact, causing an explosion which could seriously damage the rest of the core.

Another problem is that the core of an LMFBR is not in its most reactive configuration. If failure of the fuel cladding (likely at about 700 degrees Centigrade), for example, allowed the fuel to move in the core, reactivity may be added, causing the power to rise to very high levels. Loss of coolant and the radial crushing of the core could increase reactivity. Such an increase in reactivity would not happen in a water-cooled thermal reactor. This is because the fuel in a thermal reactor contains much less fissile material (it is less highly enriched) than the fuel in a breeder reactor. It can only sustain a fission chain reaction if water is present to slow down or moderate) the fission neutrons to make them more effective in producing fission. Fuel compaction in a LWR would expel the water moderator and reduce the reactivity, shutting down the fission chain reaction (Webb 1976).

In the words of Webb, a reactor engineer and member of the West German study group at the Max Planck Institute for the SNR-300 Risk Oriented Analysis: "What makes this compaction problem(in a LMFBR) especially serious is that only about 2% core volume reduction, such as could easily occur upon core melting, would raise the reactivity to above the delayed-neutron fraction (about 0.3% for plutonium-fuelled reactors) and thus trigger a power excursion. Yet, the potential for

fuel compaction in an LMFBR is large, since only about 50% of the core volume is taken up by fuel rods, and the rest by coolant. Hence, the core compaction potential is over 50%, should the coolant be expelled or drained, leaving void for the fuel to enter; again, fuel compaction occurs whenever fuel fills voided coolant space between the fuel rods. Also, upon melting, the fuel rods of the core would lose their rigidity, and the fuel would then be easily compressible, as by gravity compaction" (Webb 1976).

In a LMFBR, the rapid expulsion of sodium, by boiling, for example, can also increase the reactivity. In a LWR, however, a loss of coolant will reduce the reactivity and shut down the fission chain reaction (Ott 1988).

Webb also points out that, in a LMFBR, an explosion due to a power excursion might rapidly compact a region of the core sufficient to make it prompt critical, producing a second, more powerful explosion (similar to the second explosion in Chernobyl Unit 4). The more rapid the core compaction, the greater the rate of reactivity increase, and the greater the resultant power excursion.

A LMFBR, therefore, differs from a LWR in that in an accident in which fuel melts or sodium boils, the reactivity may rise and produce a rapid increase in power, resulting in an explosion. This could, in turn, cause a rapid compaction of fuel and a large second explosion produced by energy from continuing fission. The fissioning would finally stop when the explosion blew the core apart - i.e., when the explosion disassembled the core.

LMBFRs are designed with a negative Doppler reactivity effect, which provides prompt negative feedback, reducing reactivity if the fuel temperature increases. If reactivity is added in some way, the power does not increase exponentially but more slowly. The threshold for a power excursion is the prompt critical reactivity level. The Doppler effect can stop small power excursions caused by small increases in reactivity above this level.

The positive coefficients of reactivity of a LMFBR under certain operating conditions, is a technical parallel with the Chernobyl reactor; another is the inflammability of the coolants used, graphite and sodium.

Core disruptive accidents

An event resulting in significant damage to a reactor core is called a core disruptive accident (CDA). In a FBR, a CDA could be the melting of part of the reactor core, a meltdown of the core, or an energetic explosion.

CDAs are sometimes called Hypothetical (or unthinkable) core disruptive accidents. This is usually done by those not wishing to acknowledge that such accidents are credible and

could happen.

An energetic CDA is sometimes called a Bethe-Tait event. Beth and Tait devised a method of providing a rough estimate of the energy released in an energetic CDA, founding an approach widely used to find an upper limit for the containment of a FBR (Bethe and Tait 1956).

Events that can lead to a CDA in a FBR are: a loss of flow of the sodium together with a failure to automatically insert the control or safety rods to shut down the fission chain reaction (i.e., a failure to scram); or the introduction of too much reactivity into the core of the reactor causing a rapid increase in power (called an over-power transient) together with a failure to scram. In short, a serious accident can occur with a FBR either from losing cooling capacity without reducing the power level, or from increasing the power without increasing the cooling capacity (Cochran 1991).

A scram has to be automated because a human being cannot generally react quickly enough to control a reactor in an emergency. For example, there is less than a millisecond to control a reactor which has gone prompt critical whereas the reaction of a human is typically about 200 milliseconds.

The Fermi 1 accident was an example of a loss of flow of sodium, caused by a blockage of the coolant, causing the fuel to melt. The melting point of the fuel is about 2800 degrees Centigrade.

There may also be a major fracture in a pipe carrying coolant. A loss of power to the main pumps circulating the coolant and a failure of the diesel emergency generators to restart these pumps, or any stand-by pumps, in time, could lead to a CDA.

Because of the large mass of sodium in a pool-type FBR it takes a few hours for the temperature to fall to the temperatures at which the cladding fails if the emergency cooling system does not work and no decay heat can be removed from the primary circuit. If there is a total loss of power to the pumps, the sodium will circulate naturally and cool the reactor core sufficiently to maintain its integrity. This will make few hours available to provide emergency cooling. An accident will, of course, be avoided only if the reactor is scrammed immediately power to the pumps is lost.

An earthquake could destroy the pumps and the control and safety rods and inevitable damage to the core of the reactor. An earthquake could also produce an over-power transient (a rapid increase in power due to the addition of reactivity) which could also be produced from the misuse or malfunction of the control and safety systems. As described earlier, unexplained positive reactivity fluctuations occurred in the

Phenix FBR, which is still shut down.

A serious loss of flow of the sodium coolant or a fluctuation in positive reactivity could cause the fuel elements to melt. This may cause an explosion in the core of the reactor. Cochran describes how such an explosion could be produced after a loss of flow of the coolant.

The accident begins when power is lost to the pumps and the redundant safety and control systems fail to shut down (scram) the reactor. Sodium begins to boil near the centre of the core of the reactor (the hottest part of the core). Bubbles are formed in the coolant when the sodium boils, reducing the moderating effect on the neutrons and causing the average energy of the neutrons to increase. The fission cross-section for plutonium increases with increasing neutron energies. The rate of fission, therefore, increases. In other words, the loss of coolant leads to a positive reactivity coefficient in the reactor core and an increase in the power level.

The increase in power causes the sodium to boil more vigorously, which adds more reactivity, and so on. Webb calls this process 'autocatalytic reactivity' increases. The fact that a LMFBR is its own catalyst for generating power excursions is an inherent safety problem in the reactor (Webb 1976).

In Cochran's accident scenario, almost immediately after the sodium begins to boil, the cladding on the fuel elements begins to melt. The molten cladding flows up the channels between the fuel assemblies (bundles of fuel rods). Immediately after the cladding melts, the fuel itself melts and molten fuel flows up the channel. When the cladding and fuel flow into a part of the core which is colder they refreeze and clog up the flow of sodium in the fuel assemblies. Chunks of cladding and fuel fall to the bottom of the core, clogging it.

Fuel at the top of the reactor core could fall to the bottom of the core under gravity. If enough falls, in re-criticality could occur. The extent of the accident would, of course, depend on how much mechanical energy was released. If enough energy is released (i.e., a powerful explosion occurs), the seal between the reactor head and the reactor vessel could be breached and the total energy released may be more than the reactor containment can withstand (Cochran 1991).

If, in an accident, molten cladding or molten fuel comes into contact with liquid sodium, a sodium vapour explosion might take place, damaging the rest of the core of the reactor. This is analogous to a steam explosion, like the first explosion in the Chernobyl reactor, which can take place when water is mixed suddenly with some molten metals, due to the rapid transfer of the heat from the metal to the

water.

A CDA which does not cause an explosion, but in which the core melts and collects on the floor of the reactor vessel, is likely to result in a melt-through of the reactor vessel. This could lead to a sodium fire which could eventually breach the secondary containment.

As Cochran points out, if a CDA causes cladding and fuel to melt, it is not possible to evolve accurate computer models of what happens subsequently. He puts it graphically: "Computer modelling of fuel and cladding movements, and their interaction with sodium coolant, following the loss of geometric integrity of the reactor core borders on witchcraft. The possible scenarios from this point to the end game are infinite. Many simplifying assumptions have to be made. There are so many variables and assumptions that an analyst can manipulate the calculations to predict any size energy release - anything from a partial core melt as occurred in the Fermi 1 reactor to a catastrophic explosion rupturing the integrity of the reactor vessel" (Cochran 1991).

For these reasons, LMFBR safety analyses must be treated with considerable caution. Typically, loss of flow and over-power transient accidents (so-called design base accidents or DBAs, accidents that produce the most severe consequences of all accidents considered credible) are the most serious ones analyzed. Applicants are likely to choose parameters and assumptions which lead to energy releases which do not breach any of the reactor's barriers. But small changes in one or two of the assumptions would lead to energy releases which breach the containment of the reactor.

It must be emphasised that the processes in a LMFBR are so complex that no theory can be credible without a full-scale test, which would, of course, require reactor destructive tests.

The SNR-300 saga

In 1984, the Federal German Minister of Research and Technology asked the Gesellschaft für Reaktorsicherheit (GRS) to perform a "Risk-Oriented Analysis of the SNR-300". The GRS report identifies three potential causes for core reactivity increases which may lead to rapid power excursions: displacement of sodium from the core, due to sodium boiling or gas bubbles in the core; direct reactivity addition by a deformation of the core geometry or by relative motions between core and absorbers; and the failure of one or several fuel rods propagating to surrounding fuel rods resulting in, for example, the dislocation of the fuel or the release of fission gas.

Initiating events for core destruction include:
insufficient flow of coolant inside the core without scram;

insufficient heat removal without scram; direct reactivity addition; fuel rod failure; failure of the decay heat removal system with scrammed reactor; and loss of coolant and failure of the decay heat removal system with scrammed reactor or coolant level below the emergency level and failure of the immersion cooling system (GRS 1984).

The report says that in the SNR-300 "the predominate contribution to the expected frequency of core destruction is attributed to the failure of the reactor shutdown system in case of transients. The main reason consists in the fact that ...a failure of reactor shutdown may lead in a short time to superprompt criticality, and subsequently to a power excursion. Under certain circumstances this may be accompanied by the release of considerable amounts of mechanical energy".

Leakages in the primary circuit do not, according to the GRS report, significantly contribute to the risk. The high boiling point of the coolant and the resulting low system pressure prevent the coolant from evaporating completely, providing the reactor is scrammed. The report came to the optimistic conclusion that the probability of core destruction in SNR-300 was negligible (the expected frequency was once in about a million years) (GRS 1984).

Nevertheless, the state government of North Rhine-Westphalia refused to licence the SNR-300. It had specific fears that SNR-300 had a large positive reactivity coefficient; a weak secondary confinement; a high potential for exothermic chemical reactions that could lead to sodium interactions with various materials, sodium fires, and gas explosions; and a lack of separation of the redundant electrical systems. Consequently, in March 1991, SNR-300 was abandoned. Probably, comparisons between SNR-300 and the Chernobyl reactor led to this decision.

Worse possible accidents

The circumstances under which a sodium vapour explosion, due to an interaction between molten cladding or fuel and sodium, could take place is unresolved. That no sodium vapour explosion occurred in the EBR-I and Fermi 1 LMFBR melt downs does not mean that such an explosion could not happen. The rapid and comprehensive mixing of molten fuel and sodium necessary for a sodium vapour explosion did not occur in these accidents; there were no super-prompt critical power excursions in them to produce such a mixing.

Also unresolved is the crucial question of how energetic a subsequent explosion in a LMFBR could be. Both Cochran and Webb discuss these issues (Cochran 1991 and Webb 1976). They are crucial because, as already described, in the Chernobyl nuclear accident a nuclear explosion followed a steam explosion.

The fear is that an explosive interaction between molten fuel and sodium could force two subcritical masses of together at a high speed (greater than that which would occur due to gravity alone). The scenario is that the central region of the LMBFR core is melted away. A sodium vapour explosion then forces the fuel in the top region of the core at high speed down into the fuel at the bottom of the core (Boudreau and Jackson 1974).

The blanket rods surrounding the active core, which may be intact and much cooler than the rest of the central regions, could act as a sort of gun barrel. As Cochran points out such a recriticality event is similar to the gun-assembly system used in the atomic bomb which destroyed Hiroshima. Fission may continue until the core is disassembled by the force of explosion.

Although the explosion which could result from such an event would be less than that from a typical nuclear fission weapon, it could easily cause enough pressure to breach the reactor containment, allowing plutonium, fission products, and radioactive debris to escape into the environment. In this context, it should be remembered that this type of nuclear explosion in the Chernobyl reactor produced 1000 GJ of energy.

Using a crude theoretical calculation, Webb concludes that a sodium-vapour explosion followed by a large secondary power excursion (due to a rapid increase in reactivity due to fuel reassembly) could produce a nuclear explosion with an explosive power which no reactor containment could withstand. In fact, his calculations suggest that such a chain of events in Monju could produce an explosion equivalent to that of 1.3 kT of TNT.

Webb points out that predicting such power excursions in LMFBRs can only be done by making many simplifying mathematical assumptions and approximations. One of several problems is the extremely complicated fuel and coolant movements in the core under various temperature and pressure conditions, which can vary throughout the core. Also extremely complicated is the prediction of changes in reactivity and variations in core power density resulting from the motions of materials in the core.

All in all, because so many assumptions and approximations have to be made in theoretical calculations, we will only know the severity of potential explosions in LMFBRs if a large series of full-scale accident tests are made. These are simply not practicable, given the costs and dangers involved.

The need for and the impracticability of full-scale tests to verify accident analyses mean that we cannot know whether or not accidents in LMBFRs can be contained. The probability of occurrence of accidents cannot be adequately assessed.

This situation presents society with two possibilities. Either LMBFRs are abandoned or they are built without much idea of the explosive potential in the hope that accidents will not occur or, if they do, are contained.

PRISM (Power Reactor Inherently Safe Module) and SAFR (Sodium Advanced Fast Reactor) are new designs which may appear safer than existing designs (Van Tuyle et al 1990 a and b). They have, for example, passive shutdown heat removal for loss-of-coolant events. But there are still scenarios in which they could melt if, for example, there is a major flow blockage. They are also very expensive and they do not breed fuel efficiently. They are no answer to the safety problems of LMFBRs.

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a5. THE CONSEQUENCES OF THE MONJU PLUTONIUM-BREEDER REACTOR

Worldwide development activities have shown that the fast breeder reactor fuelled by plutonium is uneconomical and will remain so for the foreseeable future. Obtaining the security of nuclear energy resources is not a good reason for

acquiring breeder reactors. Stockpiling uranium is a far cheaper way.

But economic considerations are not the only issue with breeder reactors, or even the most serious. More serious ones concern the proliferation of nuclear weapons and the safety of breeder reactors.

The use of plutonium breeders involves the use of huge amounts of plutonium which can also be used to manufacture nuclear weapons. This plutonium is in the reactors and in the nuclear fuel cycle needed to support them. The plutonium – particularly that in reprocessing and MOX-fuel fabrication plants – cannot be adequately safeguarded to prevent some of the plutonium being diverted to military programmes (Barnaby 1993, Miller 1990).

The plutonium produced in the blanket of Monju will be weapon-grade, suitable for the manufacture of the most efficient nuclear weapons. If Japan chooses to reprocess the plutonium produced in Monju's blanket separately it could accumulate enough weapon-grade plutonium to produce 20 high-quality nuclear weapons a year.

The stockpiling of weapon-usable plutonium and the ability to produce large amounts of weapon-grade plutonium in Monju will have serious security consequences for the East Asian region, whether or not Japan intends to manufacture nuclear weapons. In this context capability is more destabilising than intentions. The operation of Monju may, therefore, provoke North Korea to produce nuclear weapons, starting a nuclear arms race in the region involving, in addition, South Korea and Taiwan.

Japan's continued development of breeder reactors will encourage the acquisition of breeders by other countries. Presumably, Japan's ambition is eventually to export commercial breeders. The resultant accumulation of plutonium in non-nuclear-weapon states would have dire consequences for the spread of nuclear weapons.

Monju and its safety

So far as safety is concerned, Monju, like other plutonium breeders, present special problems because of their use of liquid sodium and plutonium. The total amount of sodium in Monju, a loop-type reactor, is about 1700 tonnes, contained in the primary and secondary coolant circuits and in the storage tank system.

Sodium, which is such a reactive substance that it does not occur in nature in a free state but as the chloride, nitrate, etc., has a boiling point of 883 degrees Centigrade and a melting point of 97.5 degrees Centigrade. In the reactor the sodium has to be kept at a temperature above the melting point to prevent it solidifying.

The primary sodium is fed into the bottom of the reactor vessel at a temperature of 397 degrees Centigrade, removes heat from the core, and flows out of the top at a temperature of 529 degrees Centigrade. The sodium in the primary system is covered with a layer of argon at a pressure of about 5000 mmAq.

The active height of the Monju core is 0.93 metres and the active diameter is 1.79 metres, giving a volume of 2335 litres.

In the core, the sodium is irradiated with neutrons which escape from the fuel assemblies and the stable isotope sodium-23 is converted to the radioactive isotope sodium-24. Because the sodium in the primary circuit becomes radioactive, heat is removed from the primary sodium by sodium in a secondary circuit which does not become radioactive.

Sodium in the secondary loop removes heat from the primary sodium in an intermediate heat exchanger. Sodium goes in to the heat exchanger at a temperature of 325 degrees Centigrade and is heated in the exchanger to 505 degrees Centigrade. Heat from the secondary sodium is then transferred to water in a steam generator which includes a superheater. Superheated steam with a pressure of 127 MPa (a temperature of 483 degrees Centigrade) is fed to a turbine directly connected to a generator with an electrical output of 280 MWe (714 MWth) (Akebi et al 1991).

Reactivity changes due to fuel burnup are controlled with 10 coarse control rods. Reactivity changes during reactor operation are controlled by 3 fine control rods. The rods use boron carbide(B₄C) to absorb neutrons.

The Monju hexagonal core contains a total of 1.4 tonnes of reactor-grade plutonium (containing 1.0 tonnes of fissile plutonium) 4.5 tonnes of depleted uranium (containing 0.3 per cent of uranium-235). There are two kinds of fuel assemblies, each containing a mixture of plutonium oxide (PuO₂) and depleted uranium oxide (UO₂).

In the initial fuel load, the assemblies in the inner core have a plutonium enrichment of 15 per cent (per cent weight of fissile plutonium in the mixed oxide fuel); those in the outer core have a plutonium enrichment of 20 per cent. The more highly enriched fuel is on the outside to equalize the output power of the core. In fuel used to reload the core, the percentages are 16 and 21 respectively.

The average burnup of discharged fuel assemblies is 80,000 MWd per tonne of fuel. About one-fifth of the core and blanket fuel assemblies are changed every six months, giving a 30-month cycle.

The upper part of the blanket is 0.3 metres thick; the lower part is 0.35 metres thick; and the radial part is 0.3 metres thick. The blanket contains a total of 17.5 tonnes of depleted uranium, of which 13 tonnes are in the radial blanket. Each year, after the first year of operation, about 0.5 tonnes of plutonium and 8 tonnes of depleted uranium are loaded into the reactor. The net production of fissile plutonium (the amount bred) is about 144 kilograms a year. The breeding ratio is about 1.2 and the doubling time about 42 years (Takagi 1944).

Proponents of Monju claim, of course, that it is safe. If there is a loss of flow of the sodium coolant the control and safety systems will prevent a serious accident, they say. The same claim is made for an over-power transient. Much is made of the presence of redundant safety and control systems. But the nuclear accidents at Chernobyl and Three Mile Island challenge the credibility of such statements.

One of a number of worrying scenarios is that the sodium pumps and the scram system in the Monju reactor both fail. The sodium then boils in the core. Pressure from the sodium vapour drives out the remaining coolant, and the cladding of the fuel rods melts. Within seconds the fuel itself melts and disintegrates. At this stage, the loss of coolant in the core has left large spaces in the core. This allows the fuel to compact.

Fuel compaction occurs due to 'slumping' under gravity. Alternatively, the sodium vapour explodes due to an interaction between molten fuel and sodium on the boundary of the core. The explosion drives fuel in different parts of the core together to produce a mass containing enough fissile material to be critical.

The pulse of fission energy generated by this recriticality produces enough energy to breach the containment of the reactor and release plutonium, fission products and radioactive debris into the atmosphere, just as happened at Chernobyl. It is important to emphasise that this type of explosion is a nuclear explosion produced by energy released by nuclear fission. And this energy will continue to be generated until the core is blown apart (i.e., 'disassembled').

Fast breeders like Monju have a greater potential for this sort of nuclear explosion than thermal reactors because of the high concentration of fissile plutonium (relative to non-fissile uranium-238) in the fuel; in thermal reactors the concentration of fissile material (uranium-235) is only 3% or less.

Webb has calculated that core of the SNR-300, a similar FBR to Monju, could explode with an explosion energy equivalent to that of up to 3 kT of TNT (equivalent to 20 GJ). This greatly exceeds the 370 megajoules needed to destroy the

containment and release vapourized plutonium fuel and fission products into the atmosphere (Webb 1986).

Even if no significant explosion occurs, the molten fuel could collect at the bottom of the reactor vessel and melt through it. Sodium fires may become fierce enough to breach the containment, releasing radioactivity into the atmosphere. The interaction of sodium with some materials produces hydrogen, which is also inflammable or can accumulate to a concentration which is explosive.

The designers of Monju will, of course, have chosen materials to minimise the probability of these (and less serious) accident scenarios. Or at least they will have done so within the financial limits to which they worked. And it is to a large extent a matter of money. Better containment can always be provided if there is a willingness to spend more money.

What the owners of Monju cannot do is assure us that accidents will not happen or even estimate with any precision, the probability of their occurrence. It is still not known, for example, what caused the four negative reactivity insertions which caused the Phenix FBR to be shut down in 1989 and 1990.

The truth is that once the cladding of the fuel melts the subsequent course of events cannot be adequately modelled by computers. The processes are much too complex and the variables too numerous. Change a few assumptions and almost any answer can be obtained.

Worse still, the basic information needed to make even a rough judgement about the safety of Monju has not been made publicly available. The safety analysis of the Science and Technology Agency does not give this basic information. For example, the amount of energy release (i.e., the size of the explosion) which would challenge the containment is not publicly known. Nor is the strength of the secondary containment or the weight of the reactor cap or the protection of the redundant electrical systems or the adequacy of the measures taken to keep argon bubbles out of the core and oil out of the sodium. Until core information is forthcoming it is reasonable to demand that Monju should not be operated.

The consequences of a serious accident at Monju

The amount of the radioactive fission products in the core of the 280-MWe Monju LMFBR will eventually build up to about 300 million curies (MCi) (Pershagen 1989). This is equivalent to the amount of radioactivity initially released by the explosion in air of a nuclear weapon with the explosive power equivalent to that of the explosion of about 3000 tonnes of TNT (3 Kt) (Rotblat 1981). The explosive power of the nuclear weapon which destroyed Hiroshima was about

12.5 Kt.

Although the radioactivity produced in a reactor is of the same origin as that produced by a nuclear weapon, its composition is very different. The main difference is that in a nuclear weapon only the primary fission fragments are present at the moment of explosion. These are mostly short-lived radioisotopes which subsequently decay into longer-lived ones. In a reactor, these longer-lived radioisotopes are continuously produced by the decay of the shorter-lived ones. The former, therefore, steadily accumulate.

This means that in a nuclear reactor the proportion of long-lived radioisotopes is much greater than in a nuclear weapon. The decay of the radioactivity from a reactor is much slower than that from a nuclear weapon. Thus, after one week the radioactivity of the fission products from a nuclear weapon will have decayed to only 0.5 per cent of the initial amount whereas the radioactivity from the fission products of a nuclear reactor will have decayed to one-third of the initial amount.

It is nearly 3 months before the radioactivity from the fission products of a nuclear reactor has decayed to a tenth of the initial amount. Therefore, the radiation doses resulting from a release of fission products from a nuclear reactor would remain at unacceptably high levels for a great deal longer than those from a nuclear weapon which initially produced the same amount of radioactivity (Rotblat 1981).

The nuclear accident at the Chernobyl reactor released about 50 MCi of radioactivity, some 5% of the core inventory. If an extremely serious accident at Monju released about 17% of the maximum amount of radioactivity in the core it would release about the same amount as did the Chernobyl accident. In addition, a large amount of plutonium could be released. Since the Chernobyl accident gives actual knowledge of the consequences of a nuclear accident it is useful to consider the lessons it gives for an accident at the Monju reactor releasing a similar amount of radioactivity.

A nuclear accident of the sort we are considering will involve an explosion and, or, a fire. These will inject radioactive materials into the air. The radioactivity will be carried down wind. As the particles fall back to the earth they will contaminate it. The pattern of the contamination will depend on the height to which the radioactive plume rises, which will in turn depend on the explosive power and the fierceness of the fire, the direction and the speed of the wind, and the weather conditions (rain, for example, will bring down the radioactivity and so areas under the radioactive plume rained on will be more contaminated than dry areas). Larger fall-out particles will descend first and cause the highest radiation dose.

Humans in the contaminated areas will be exposed to: external radiation by the radioactive cloud as it passes overhead; internal radiation through the inhalation of radioactive particles in the air; external radiation, mainly by the gamma rays emitted by the radioisotopes deposited on the ground; and internal radiation through eating milk or drinking milk from animals which had ingested radioisotopes or by drinking contaminated water (Rotblat and Lindop).

The effects of inhalation depend on the size of the particles in the fall-out. Particles of less than 5 micrometres in diameter will not be filtered out by the nose and will get into the lung (Rotblat 1981). These particles may stay in the lung or migrate to the bones, liver, gastro-intestinal tract, etc.

It is the inhalation hazard which makes plutonium such a toxic substance. The deposition of plutonium in the lung will give rise to such intense local irradiation (due to alpha particles) that a very small particle in the lung can cause lung cancer with a high probability.

In the fire which is likely to occur in a serious nuclear accident at Monju, plutonium will burn, producing very small particles. These will be spread down wind. After they have fallen back to the ground, they may become airborne again if blown by the wind or if the ground is disturbed. Because of the great toxicity of plutonium, areas contaminated with it are uninhabitable until decontaminated; the decontamination process can take a long time.

Ingested radioisotopes also often concentrate in certain organs and remain there for various times. If concentrated in a particular organ, a radioisotope may give a much larger radiation dose than it would if spread throughout the body. For example, radioactive iodine concentrates in the thyroid gland. If people ingest radioiodine (particularly iodine-131, with a half life of 8 days) their thyroids will receive a relatively large dose of radiation. This is a particular hazard for children, who have smaller thyroids than adults, and for populations who drink fresh milk.

People living relatively close to an accident at a nuclear reactor will be affected by a wide range of radioisotopes. Those living further away will be affected mainly by the longer-lived radioisotopes. Of these, those of the most radiobiological concern are strontium-90 (half-life, about 29 years) and caesium-137 (half-life, about 30 years).

The half-lives of these two radioisotopes are so long that they remain a hazard for a very long time. They are present in fission products in relatively large amounts. Strontium is ingested by humans mainly from milk and meat; in the human body, it concentrates in bones and teeth. Caesium enters the body through vegetables, salad, and fish; it

accumulates in soft tissues.

The beta-particles and gamma-rays emitted from iodine-131, strontium-90, and caesium-137 can deliver large internal radiation doses. In fact, for those living a distance away from the accident, the internal radiation hazard predominates over the external radiation from gamma rays emitted by fission products deposited on the ground.

People exposed to ionising radiation, from internal or external sources, may suffer a range of health effects, the type, severity, and time of appearance of which will depend mainly on the magnitude of the radiation dose received. If the dose is very high, symptoms, which may result in death, appear very soon after the exposure. Lesser doses may produce long-term effects - somatic, suffered by the individual exposed, and genetic, which occur in the children of the individual exposed or future generations.

Short-term (or acute) effects include radiation sickness, the symptoms of which include nausea, headaches, anorexia, and so on. Death from very high doses is due to damage to the central nervous system or disturbances to the gastrointestinal system.

Somatic long-term effects may not become apparent for many years, perhaps decades, after the individual has been exposed to the radiation. The somatic effect of most concern is the induction of cancer.

The total risk factor for the induction of cancer is 0.0625 per sievert (the unit of radiation dose) (Lambert 1987, ICRP 1985). In other words, if a million people are exposed to a radiation dose of 1 sievert, 62500 of them may be expected to die of cancer induced by the radiation (ICRP 1977). This risk factor does not include non-fatal cancers (such as thyroid cancer). The number of these may be about the same so that the total number of lethal and non-lethal cancers induced in the above population may be 125,000.

There is much controversy amongst scientists about the real magnitude of the cancer risk, particularly the risk of exposures to low radiation doses. Some scientists believe that the cancer risk at low doses may be as high as 0.13 per sievert (Rotblat 1981).

Estimates of the number of cancers induced, or which will be induced, by exposure to radiation from the Chernobyl nuclear accident vary considerably. American estimates, sponsored by a number of institutions such as the Lawrence Livermore Laboratory, suggest that the collective dose in Europe (outside the USSR) was about 148700 sieverts which may eventually (over a 50 year period) induce about 10000 fatal cancers (Anspaugh et al 1988). This would suggest a total of 20000 cancers induced (fatal and non-fatal). But other estimates suggest that the number of fatal and non-fatal

cancers in Europe may be as high as 120000 (von Hippel and Cochran 1986).

The variation in the estimates is mainly due to the particular cancer risk taken. Until there is more certainty about the magnitude of the health effects of radiation, particularly at low doses, it will be impossible to estimate with any precision the consequences of exposure to radiation from radioactive materials released by accidents at nuclear reactors.

The health impact of Chernobyl inside the Soviet Union was extremely serious and will remain so for generations. According to official Soviet government figures an area of 25,000 square kilometres was contaminated by more than 5 Ci of caesium-137 (IAEA 1991). This is likely to be a considerable underestimate.

About 600,000 people, including those who lived in the 30-kilometre exclusion zone around Chernobyl and other heavily contaminated areas, are officially classified as having been 'significantly exposed' to radiation (Medvedev 1990). Exactly how many people have been evacuated from their homes is not publicly known but the figure is greater than 115,000 and may be as high as 400,000.

It is planned that their health will be monitored for as long as they live. The number of fatal cancers inside the Soviet Union induced by radiation from the radioactivity released by the nuclear accident is likely to be at least as many as the number induced outside.

Bearing in mind the great uncertainties in estimates of the health effects of radiation, it can be concluded between 100,000 and 500,000 people may die prematurely worldwide as a result of Chernobyl, with similar numbers dying inside and outside the Soviet Union.

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