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Nuclear power

"Pollution-free nuclear power" is a blanket phrase increasingly used by people who should know better. Apart from inevitable waste heat, nuclear power stations discharge significant amounts of low-level radioactivity, which are dangerous, though how dangerous is controversial. In this article, Walter Patterson, Editor of Your Environment *and a nuclear physicist, discusses two still more important disadvantages of nuclear power: the danger of reactor accidents - great enough to dissuade those experts in risk assessment, the insurance companies, from covering the nuclear industry against them; and the apparently insoluble problem of the responsible disposal of high-level wastes. The article is taken from* Nuclear Reactors, *the first of the Red Alert books, a series of urgent environmental studies published by Earth Island.*

Reactor safety

Designers, buildings and operators of nuclear reactors have laboured long and hard to dispel the public suspicion that a nuclear reactor could explode "like an atom bomb". It is worth saying here at the outset that under no circumstances could a thermal neutron reactor of whatever design cause a nuclear explosion. The fissile material is simply too dilute, and could not, by whatever mishap, become sufficiently concentrated. However, like many other types of large industrial installation, a nuclear reactor could conceivably experience, as a result of drastic internal malfunction, a non-nuclear explosion. The consequences would be comparable in every way but one to those of such an accident in any industry: deaths, injury, property damage. What uniquely distinguishes a reactor from other installations is the radioactivity it contains, which in the event of an accident might be released.

After a large power reactor has been in operation for some months, the accumulated fission products in its fuel charge dwarf the amount of radioactivity released over Hiroshima. A 1957 study prepared at Brookhaven National Laboratory by the US Atomic Energy Commission (AEC), called "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants", or WASH-740 as it is commonly known, predicted that the "maximum credible accident" at their theoretical reactor would lead to 3,400 deaths, 43,000 injuries and property damage of $7,000 million. A study by the University of Michigan using the same basis forecast as many as 133,000 deaths. (The term "credible accident" occurs frequently in reactor safety studies - the sparseness of operating experience to date does not give a statistical basis for evaluation beyond the assertion of the "incredibility" of certain accidents which have not yet happened.) The AEC, for reasons known only to themselves, have since refused to publish an up-dated study of accident possibilities, although the reactors now operating and under construction will be at least an order of magnitude larger than that assumed in the 1957 study. Clearly, the radioactive contents of a reactor must not, under any circumstances, be allowed to escape.

Such an absolute requirement comes up against three obstacles: technological, economic, and human. Reactors of whatever kind are designed to confine the fission products no matter what credible accident happens. To begin with, the fuel itself, in which the fission products are generated, is hermetically sealed in cladding. Then the fuel elements are enclosed within the sealed volume of the reactor vessel and its cooling circuits. There will then be at least one further shell of so-called containment, say the reactor building itself, which will be designed so that it can be completely sealed against the escape of gases, providing a third line of defence against release of fission products to the outside air.

It sounds encouraging. But the first line of defence - the fuel cladding - has manifested with disconcerting regularity a tendency to leak. When this happens, gaseous fission products get into the primary coolant (water, carbon dioxide, etc.). In addition, impurities in the coolant may, under the intense neutron bombardment, be transmuted into radioactive forms, as may corrosion products formed on the outside of the cladding, adding to the activity in the coolant. So the real "first" line of defence is the reactor vessel itself.

If the coolant is pressurised, as it is in most thermal reactors to a greater or lesser extent, the integrity of the pressure system becomes of the utmost importance. The two most common designs are those which use steel (such as light-water reactors, the early Magnox reactors and the European HTGR) and those which use pre-stressed concrete (such as the later Magnox reactors and the AGRs). The heavy-water systems (like the SGHWR and the CANDU reactors) have the coolant passing not through a single large vessel but through a battery of hundreds of parallel pressure-tubes.

A pre-stressed concrete vessel is held in compression by thousands of steel cables, individually secured. The integrity of such a pressure vessel, more than 10 feet thick in every direction, against even the most violent phenomenon conceivable in its interior, seems unquestionable. The same is said, by both British and American reactor builders, about welded steel. vessels, at least by implication: because for both industries the "maximum credible accident" they consider is a double-ended break of the input coolant duet between pump and pressure vessel. But a steel pressure vessel is a huge barrel of welded steel, subjected to high pressures, high temperatures and intense neutron bombardment. Boilers in non-nuclear plants have been known to burst. Such boilers, while perhaps subjected to higher pressures or temperatures than a reactor pressure vessel, have not undergone intense neutron bombardment. The reactor vessel has. Neutron bombardment changes crystal structures; the distorting and destructive effects it produces on a srnaller scale are well known but continue to reveal new aspects. Thus far, the long-term effects of intense neutron bombardment on large-scale structures are simply outside the realm of practical experience.

Be that as it may, the maximum credible accident considered by reactor builders is effectively an abrupt and total loss of pressurisation. It is assumed - and this is important - that the immediate consequence of this or any less serious accident is an automatic reactor scram: emergency insertion of control rods to shut down the fission reaction. (This is also known as a "reactor trip".) Emergency scram devices include. for instance, control rods suspended by electromagnets so that the rods will drop into the core if the magnet current is shut off; sprays of boron solution or powder; and baskets of boron-steel balls electromagnetically magnetically suspended, used in graphite-core reactors in case distortion should interfere with rod insertion. Nonetheless, there have been instances of scram failure - fortunately not in the context of a loss of pressurisation. When, as in such a case, a parallel set of identical safety devices all fail for the same reason (usually a design flaw), the result is called a common-mode failure. Records of reactor operating experience reveal many examples, in a wide variety of contexts - none serious, thus far.

Once a reactor is scrammed, and its fission reaction shut down, the majority of the internal heat generation is cut off - but not all. Some of the heat in the core comes not from fission but from the radioactivity of the fission products themselves; in gas-cooled reactors perhaps 6 per cent, in water-cooled reactors with higher power density perhaps 10 per cent or more. This "decay heating" is unaffected by scramming the reactor, although it decreases as the fission products decay. Loss of pressurisation. even if followed within seconds by a reactor scram, means less efficient cooling, leading to a surge of temperature within the core. In a gas-cooled reactor the surge brings with it the possibility of melting or even ignition of Magnox cladding, coupled with serious distortion of the uranium metal; however, stainless steel cladding and uranium dioxide fuel in AGRs will have a margin of safety some hundreds of Centigrade degrees above the probable temperature maximum. Gas-cooled reactors are provided with emergency blowers and emergency supplies of carbon dioxide; even the relatively slow circulation of coolant should be enough to keep the fuel below dangerous temperatures. The mass of graphite moderator itself tends to soak up excess heat. The main requirement is that air be excluded from the core; if air were to enter, it might lead to ignition not only of the fuel but also of the graphite. In 1957 the Windscale Number One plutonium reactor was destroyed by an internal fire caused when an unexpected surge of heat ignited fuel and graphite in the air coolant. Only filters, installed in the preceding months as a belated precaution on the coolant-discharge stacks, prevented a disastrous spread of radioactivity over the surrounding countryside. As it was, many thousands of gallons of milk contaminated with radioactive iodine 131 had to be poured into the sea.

Loss of pressurisation in a water-cooled reactor, with its higher power density, could have a much more alarming sequel. In the maximum credible accident - a break in a coolant inlet duct just outside the reactor vessel - the whole of the cooling water might be lost in a matter of seconds. Recall that the water is under very high pressure; such a loss-of-coolant accident or LOCA is often referred to as a "blowdown". In the first few seconds after blow-down the decay heating from the fuel will cause the core temperature to shoot up; if this surge of temperature is not arrested within 15 seconds the consequences may be very serious indeed. The zircaloy cladding may weaken or melt; the zircaloy may react with the water, releasing hydrogen which may cause a major explosion; the buckling fuel elements may totally block coolant flow; the resulting collapse of the core may lead to a major "melt-down", in which the pool of intensely radioactive molten metal, still generating its own heat, plummets through both pressure vessel and containment, melting., burning and exploding its way downward under gravity, impossible to arrest. Such an eventuality has been sardonically termed, because of its direction of progress, the "China syndrome'". The release of radioactivity caused by such an accident at a large modern light-water reactor could would make even the Brookhaven figures look comforting.

To forestall such an outcome. water reactors are fitted with ernergency core cooling systems, or ECCS. In a pressurised water reactor the ECCS is designed to flood the core with emergency cooling water from below; in a BWR the ECCS is designed to spray emergency cooling water from above. However, such systerns have never been tested under accident conditions in a full-scale reactor; and, despite prolonged and expensive computer simulations and tests of models, there seems every possibility that the ECCS on both PWRs and BWRs may not work.

The intense controversy over ECCS is only one of several themes relating to reactor safety, or the lack thereof, now coming increasingly into prominence. Another was revealed when fuel elements discharged from the Beznau Number One reactor, a PWR in Switzerland, and from the Robert Ginna reactor in Rochester, New York, both proved to have undergone serious deformation under irradiation. The fuel pin cladding was crushed and crumpled, and upon examination was found to be partially empty inside. No reason for this development has thus far been reliably established; but fuel of a similar type is being used in several reactors now in operation in the US, and worries are being expressed that a wholly new phenomenon has been discovered, not necessarily confined to this type of fuel element. The AEC, belatedly informed of the discovery, reacted by issuing an edict that, in effect, nothing be done: that power levels of other reactors using the type of fuel in question be neither increased nor decreased. As edicts go it was comparatively easy to obey. Whether it meets the needs of the situation is more questionable.

Lesser accidents could involve for instance: partial failure of coolant circulation, due to internal blockage or pump failure; failure of control-rod drives; valve failure; electrical failures of many kinds; and - above all - simple human failures. As reactor operation becomes more and more routine, as personnel come to take it for granted, as earlier dedication gives way to everyday job-holding, the probability of operator error grows. There have already been spectacular instances; in 1970 the Dresden 2 BWR near Chicago spent several hours with its water coolant falling and rising in the pressure vessel like a stormy sea, alternately leaving its core exposed or feeding water into the turbine-line - abetted by both junior and senior operators doing one wrong thing after another. Control was recovered more by luck than management. In questions of reactor safety, luck is much too fickle to count on.

It is necessary to add one more word, with particular reference to the safety of liquid-metal-cooled fast breeder reactors. In contrast to most thermal reactors, the liquid metal coolant of a fast breeder is under near-atmospheric pressure, putting much less strain on the reactor vessel and piping. In addition its thermal conductivity is high, so high that it is claimed that adequate cooling would be achieved even if the coolant circulation failed. Nonetheless, the coolant is flowing at very high speeds; even a slight blockage could impose sudden severe strains on pipework and internal structures. Such a blockage, with the resultant cooling impediment, led to the partial meltdown of the core of the Detroit Edison fast breeder reactor in 1966. If the coolant should be lost, or even be allowed to reach boiling temperature, with formation of bubbles in the core, the consequence would almost certainly be very rapid meltdown. Needless to say, metallic sodium reacts explosively with water and indeed, at these temperatures, with many other substances, even including air; there is no possibility of emergency core cooling in a fast breeder. In addition, to all the problems associated with equipment malfunction and operator error, there must be added one last caveat.

The fuel in a fast breeder, unlike that in a thermal reactor, might, during the course of a ineltdown, collapse into a shape in which the concentrated fissile nuclei could produce a fast chain reaction: that is, a nuclear explosion.

Which is where we came in.

Reprocessing

One feature distinguishes nuclear power technology from all others: the left-overs. Unlike the ash, say, from a coal-fired station, the used fuel from a nuclear power station contains both very valuable material and uniquely troublesome waste. The first large reactors were built expressly so that, under neutron bombardment, the uranium 238 in the fuel would be transmuted into plutonium 239. This plutonium had to be recovered, as did the unused uranium 235 which was still left after fission products had poisoned the chain reaction. The same requirement holds today; both plutonium and uranium are much too valuable to throw away. Nor must the remainder of the fuel, the fission products, be thrown away - not because of their value but because of their dangerous radioactivity. So the irradiated fuel from a reactor must be "reprocessed".

A reprocessing plant is a chemical plant - but no ordinary chemical plant. Because its raw material, irradiated fuel, is intensely radioactive, all the operations must be carried out by remote control, behind shielding. The process-equipment must be highly reliable, and require a minimum of maintenance: once it has been contaminated by the radioactivity, any malfunction will necessitate months, or indeed years, of decontamination before it can be set right. Accordingly the process-line uses a minimum of mechanical parts, and depends instead on gravity-flow and simple valves.

Different designs of fuel require different handling. The British reprocessing plant, at Windscale, was set up to handle fuel elements from the plutonium reactors and the Magnox reactors. Fuel elements enter in shipping casks, which are opened by remote control, while operators watch on closed-circuit television. Transferred to massive shielded transport cases, the fuel elements are lifted 15 storeys to the topmost floor of the plant, and fed into the first of a series of "hot cells". Operators viewing through yard-thick double windows filled with orange-tinted bromine solution pick up the elements by remote control and drop them on to a stripping machine which unzips the metal cladding as easily as peeling a banana. The contaminated cladding drops down a chute into the thick concrete bin which extends from ground level to the tenth storey of the plant, there to remain indefinitely. The bare fuel rod is chopped into short slices and dropped into a vat of acid, which dissolves it.

Zirealoy-clad fuel is treated the same way, except that entire fuel elements, up to nine inches in diameter, are simply chopped into slices without being stripped. The irradiated fuel is dissolved out of the cladding by acid. The Zircaloy remains fall into a bin adjoining that for Magnox. By chemical means the acid solution is separated into three streams: one containing uranium, one containing plutonium, and one containing the fission products. The uranium and plutonium streams each pass through recovery plants and emerge again as solid compounds, ready to be returned for fabrication into new fuel elements (or weapons).

In the course of the process, gases - notably radioactive Krypton 85 - and liquids from the hot cells accumulate; they and other dilute radioactive fluids from contaminated areas are discharged through stacks, or out to sea by means of a pipeline two miles long. The fission-product stream is concentrated as much as feasible, to reduce its volume, after which it passes through a 2-inch pipe encased in a 12-foot concrete conduit to another building nearby, in which are the waste storage tanks. To call these vessels "storage tanks" is to do them less than justice. They are in fact elaborate refrigerators: double-walled stainless steel chambers, about the size of a small room containing seven separate circuits of cooling pipes. Each tank is situated in a concrete cubicle, lined on the floor and up to head-level with stainless steel. There are at present nine tanks each of 70 cubic metre capacity, and three of 150 cubic metre capacity. The most recent tanks are still under construction, and accessible, but the tanks in use are permanently walled in behind thick concrete shielding, never to be seen again. If a tank in use should develop a flaw, its contents can be pumped into standby tanks kept for the purpose.

Similar facilities are in operation in several other parts of the world. The most famous is at Hanford, where the waste from the military plutonium production is stored in some 150 huge tanks, of which some have already begun to leak.

The problem of the high-activity waste from fuel reprocessing is probably the most daunting of all the problems posed by nuclear reactor operation. A significant proportion of the radioisotopes in the storage tanks are long-lived; their activity will not fall below dangerous levels for decades, or, in some cases, centuries and indeed millenia. The fission product radioactivity, once created, can never be destroyed; it must die away of its own accord, in its own time. Occasional suggestions refer to the possibility of transmuting long-lived waste to short-lived, but this would require more energy than the nuclear fuel itself could ever produce. It has been seriously proposed that high-Ievel waste might be fired from the earth by rocket to the sun; but once again the cost would be - excuse the expression - astronomical: requiring eventually several launches per week with the ever-present danger of a rocket failure dumping the waste back to earth. Other equally futuristic proposals include the notion of dumping such waste in casks on the ocean bottom, where geological movement might gradually swallow them into the earth's interior. But a realistic view is that we are stuck with however much high-activity waste we create - and so are our children, and our children's children for centuries hence.

The waste cannot be simply be left to itself. Under the action of the hot acid, tanks will corrode and must be replaced. The cooling must be maintained, lest the liquid boil and burst the tank. Accordingly, attempts are now under way to find a way to solidify the waste and at least simplify the storage problem. It has been found possible to "glassify" the waste: to evaporate it and melt the solid into a - hopefully - impermeable glass brick, which can then be stored, perhaps, underground. But the annual waste from a 1000-MWe power reactor would still require about 15 cylinders some 30 cm in diameter and 3 m long: and these cylinders would be both hot and highly radioactive. Hopes are being pinned on the possibility of storing such cylinders in salt caverns underground. It is believed that the salt, heated to melting by the radioactivity, would provide protection against contact with ground water, and adjust itself into snug heat-conductive packing around the cylinders. But one attempt at least, at Lyons, Kansas, came to grief when the salt beds proved to have unexpected fissures. Canada has flatly announced that her high-level waste is to be stored above ground in tanks until a fully proven technique has been established for any alternative method.

Nuclear insurance

Energy economics is becoming a major discipline in its own right. One of its most urgently needed areas of study is that of the comparative costs (and benefits) of nuclear as against non-nuclear energy sources. Is it too much to hope that any such study would accept as a third alternative the more fundamental possibility of simply using less energy? As it is, the ascertaining of true costs, capital and running, taking account of research and development, reasonable amortisation of plant, subsidised services, and countless other niceties, is a challenge crying to be met.

The most blatant example of dishonest financing of nuclear technology occurs in the field of insurance. In the US in the mid-1950s it became apparent, especially after publication of WASH-740, that electrical utilities were shying noticeably away from the "promise of cheap, inexhaustible power" ostensibly there for the taking. The problem was simply that no insurance company, indeed not even a huge consortium of insurance companies, could be persuaded to provide coverage against the possibility of a major reactor accident. Although insurance could be obtained for almost any other conceivable eventuality, the mind-numbing consequences of a massive release of radioactivity froze the insurance companies in their tracks.

Accordingly, two members of the Joint Congressional Committee on Atomic Energy (JCAE), Price and Anderson by name, drafted, and in 1957 won Congressional backing for, the Act which now bears their names: The Price-Anderson Act specifies, in effect, that reactor operators shall chase up as much coverage as they can persuade private insurance to offer - even now only some $66 million. To this the US Government adds another $500 million. Beyond this - remember that WASH-740 foresaw property damage alone reaching $7,000 million - it's every man for himself. Furthermore, if no claims have to be covered, even the grossly inadequate premiums paid by the operators are eventually refunded - which must make other industries, not to mention ordinary householders, more than somewhat envious. In 1965, two years before the Price-Anderson Act was due for renewal, the renewal was hustled through, lest later objections prove an embarrassment to the suddenly uncovered nuclear industry. Accordingly, 1977 will be an interesting year in the US nuclear business.

Meanwhile, a similar pantomime was taking place in Europe, both nationally and internationally. In Britain, for instance, according to the Nuclear Installations Acts of 1965, a reactor operator need provide coverage for only £5 million liability; the government adds another £43 million - and that's the lot, which makes even Price-Anderson look generous. Furthermore, there have been efforts since before 1960 to reach international agreement on insurance against nuclear hazards; the vagrant habits of radioactive clouds are all too well documented. But the efforts have been thus far quite in vain. Draft documents have been calculated several times, but not ratified.

Nuclear economics

Despite the feather-bedding, the nuclear industry has long made great play with the economies to be gained by nuclear generation of electricity. In the early days - the late 1950s in Britain, the early 1960s in the US - it was not unusual to be told that nuclear power would be so cheap that it would totally wipe out the coal industry. Within a decade the nuclear proponents have done a somersault. Indeed, in the past two years the warning has gone out that supplies of uranium are growing scarce; that the fast breeders are arriving in the nick of time to generate new fissile fuel, since natural supplies cannot otherwise last out the century. Neither extreme position bears close examination.

The early euphoria has, of course, been long since discredited. Nuclear fuel may have its advantages, but its manufacture is a lot more complicated than breaking coal. Nuclear plant, too, involves capitalisation perhaps five times as high per kilowatt of output as does fossil-fuel plant. When the nuclear plant involves new and otherwise untried technology, and must be debugged as it is built, the costs have a tendency to spiral skyward, and construction schedules seem the stuff of fantasy, even without external hindrance from neighbourhood doubters.

Nonetheless, having displayed their inability to forecast the current situation accurately, the forecasters are moving enthusiastically onwards, and insisting that energy "demands" "requirements" "needs" - vigorously encouraged by advertising and promotional rates - can only be met by a crash programme to construct commercial fast breeder reactors. Otherwise the supplies of uranium presently mined, costing (in the US) only some $6 to $8 per pound of yellowcake, will soon be exhausted, and more expensive uranium must be mined. This argument ought to be examined minutely. The cost of fuel - that is, of ore - for a reactor is a much smaller proportion of its total cost than is the cost of fuel for a fossil-fuelled station. Accordingly, an increase in the cost of uranium, even an increase by a factor of 10 or more, will produce only a trivial increase in the cost of the electricity generated. The supplies of cheap uranium, at least those in proven reserves, are indeed not likely to last very long; but moving to more expensive uranium (that is, to lower-grade ores requiring more processing) extends the available reserves by centuries. That being the case, the urgency of fast-breeder development looks more than somewhat specious, especially since - as usual - the taxpayers are taking all the risks, both financial and physical.

Cross-examining your friendly neighbourhood reactor

One way and another, the international nuclear industry, though pampered by governments, is more and more facing informed dissent, and problems are less and less readily possible to conceal or deny. In the early days a reactor was a military installation: it could be set up anywhere, and protests were not only unpatriotic but futile. This is no longer so. Since the historic opposition to the plan for a power reactor on the California coast at Bodega Bay succeeded, nearly 10 years ago, in stopping its construction, reactor-siting has become a matter not only of economics, geology, and hydrology, but of politics; and the opponents may also have a good deal to say about the geology and hydrology. In the US and on the European continent there has in the past five years been an unending series of confrontations over planned construction of reactors - although it is true that there has been thus far, virtually no opposition to reactor-siting proposals in the UK. But signs are increasingly evident that the international fellowship of reactor-adherents will soon be matched by an international coalition of opponents.

The whole life-cycle of a reactor is now being questioned. The cross-examination includes at least the following questions:

1. Why is it to be built? If for power, is nuclear power clearly the best choice? Is the power itself clearly needed?

2. Why is it to be built at that location? Has note been taken of possible seismic hazards? (If a reactor were to encounter an earthquake, even a pre-stressed concrete containment might not survive intact.) What about tornados? Hurricanes? Floods? What about cooling? What about local ecology? Aesthetics? Should it be so close to centres of population? In the event of an air crash, might it be underneath? Should it be underground?

3. Who is to pay for it and how? (This is never easy to find out, but even in the most aggressively "free enterprise" context it is a near-certainty that the taxpayers' money will be in there somewhere - and not just via his electric bills).

4. What are the benefits, and who gets them? (Orders for plant and machinery, local employment on construction, and similar factors will be cited, and will be significant. But remember the answers to question 3.)

5. Who will run the facility? (By this is meant not "what board of directors?" - although that is relevant - but "what qualified staff, and how qualified?" Does a junior technician know what a mistake on his part might lead to? Does he care? Do his superiors?)

6. What safety features does the plant embody? Do they work? Who says so - merely a computer?

7. What contingency plans and emergency procedures are envisioned? Will they be adequate to limit the consequences of an accident? Or will they just make the consequences better documented?

8. What insurance cover will the plant carry? How will it be financed? By whom?

9. What running releases of radioactivity will take place during normal plant operation? Who will measure them? What will be their effects? Are they necessary? That is, would the extra cost of not releasing radioactivity make the nuclear option less economically enticing?

10. What services will the plant require? In particular what fuel shipments will be involved? By what means? Along what routes?

11. What will become of the plant at the end of its useful life? (Nowhere in the world has anyone thus far dismantled a large power reactor which has been running for years. The problem of "decommissioning" even small reactors is considerable. The

fuel and coolant can be removed, but nothing can be done about the radioactivity of the core materials. It seems probable that a site on which a large reactor has operated will have to be "dedicated in perpetuity" - that is, left with the hulk of the reactor, possibly entombed in concrete, as an everlasting monument to, say, 30 years of electrical output.)

12. What security can be offered, at every stage, against damage which is not accidental but wilful? - that is, against sabotage?