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The British Atom

There has been very little public opposition to nuclear power in England, although that country, the first in the world to generate commercial electric power from the atom, has proportionately a far larger nuclear electric power program than the US or any other country. One reason for this lack of protest is a critical safety advantage held by British reactor designs as compared with those of the US.

In the US much current opposition to nuclear power plants centers on the possibility of a catastrophic reactor accident. Hearings currently being conducted by the Atomic Energy Commission (see "Nuclear Safety," *Environment*, September 1972) are exploring this difficult issue. The most likely cause of a serious accident in a nuclear power plant is believed to be the bursting of a pipe carrying cooling water, which would leave the fuel of the reactor briefly exposed. Following such an accident, the fuel would heat very quickly and, without cooling water, would rise to temperatures at which the fuel itself and supporting structures would melt. Once such a meltdown had occurred, even a small leak in surrounding structures would allow release of large quantities of radioactive material to the surrounding air.

In British reactors of the Magnox type - essentially all of the nuclear power plants in Britain - much more fuel is used to generate a given power level. The "power density" in these plants is therefore much lower; less vigorous cooling is needed; and in the event that forced cooling is lost through some accident, the fuel would not heat up to the point of melting. (The power density of British Magnox reactors is typically 2.4 kilowatts per kilogram of uranium fuel, one-quarter or less of the power densities in US reactors.)

This safety advantage, which appears more substantial as US reactors are increasingly criticized, is to some extent a fortuitous development of the British reactor program. As that program may have other advantages over its US counterpart, a more detailed examination may be worthwhile.

On October 17, 1956, at Calder Hall, Cumberland, England, Her Majesty the Queen switched on the supply of electricity generated by a nuclear power station. Fifty-one weeks later, on October 8, 1957, at the Windscale Works across the narrow ravine of the Calder River from Calder Hall, a technician switched on the Windscale Number One plutonium-production reactor for routine maintenance, did so too soon, and set off what became the classic reactor accident. Although no one was injured directly, substantial quantities of radiation, particularly radioactive iodine, were released and drifted with the wind across England and into northern Europe. These two events, occurring within a year and a quarter-mile of one another, could well be considered the high and low points of peacetime nuclear technology.

US and England

In appreciation of the service rendered by British and Canadian scientists in the wartime development of fission weapons, the US Congress in 1946 passed the

McMahon Act, which firmly denied foreigners access to US nuclear data. Since that time, Britain's development, first of nuclear weapons, and thereafter of nuclear power stations, has taken place at a pace and within a context strikingly at variance with the American situation. Like the US reactors at Hanford, Washington, the first large-scale reactors built in Britain were principally for the production of plutonium for the manufacture of nuclear weapons. But unlike the water-cooled Hanford reactors, the British plutonium-production reactors at Windscale were cooled by air blown straight through the "piles" and discharged from tall stacks directly into the outside atmosphere. Military urgency dictated the cooling method used in each case: Hanford had the Columbia River, whereas the British could find no suitable water supply sufficiently far from population centers. This early choice of coolant had a pronounced effect on the consequent development of power reactors in the two countries. Only within the past five years has the British industry manifested a serious interest in water-cooled power reactors, and the American industry a similar interest in gas-cooled power reactors. Even this belated interest on either side has an element of contrast and irony, as we shall see.

In the early 1950s, the two Windscale reactors working to capacity could not satisfy the British military craving for weapons-grade plutonium. But with a breathing spell after the first frantic design and construction job, the British engineers determined that all that heat should not simply go up the stacks. So the four reactors of the Calder Hall installation, built just across the ravine from Windscale, while optimized for plutonium production, were no longer cooled by single-pass air at atmospheric pressure like their elder brothers, which, as it turned out, was just as well. Carbon dioxide in a closed cooling circuit was used, and the heated gas leaving the reactor was used to generate steam to produce electricity. The Calder Hall reactors, however, like the Windscale reactors, did use a graphite moderator and natural uranium fuel. This was to set a pattern unique to British power-reactor design. Although the two Windscale reactors were shut down permanently after the accident, the Calder Hall reactors and those of the sister plant at Chapelcross in Scotland have been in almost continuous service since their commissioning, as the cornerstones of the British nuclear power industry. Their design characteristics were adopted, with cumulative minor modification, for the entire first generation of British civil power reactors.

Each of the eight Calder Hall and Chapelcross reactors is housed inside a cylindrical mild steel pressure vessel about 70 feet high and 37 feet in diameter. The fuel core is a.polygonal prism of machined graphite, 650 metric tons in 58,000 bricks. There are 1,696 vertical fuel channels. Each channel holds a stack of six fuel elements, which are made of natural uranium clad in a magnesium alloy called Magnox. (This alloy gave its name to the whole family of British natural-uranium reactors, which have always been known as Magnox reactors.) The total fuel charge consists of 110 to 115 metric tons of natural uranium. Each fuel element has a finned outer surface to improve heat transfer to the carbon dioxide coolant, which passes through the channels at a pressure of 115 pounds per square inch and emerges at an outlet temperature of 345 degrees C (653 degrees F). The carbon dioxide then passes through four heat exchangers to generate high-pressure steam at 320 degrees C (608 degrees F), at 225 pounds per square inch, and low-pressure steam at 180 degrees C (356 degrees F), at 55 pounds per square inch. Each reactor is rated at 268 megawatts (thermal), 50 megawatts (electric); in addition, the Calder Hall reactors supply the steam requirements of the elaborate Windscale fuel-reprocessing and other plants.

Magnox and After

It is important to note at this point that unlike those of the US the electrical utilities of Britain are nationally-owned. The Central Electricity Generating Board (CEGB) is the one utility which provides electricity for all of England and Wales; in addition there are two utilities in Scotland, of which the North of Scotland Hydroelectric Board is as yet the only one to operate nuclear power stations. Northern Ireland does not have any nuclear power stations, which, in present circumstances, may be one of that troubled area's few blessings.

The Calder Hall and Chapelcross stations are now owned and operated by British Nuclear Fuels Ltd (BNFL), which until recently was part of the United Kingdom Atomic Energy Authority. As indicated, these eight reactors were intended as plutonium-production reactors; but the electricity they generate is sold to the utilities, making BNFL a tidy income quite apart from its fuel-handling operations. In addition to buying electricity from Calder Hall and from the Atomic Energy Authority reactor-development site at Winfrith in Dorset - about which there will be more later - the CEGB also operates eight of its own nuclear power stations, each with two Magnox reactors now in operation. The North Scotland utility, in addition to buying electricity from BNFL's Chapelcross station, has its own nuclear power station at Hunterston, with two Magnox reactors currently in operation.

As in the US program, problems have appeared during operation of the Magnox reactors. The most serious difficulty to date has been unexpected corrosion in the reactors, which has forced BNFL to operate the plants at less than maximum power. Despite these problems, in April 1972, the *Daily Telegraph* reported that the CEGB had assessed the cost of electricity generated by its coal-fired, oil-fired, gas-fired, and nuclear power stations and found that the nuclear stations are now producing the nation's cheapest power. A framed copy of the *Telegraph*'s news story now hangs triumphantly on the wall of the display room at the CEGB's Dungeness A Magnox station. It brings, however, little solace to those whose responsibility centers on Dungeness B. The story of Dungeness B encapsulates the end of the halcyon days of the British nuclear power industry.

Although the original Magnox design underwent innumerable incidental modifications as successive stations were constructed and commissioned, it was decided in the late 1950s that a new design was indicated. In 1962 a small prototype of this design was commissioned at Windscale, christened the Advanced Gas-Cooled Reactor. A decade later the Windscale AGR - 105 megawatts (thermal), 33 megawatts (electric) - remains the only AGR which has supplied any electricity whatever to the national grid.

On the basis of the generally encouraging experience with the Windscale AGR, the CEGB in 1965 opted for two AGRs for its Dungeness B station, which would be built next to the A station with its two Magnox reactors. The AGRs were selected in preference to American light-water reactors; it is piquant to speculate whether with hindsight the CEGB would have made either choice, given the present chaos at Dungeness B and the growing uncertainty about the safety of US light-water designs. More than one CEGB staffer has since been heard to mutter that "they should have stuck to the Magnox reactors," which Tom Tuohy, former general manager of

Windscale and now a managing director of BNFL, says have "the only fully-proven reactor design in the world."

On paper the AGR design looks very promising. Instead of a steel pressure vessel, the AGR has a pressure vessel made of prestressed concrete, which encloses not only the core, but also the gas-circulators and the boilers. A bell-shaped inner pressure cylinder separates the core from the boilers. The safety advantages of such an arrangement are obvious. For Dungeness B the moderator is 1,140 metric tons of graphite. The 408 fuel channels include 3,264 elements, each of 36 pins, 8 elements to a stringer; each element is clad in stainless steel. The fuel is uranium dioxide; the initial charge is 1.47 to 1.76 percent enriched in uranium-235, and enrichment of feed is 1.99 to 2.42 percent. The total fuel charge is 151 metric tons of uranium dioxide, including 24 kilograms of U-235. The design-rated specific power of each Dungeness B reactor is 9.5 kilowatts per kilogram uranium, as against only 3.16 kilowatts per kilogram uranium for the Wylfa reactors, the largest of the Magnox generation. As a result, the outlet temperature of the coolant carbon dioxide is 675 degrees C (1,247 degrees F), offering a greatly-increased conversion efficiency over that of the Magnox reactors (and incidentally leaving the light-water reactors far to the rear). The higher thermal efficiency means less thermal pollution, a consideration which has been important in growing US interest in this design. However, design is one thing; constructing and commissioning are quite another.

The first reactor at Dungeness B was originally intended to go into production by April 1970; the second, a year later. But the builder, Atomic Power Constructions Ltd, fell into financial difficulty; and cracking and corrosion problems began to materialize. The design of the AGR called for the steel inner containment, including the core, all the ancillary pipework and fitments, and the gas-circulators and boilers to be suspended from the concrete roof of the outer pressure vessel. The engineering problems created by this design have contributed to delays which have set the project so far back that it is now not expected to go into production before 1974. The AGRs at Hinkley Point B station in Somerset, which were begun well after those at Dungenees B, are now very likely to come into service before the Dungeness AGRs. Three other AGR stations are under construction, but the design's early promise now seems farther than ever from fullfilment.

Sales and Safety

The disappointing history of the AGRs has another corollary of significance. Only two stations using Magnox designs have been built outside Britain. One was built at Latina, Italy and the other at Tokai Mura, Japan. Although Britain was the first country to generate electricity commercially from nuclear fission, the US, a comparative latecomer to the field, expanded its nuclear program both at home and abroad. Lightwater reactors sprang up not only all over the US, but in many other countries, including those of continental Europe. Britain had hoped that her gas-cooled designs, particularly the AGR, would win her at least a share of the burgeoning market. For a number of reasons this did not happen. The effect on the indigenous industry was inevitable. The British nuclear industry stumbled into a series of crises which seem now to be blurring into one continuous crisis - despite the probability that the gas-cooled designs are not only more efficient, but more environmentally sound and considerably less suspect on the score of safety.

Expert opinion both inside and outside the British nuclear industry acknowledges that, paradoxically, the Windscale accident may have been a good thing. The jolt that it gave the British nuclear community has never been forgotten; the episode is still clearly vivid in the minds not only of senior executives but also of nuclear wage earners. As a result, the safety-consciousness of Britain's reactor builders and operators is unquestionable. The provisions and controls regarding reactor accidents and planned release of radioactivity both deserve thoughtful scrutiny, particularly by those familiar only with the nuclear industry in the US.

To begin with, no British nuclear executive within recent memory has been known to resort to the traditional cliche, beloved of US reactor adherents, "in the unlikely event of an accident." British reactor sites, which thus far are located as far as possible from centers of population (given Britain's limited area), have regularly scheduled, elaborate accident drills. The arrangements at the Dungeness station seem to be more or less typical. In an office in the Health Physics section of the plant is a large-scale map of the south Kent coast around Dungeness. Several roughly concentric road patterns at increasing distances from the station are traced on the map, which is studded with color-coded pins. In the event of an accidental release of radioactivity from the station, specially-equipped Land-Rovers with scintillation counters mounted on their exteriors would set out at once along the different routes, radioing back readings to monitor the drift of activity. Every six months the Land-Rovers do a practice run, and the readings they take provide a continuous watch on the background radioactivity of the surounding countryside. Around the Dungeness site this background activity is attributable almost totally to natural radioactivity and to fallout from nuclear tests. The monitoring teams have regularly looked for radionuclides characteristic of power station emissions and found them virtually undetectable.

Not only the station operators but also a variety of independent official bodies keep an eye on radioactive emissions. This is probably the single feature which most distinguishes British applied nuclear technology from American. The American situation, in which the US Atomic Energy Commission sets radiation standards and polices them while simultaneously promoting reactor technology, has no parallel in Britain. In Britain the reactor builders and operators are subject to control by bodies that could not care less whether Britain ever built another reactor.

At the outset - and indeed from the design state - the Nuclear Inspectorate (NI) of the Government's Department of Trade and Industry looks over the shoulder of the builder and operator, ascertaining that conditions within the plant conform to requirements. Once the plant commences operation, the NI is joined by the Ministry of Agriculture, Fisheries, and Food, which carries out continuing analyses of radioactive discharges to inland and coastal waterways at its Fisheries Radiobiological Laboratory in Suffolk; and by the Alkali and Clean Air Inspectorate of the Department of the Environment, which monitors the airborne emissions. The Agricultural Research Council Radiobiological Laboratory monitors radiation in milk. This system has some serious deficiencies, however: although the Fisheries Radiobiological Laboratory publishes annual reports of the activities discharged to waterways, the NI and the Alkali Inspectorate operate on a basis of confidentiality. Their evaluations of reactor performance and their dissatisfactions, if any, are communicated to the reactor operator, but not to the public. The air of cosiness exuded by this hand-in-glove relationship between industry and its governmental watchdogs has begun to draw considerable fire in the British press and in Parliament; but it is unlikely to undergo any drastic change in the near future.

Statutes and Standards

The standards that must be satisfied begin with a general requirement laid down in the Nuclear Installations Acts of 1965. If you dissect away the bureaucratese, the import of the relevant clause is that the licensee of a nuclear installation must "secure" that no "occurrence involving nuclear matter" or "ionizing radiations" "cause injury to any person or damage to any property other than that of the licensee." Allowing for the fact that the said "licensees" are invariably corporate, and that a body corporate is much less susceptible than a body human to the effects of ionizing radiation, the clear implication is that the licensee must avoid any nuclear-related happening which causes injury to the public. It is frankly almost an impossibility to decipher the subsequent penalty and compensation sections of the act, which seem to have been drafted for maximum impenetrability; but a figure not entirely concealed in the verbiage is "up to an aggregate amount of forty-three million pounds," to be "made available out of moneys provided by Parliament" for satisfying claims. This is similar to provisions of US law (the Price-Anderson Act).

In any event, the act's requirement implies concern for reactor safety - which is demonstrably present - and control of planned releases of radioactivity. This control must satisfy criteria very different from those in effect in the US. In the US the restrictions on release of radioactivity to the environment are applied on a nationwide basis, in terms of concentration of radionuclides in the discharge. In Britain each single discharge is subject to particular conditions, which depend on its individual circumstances.

As in the US, the general guidelines of the International Commission on Radiological Protection (ICRP) are accepted as a basis, establishing upper limits on the permissible radiation dose to members of the public. For each discharge, a "critical path" and "critical group" are identified. The critical path is the geographical and biological route through which a discharged radionuclide travels and is reconcentrated until it reaches the "critical group" of human beings receiving the most exposure as a result of the discharge in question. The ICRP limits on exposure of the critical group are applied, and followed back along the critical path until they can be translated into an upper limit on the amount of allowable discharge of radioactivity.

This working limit is still only an upper extreme. Anyone wanting to discharge radioactivity has to "make a detailed case to the relevant Government Department showing how much waste he needs to discharge and why it is impracticable for him to achieve a lower figure. After a process of negotiation, a final control figure having statutory force is fixed by the Government Department for that particular discharge. This statutory figure is never higher than, and very rarely equal to, the figure derived directly from the ICRP dose limits."

The "negotiations" in question take place in private; the usual arguments about secrecy versus public lack of expertise continue to percolate without much effect.

(The exceptions to this are the Fisheries Radiobiological Laboratory reports mentioned above.) But the public does at least have the ICRP limits to go on. It is not known, however, if any transgression of these limits has been permitted by the controlling bodies; public records are silent on the point.

Newcomers

The Magnox stations are now all operating; the five AGR stations are under construction. But the third generation of gas-cooled reactors, intended to be the high-temperature HTGRs, have fallen by the wayside. Britain has, it is true, been the main participant in an experimental European Nuclear Energy Agency development project for such a reactor, and a prototype HTGR called Dragon has been in operation at the AEA's Winfrith site since 1964. But the most recent government statement on reactor policy, delivered by John Davies, minister for trade and industry, on August 8, 1972, effectively set aside any foreseeable commercial encouragement for this design. The waning British interest in the HTGR is ironic, set against the sudden success of Gulf General Atomic in the US, which has sold more than half a dozen HTGRs this year even though its prototype at Fort St Vrain, Colorado, is still not in commercial operation. Preliminary discussions between Gulf and the Europeans have given rise to speculation about a possible collaborative effort. That now seems likely to be the only avenue which British HTGR experience can still travel, given the concomitant circumstances.

Meanwhile, also at the Winfrith site, the British on their own have developed a radically new design of water-cooled reactor, the Steam Generating Heavy Water Reactor (SGHWR). The prototype was commissioned in 1968 at a design rating of 292 megawatts (thermal), 100 megawatts (electric), and has been feeding electricity to the grid, with some interruptions, since that date. The SGHWR core consists not of a pressure vessel but of a bank of pressure tubes passing through vertical channels in a vessel filled with heavy water at atmospheric pressure. Each pressure tube contains a fuel element in the form of a bundle of 36 fuel pins; each pin is a column of low-enriched uranium dioxide fuel pellets in a zirconium alloy can. Light water coolant passes through the pressure tubes and boils, producing steam at 278 degrees C (532 degrees F). Superheating channels are also provided, in which the fuel elements are clad in stainless steel; the steam outlet temperature from these channels is 538 degrees C (1,000 degrees F). The specific power in the boiling channels is 13.9 kilowatts per kilogram, comparable to present US reactors, and in the superheat channels 16.4 kilowatts per kilogram. The reactor is shut down by flooding interlattice tubes with boric acid solution and by dumping the heavy water. The reactor power is changed by adjusting the level of the heavy water, and (to allow for burn-up) by poisoning the heavy water with boric acid.

The SGHWR design has a number of distinctive features. Unlike most other reactor designs the SGHWR can vary its output with demand; it can be built to smaller sizes without loss of efficiency; and it is both flexible and amenable to in-service maintenance. (At one point in the experimental program six pressure tubes, which had been installed on a trial basis for the early stages of reactor operation, were removed entirely from the interior of the reactor and replaced with others.) The SGHWR did have some early problems with leaky fuel, but these have apparently been fully overcome. The SGHWR has emergency cooling systems which pump emergency coolant through the axis of each fuel element; performance of the systems has been extensively investigated with a full-length (12-foot) electrically-heated element test-rig on the Winfrith site - for which power is supplied by the SGHWR itself.

The North of Scotland Hydroelectric Board showed great interest in the possible selection of SGHWR power for its planned station at Stake Ness on the east Scottish coast. But government temporizing finally scuttled this idea, and there are now no plans for construction of a commercial SGHWR in Britain. Recent Australian interest in the SGHWR has been hampered by the obvious question: if this new design is so good, why has Britain not built one?

A Question of Breeding

The immediate reason was cogently expressed by A. E. Hawkins, recently-appointed chairman of the CEGB, in the summer of 1972. He told the House of Commons Select Committee on Science and Technology that Britain's electrical needs were growing so slowly that it would not be necessary even to decide on any new power stations - of whatever kind - for at least a year. The slow rate of growth is in part due to discoveries of extensive gas and oil reserves in the North Sea, which can be used for heating and other purposes served in the past by electricity. Beyond the lack of current necessity for new reactor power there lies Britain's long-term commitment to the liquid-metal fast breeder reactor.

The Dounreay Fast Reactor (DFR) on the remote north coast of Scotland is the world's leading candidate for most photogenic reactor, a futuristic structure nestling amid rugged rocks. It has been in operation since 1959, far-and-away the longest-running fast breeder reactor in the world. The first American fast breeder of comparable size was the notorious Enrico Fermi 1, between Detroit and Toledo, which has been shut down almost continuously since an accident in 1966.

The DFR core is a hexagon only 21 inches high and 20.5 inches across, containing 324 fuel channels with a central channel for experimental assemblies. The core is surrounded by a breeder blanket of 1,872 fuel channels. The fuel elements are 75 percent enriched uranium clad in niobium. There is, of course, no moderator. The coolant is a sodium-potassium alloy, a liquid at room temperature which emerges at an outlet temperature of 350 degrees C (662 degrees F) and passes through 24 heat exchangers which are also contained within the biological shield of concrete five feet thick. The whole reactor is enclosed within a steel containment sphere 135 feet in diameter. Control is provided by twelve groups of fuel elements which can be raised or lowered. The specific power of the reactor is approximately 300 kilowatts per kilogram uranium-235; the driver charge contains about 245 kilograms of U-235. The design power of the reactor, which was reached in 1963, is 60 megawatts (thermal), 14 megawatts (electric).

The success of the DFR paved the way for a larger commercial prototype, the Prototype Fast Reactor (PFR). It is interesting to note in passing that consideration was given to siting the PFR at Winfrith, in Dorset; but pressure from the residents of Dounreay and Caithness played a key role in the decision to site the PFR also at Dounreay. This must be one of the few instances on record in which a local population has lobbied vigorously to have a large experimental reactor on its collective doorstep.

The PFR was scheduled to be commissioned in 1971, but the by-now seemingly inevitable delays have set it back until, probably, 1973. It differs from the DFR in a number of important respects apart from its size, which is a full order of magnitude larger: 600 megawatts (thermal), 250 megawatts (electric). Its core is an array of hexagonal subassemblies 5.6 inches across the flats and 12.5 feet long; 78 are core subassemblies, 42 radial breeder subassemblies. Each fuel assembly contains 325 fuel pins, each 9 feet long and 0.23 inches outside diameter, clad in stainless steel; each fuel pin contains a 36-inch length of fuel with uranium oxide above and below as axial breeder. The fuel is a mixture of uranium and plutonium dioxides; in the inner core the mixture contains 19 percent plutonium, in the outer core 25 percent plutonium. Curiously enough the specific power of the PFR is less than half that of the DFR, a mean of 142 kilowatts per kilogram oxide. Again there is no moderator. The coolant is liquid sodium, whose outlet temperature is 560 to 600 degrees C (1,040 to 1,112 degrees F) producing steam at 513 to 438 degrees C (955 to 1,000 degrees F) and 2,315 pounds per square inch.

The initial fuel charge for the PFR is now being manufactured at Windscale. Talk in industry and government circles suggests that the first commercial fast reactor (CFR) will be ordered about 1978 to go into production in the early 1980s, when the US first prototype is expected to begin operation. But the hitherto unhesitating acceptance that the CFR is the long-term objective of the industry is now at last beginning to receive some cogent questioning. At a press conference in September 1972 for publication of the AEA annual report for 1971, queries referred repeatedly to matters of safety and public health and, particularly, to the matter of plutonium hijacking - or "diversion," in the nuclear euphemism. The answer given by Sir John Hill, AEA chairman, echoed that given in private conversation by Tom Tuohy of BNFL - in effect, "Yes, we are aware of the possibility; yes, we have taken the necessary steps to provide satisfactory security; no, we cannot say what these steps are, because to do so would reduce the security."

Newspaper reports, television programs, and public discussion are, however, at last beginning to take a more critical attitude toward nuclear power than has heretofore been the case in Britain. Whatever line of development does materialize out of the present lack of direction, one thing is certain - more people will be watching, and more questions will be asked.