

## **THE BACKGROUND TO THE DOUNREAY FAST REACTOR**

The reconstruction of the UK in the aftermath of the war was hampered by a number of important shortages. In particular, indigenous, readily extractable coal supplies were scarce and the adverse balance of payments was made worse by the necessity to import fossil fuel.

Nuclear power, seen as an energy source which could meet these urgent needs, was threatened by a shortage of uranium and this shortage was soon compounded when the demand for nuclear weapons made large inroads into existing uranium supplies. The only methods then in use for producing power from uranium were based on water-cooled thermal reactors which could utilise only one per cent of the natural element.

The utilisation of the uranium, which had been discharged from the thermal reactors, provided the strong incentive to develop a type of breeder reactor which could utilise a very much higher fraction of the available uranium.

While the possibility of successfully building a breeder reactor utilising slow neutrons was not ruled out, there was more confidence in a fast neutron reactor system and this led naturally towards DFR.

The Dounreay Fast Reactor was a completely new venture; the only other fast reactors then in existence world-wide were of low power output, and detailed information about them was unavailable to the UK. Consequently, the designers had nothing but their imagination to guide their conceptual thinking.

To appreciate the extraordinary vision of those responsible for DFR design it is necessary to reflect on the state of the UK electricity supply industry in the days immediately following nationalisation in 1948.

For new plant, the size of the preferred electricity generator unit was 60MW(E). The DFR designers decided to forego small scale experiments and aim directly for a plant large enough to be considered as a prototype for a fast reactor power station. It was a

brave, forward-looking decision. They were successful and the reactor met the original target of 60MW(H) and the fuel endurance objective of two per cent burn up.

Important lessons were learnt, probably more cheaply and certainly more quickly than would have been the case if a small-scale reactor had been interposed.

By the time construction was completed a number of developments in the electrical power industry were suggesting that radical changes would be required for the fast reactor successor to DFR. Power stations were becoming much larger and operating temperatures much higher.

To meet these demands different materials would have to be employed. A different type of fuel element would be needed, operating in a much higher temperature regime and at a higher fuel rating and a higher fuel burn-up. These developments meant that having met its original targets and shown that a fast reactor behaved as predicted and was easy to operate, the role of DFR changed to being a reactor for testing candidate fuel and constructional materials at high temperatures in a fast neutron flux. It enjoyed a very successful second career in this field. It paved the way for the fuel element development required for the Prototype Fast Reactor; it earned an appreciable sum of money from the sale of irradiation space to customers at home and abroad; it enabled the phenomenon of fast neutron induced swelling to be discovered in time to have a profound influence on the design of PFR and the second generation of fast reactors throughout the world.

By any standards it was an astonishing achievement to build successfully a plant with a power density of 600MW/m<sup>3</sup>, many orders of magnitude greater than hitherto produced by human hand. It placed UK in the forefront of nuclear technology.

The vague concept which ultimately crystallised into DFR began as a subordinate feature of the political and military situation prevailing after the war. These influences were interwoven with fast reactor development. It dilutes the early part of the DFR story but assists the sense of perspective.

In the immediate post-war years the pace of technological advance in nuclear power was extraordinarily fast. In contrast to earlier technologies it was science driven. Steam engines were developed by a process of empirical evolution over several centuries, and long before the science of thermal dynamics was developed. The electrical industry took less time to evolve from the early discoveries of Volta and Faraday to the modern

electrical power industry; but the technology developed before the electro-magnetic equations were established to put the technology on a scientific basis and so guide subsequent developments.

In contrast, the development of the technology of nuclear power was from the outset firmly rooted in basic science and its growth rate was even more expeditious. By 1939, theoretical models of the atomic nucleus had been developed and the potential energy stored in atoms, in the form of nuclear binding forces, was deduced. The first estimates were derived from the recoil energies of particles emitted from radio-active isotopes and then, more quantitatively, by accurately measuring the mass of many isotopes in Aston's mass spectrograph. When the release of fission energy was first recognised in 1939, having been "seen but not perceived" many times during the previous decade, the fundamentals of nuclear fission were already in place and consequently technological progress was very rapid.

By mid-1939 it was discovered that several secondary neutrons were produced for each neutron absorbed in a single fission event and this suggested the possibility of establishing a chain reaction. Peierls, in June 1939, published a paper in which he derived the conditions required for a chain reaction to be established in a spherically shaped multiplying system and the shape of the resulting neutron density distribution within the sphere. His treatment was based on an analogy between neutron and gaseous diffusion. Using the best data available at the time, the possibility of meeting the criteria for self-sustaining conditions seemed to be effectively zero and the war started with none of the protagonists believing that a super-bomb based on nuclear fission was possible. At the outbreak of hostilities the UK and the US decided to concentrate scientific resources on projects that were perceived to be more relevant to the war effort. Frisch and Peierls were barred from war work as they were immigrants; they therefore continued their work on atomic physics. Their memorandum, setting out the basis for a U235 atomic super-bomb, followed in the spring of 1940 and this caused an abrupt change in UK and US policies. The Manhattan Project, which led to the production of the first nuclear weapons, followed.

The production of almost pure U235 required for a bomb was a formidable task and an

alternative was sought. US work had shown that U238 could absorb neutrons and be transmuted to an element later known as plutonium.

Cambridge scientists deduced that plutonium could be fissioned by neutrons of all energies and it would be suitable as a weapon material. The production of plutonium required the irradiation of natural uranium in a chain reacting medium and the nuclear reactor pile was born, the first one being built in 1942 in a squash court at Chicago University under the guidance of Fermi.

In order to place the development of DFR in its appropriate context, it is necessary to dwell on political and national defence matters in the immediate post-war period. It was from the interplay of these forces that nuclear power for civil purposes evolved and early in this process the concept of a fast breeder reactor took shape. The production of military plutonium in thermal reactors generated a large amount of heat and although this was of secondary importance during wartime, and indeed during the "Cold War" which followed, its industrial usefulness had been noted and by the time hostilities had ceased the UK had decided to develop the peaceful use of nuclear energy. But there had been little time to formulate Government policy in detail. This was because extreme secrecy had surrounded the war time nuclear programme and no-one in the incoming Government of 1945, not even Prime Minister Attlee, had been made aware of the war-time atomic bomb development. Similar secrecy in USA led to President Truman learning of the Manhattan Project only on his assumption of office following the death of President Roosevelt.

The first positive step towards an independent UK nuclear energy programme was the decision, in October 1945, to establish a UK centre for nuclear energy studies. This development had been initiated just before Churchill was replaced as Prime Minister and it was Attlee who formally ratified the decision to create the centre at Harwell.

In November 1945 a declaration from Washington, signed by Canada, UK and USA, had sought the peaceful use of atomic energy and the prevention of nuclear war. The declaration was interpreted by UK as signalling a continuation of the war-time spirit of cooperation between USA and UK. Then, in August 1946, the McMahon Act made it illegal for USA to collaborate with anyone on atomic energy matters, not even with Canada or UK.

It effectively isolated the rest of the world from all atomic weapon technology, which was then resident mainly in the USA. This, in conjunction with the Washington Declaration, was intended by Washington to restrict nuclear weapon capability to the USA alone but it effectively covered all aspects of nuclear power. It cut off the UK from the information and fissile material supplies necessary for a military or civil nuclear power programme.

The UK Government policy was to exploit nuclear energy to the full and the effect of the McMahon Act was to compel Harwell to cover all aspects, military and civilian. Four main study targets were set for Harwell:

- A broad based research and development programme to seek fundamental knowledge
- Production of fissile material for use in nuclear weapons if Government policy so required
- Production of useful power from nuclear sources
- Production of isotopes

At about this time another formative influence on the UK nuclear energy programme arose because the USSR had become politically isolated from the West, with bitterness over war reparations and the effective control of the nations surrounding its border. This was the build-up to the cold war and it reinforced the view of the Government that it was essential for the UK to have the deterrent shield of its own nuclear weapons.

The one clear and urgent policy for the UK was the immediate launch of a programme to produce fissile material; this would create an option, though not a commitment, to produce a nuclear weapon. In 1945, before the bombing of Hiroshima, a report by Tizard, (scientific advisor to the Chiefs of Staff) had stated that the only practical answer to a nuclear bomb threat was the threat of retaliation in kind. The alternative, to provide passive protection against a nuclear attack, would require a large percentage of the population to be housed in deep dwellings, living like troglodytes.

The choice of fissile weapon material was not clear. In the USA, plutonium had been produced from water-cooled reactors and U235 from gaseous diffusion plants and centrifuges.

Britain was reluctant to incur the great expense of pursuing both plutonium and U235 production routes. The plutonium route offered the possibility that, to offset the overall cost, useful thermal power could be obtained as a by-product from a natural uranium thermal reactor. But the primary need was clear - the UK needed fissile material for military purposes; the thermal power by-product was a very secondary consideration.

It was quickly agreed that plutonium would be the UK weapon material; it had been shown at Hiroshima and Nagasaki that plutonium was superior to U235 and it was guessed that the construction cost of producing plutonium from a reactor plant would be about half the cost of a uranium 235 diffusion plant. The initial plan was to follow the US and build a water-cooled, graphite-moderated reactor. The Controller of Production Lord Portal, who knew about aeroplane production, strongly favoured this route but Cockcroft and Hinton, who knew about physics and engineering, won the hard fought argument in favour of a gas-cooled reactor

The construction of the plutonium production piles, at Windscale, led to the creation of the second UK Establishment, at Risley, where the design and project control was to be exercised. The first Windscale pile was planned to produce sufficient plutonium for 15 bombs per year and construction of a second pile was expected to follow.

The political debate over weapons continued. The preferred policy was to obtain an international agreement to outlaw the use of nuclear weapons and Britain wished to exert its influence to achieve this objective from the strong position of being a nuclear power. This led to the dual policy of political persuasion plus, as an insurance, weapon development including the production of the required fissile material.

Weapons-grade plutonium would demand very low burn up in the Windscale pile and this was going to be wasteful of scarce uranium. Furthermore, during 1946, the prospects for acquiring supplies of ore containing natural uranium were declining. The uranium, having been discharged from Windscale, and the plutonium extracted, it would be depleted in U235, and could be rejuvenated for re-use only by enrichment. This seemed necessary if the number of weapons was not to be limited to an unacceptably small number.

Recycling of scarce plutonium to enrich the depleted uranium would further restrict the availability of plutonium for weapons. In 1946 the Anderson Committee recommended

the construction of a gaseous diffusion plant to enhance the U235 content of uranium by a factor of twenty and so enable the depleted uranium to be re-used. The cost of the plant was guessed to be £30-40M and construction would take 4-5 years. Its power consumption would represent 0.5% of the total UK electrical power production

By 1947 the scope of the nuclear energy programme became clearer. Plutonium would be produced in a simple air-cooled natural uranium pile. The depleted uranium from the pile would be rejuvenated with uranium enriched in U235, this being produced from a gaseous diffusion plant. As a supplementary but subordinate enterprise, the prospect of utilising the waste heat from plutonium producing piles, an objective favoured by engineers at Risley and Harwell, was receiving increased attention, especially at Harwell. The power steering committee was convened at Harwell in January 1947. The chairman (until February 1950) was Fuchs and its terms of reference were "to consider in detail the various possible schemes for the utilisation of atomic energy for the production of power". Three types were considered: a natural uranium fuelled pile, a thermal neutron breeder and a fast neutron breeder. Cockcroft, while on a visit to Canada, wrote to Tongue, Head of Engineering Division at AERE, suggesting that sufficient work had been done for Engineering Division to prepare costed schemes for these three reactors. He suggested that the fast reactor should be similar to the Los Alamos "Clementine" which was fuelled by thin plutonium metal rods; it was believed to produce 25KW and was mercury-cooled. In requesting Tongue to obtain rough costs for the proposed three reactor types, Cockcroft wrote that financial approval would be sought as a first step towards Engineering Division (Harwell) assuming "executive responsibility for carrying out the job or jobs."

The shadow of the powerful engineering organisation being set up at Risley to control the projects for producing fissile material - the plutonium production piles and, for U235, the gaseous diffusion plant - may have influenced the last point in Cockcroft's letter. Tongue was counselled to consult Mr Hinton "to avoid the friction of responsibilities."

The division of responsibility between the Research Group at Harwell and the newly -formed Industrial Group centred at Risley seemed straightforward. Harwell were responsible for all aspects of nuclear power other than the supply of fissile material, as

required by the nation's defence chiefs. The latter function was the primary role of the Industrial Group.

Hinton did not wish to become involved in research and development work and he readily accepted Harwell's role as the provider of basic knowledge. However, he was critical of the Harwell attitude to research which, he said, was "curiosity driven" whereas he would have demanded a "mission driven" approach.

At the third meeting of the power steering committee, February 1947, the disposal of fission products was the main topic. The Geological Survey were consulted and they agreed that suitable ground formations might be found for storage without containment. Alternatively a concrete mix might be poured into suitable holes in the ground where it would then set solid. The Chairman noted that the disposal of fission products should receive its due emphasis in any report of atomic power development. This topic remained high on the list of topics for discussion and Cockcroft said that the two major uncertainties in the development of nuclear power were economic viability and the safe disposal of fission products.

In September 1947 Peierls suggested to the power steering committee at Harwell that a fast reactor might be arranged to be self-sustaining in fissile material and this would be an important step forward. Information about the chemistry and metallurgy of the processing and fabrication of fuel elements for fast reactors was virtually non-existent and if, by being self-sustaining in reactivity, a long life fuel element could be designed, the relative importance of the fuel cycle would be reduced and the difficult task of refuelling simplified. In January 1948 Fuchs undertook to prepare a case for the construction of a fast reactor.

Although the fast reactor was one clear objective, the overall range of reactor types considered was very wide. Graphite, beryllium, light and heavy water, were all candidates for moderators and the list of possible coolants was longer. The application of nuclear power for surface and submarine propulsion units was also studied in some detail. Hawker Siddeley were interested in participating in the development of an aircraft propulsion unit. The committee also noted reports giving details of overseas reactor developments.

Harwell maintained strong links with Chalk River, Canada, especially since both Canada and UK had been snubbed by the US following the passage of the McMahon Act. The Canadian programme included a fast breeder reactor, eventually to be based on the Thorium U233 cycle, but in the immediate absence of U233 the initial charge was planned to be plutonium from the NRX pile.

In July 1947 Harwell hoped that Chalk River might be persuaded to donate one gram of plutonium for fundamental studies and, possibly, 1kg at a later date although there was no chance of anything further.

Some information was available on the Los Alamos fast reactors, apart from Clementine, and this included an experiment under the direction of Frisch where a slug of U235 was dropped through the central hole of a doughnut of uranium hydride.

Though many types of reactor were considered, one feature was common to all the contending systems; there was an acute scarcity of established information in most areas of nuclear technology. Hence, in spite of the limited availability of resources, there was a general feeling at Harwell that until more information became available to make an informed selection possible, the various options should be kept open. There were a number of strong contenders but no clear favourite.

The research directed at the provision of basic data was being vigorously pursued. In the Harwell Report for the year ending September 1949 it was noted that measurements of fission, activation and removal cross-sections in epithermal regions had begun. A member of the AEA staff at Chalk River had "already produced microgram quantities of plutonium" and it was hoped to produce gram quantities when the new laboratory was completed at Harwell early in 1950. It was noted that, compared with thermal reactors, the choice of structural materials for the fast reactor was less restricted by the competitive capture of neutrons.

Therefore the structural problems caused by neutron irradiation could be avoided by a judicious choice of material, the selection being made on the basis of theoretical metallurgical principles. Technical discussions were, of necessity, heavily dependent on theoretical extrapolations and, for the fast reactor in particular, it was considered important to mount integral fast reactor experiments as soon as sufficient fissile material could be acquired.

Progress at Harwell during this period is recorded in reports written by Cockcroft to the Harwell technical steering committee and to the Government via Lord Portal's technical committee. By the end of 1949 Cockcroft reported that ideas had crystallised to a point where approval for "...certain definite reactor projects is (being) sought". The fast breeder was in the short-list because, by this time, Harwell were becoming increasingly confident that breeding was technically feasible. The possibility of thermal breeding was not excluded but fast breeder reactors were judged to be the only type which could reasonably be proposed for immediate development, and large scale efforts to exploit breeding would be justified.

There was insufficient evidence to determine the economics of power from a fast reactor and it could not then be said whether breeding should be considered primarily as a scheme to produce cheaper plutonium or economic power.

Meanwhile, the cold war had intensified. The year-long Berlin blockade had ended in May 1949 but the USSR had startled the western world when, in September 1949 a USSR nuclear test experiment was detected. For the UK the effect was to continue the emphasis on military matters.

In December 1949 Cockcroft proposed a development programme with the following financial implications:

- Reactor for submarine propulsion £2.5M p.a.
- Fast fission reactor £2M p.a.
- Site development £1M p.a.

At this point Risley began to take a direct interest in the fast reactor programme. The most urgent requirement for the fast reactor project was to construct a low power experimental fast reactor, subsequently called ZEPHYR. Engineering resources at Harwell were severely strained and although ZEPHYR was conceived and specified by Harwell, the industrial group design team, which had been devoted to fissile material production, had passed its peak load and was able to undertake design work for ZEPHYR.

However, Harwell was still very much in charge of reactor development and in September 1951 Cockcroft drafted an updated version of his December 1949 paper to the Portal committee on the prospects for nuclear power. The confidence of the design and

the technical support teams had been reinforced by the operating characteristics of the Windscale piles which were very docile and responded consistently and reliably to operator action. The nuclear physics data required for the fast reactor programme was being accumulated and heat transfer work was well in hand. An extensive appendix to the Cockcroft Paper surveyed the possibilities and problems of fast power breeder reactors. In the first version of the paper, presented to the Harwell technical committee, Cockcroft wrote that "we expect to have the co-operation of Risley in the design of fast reactors".

In contrast, the third (and final) version of the paper, carrying the same date, notes that the design and construction of the power reactor should be the responsibility of the industrial group and the reactor, of about 100MW, should be built at Windscale. It was this version that was approved by the Atomic Energy Board and the Treasury. At the same time approval was given for the construction of ZEPHYR and HIPPO .

The scientists were cautiously confident that their fast reactor deliberations, which were heavily dependent on theoretical extrapolation, were soundly based. The same confidence was exhibited by the Risley-based designers and their technical support teams who were to translate the theory into practical reality.

In a similar display of confidence, they recognised that the only available practical experience was with laboratory scale rigs and small experiments to support their conceptual thinking.

Undaunted by the prospect of stepping into the unknown, their faith lay in their ability to retain sufficient design flexibility to accommodate any changes dictated by the parallel research and development programmes which were being actively pursued.

At the outset the project had to choose between two strategies; either to establish the elements of the new technology and then, from the wide choice of alternative options, to select the most promising and progress towards a specific design or, since the significance of the many problems was not then quantifiable and their relative importance might not be revealed by general studies, to strike out boldly with an imaginative but flexible design; one which could be adjusted or adapted as experience and the parallel running research programme dictated.

The latter procedure was chosen, largely as a result of the insistence of Mr (later Lord) Hinton, who had just successfully accomplished the task of designing and building the

military plutonium production plant, also achieved from a position with an almost complete absence of an existing technology. By focusing on a real project he endeavoured to avoid spreading the limited supply of technologists too thinly, and to identify those areas of the technology which were adequately understood and those areas in which a more concentrated level of resources was required for subsequent development.

The strategy was successful. Lessons, particularly those learnt during the initial commissioning stages, proved invaluable when succeeding fast reactors were designed. The discovery of steel swelling in a fast neutron flux was made just in time to have an important impact, world-wide, on fast reactor design. Its impact on DFR was minimal but the early warning must have prevented expensive rectification for the larger subsequent fast reactors.