

## **Conception and design of DFR**

By 1950 the Risley design team had largely completed their Windscale pile design and were seeking new work. The Atomic Energy Council wished this team to be kept together so the fast reactor project was directed to Risley. The industrial group readily accepted the challenge posed by the fast reactor. Having previously responded to a Harwell request for assistance, they had experience of the ZEPHYR reactor design and although they considered the next step, as yet undefined but probably a large liquid metal cooled steam raising plant, to be a difficult assignment, their enthusiasm grew. Within two years a programme was well established. The target date for achieving DFR criticality was set for the end of 1956.

The Atomic Energy Council endorsed the AEA programme, giving first priority to the DFR. The research group regarded this involvement of the industrial group in the DFR project as a temporary expedient and they expected to remain in the forefront of the fast reactor development and in particular to direct and supervise, in conjunction with industry, the provision of the subsequent large power producing fast reactors.

In October 1951 Hinton chaired a small meeting which included senior personnel from Harwell and Risley. The concept of a fast reactor was discussed in very general terms. It was expected that the core would take the form of a right cylinder 600mm in diameter and, with all plutonium currently being required for the weapons programme, the fuel would have to be enriched uranium or possibly highly enriched uranium plus thorium. Fuel element design would, of necessity, be tentative since the properties of the fuel were not known at reactor operating temperatures. The earliest date for achieving criticality was to be determined by the availability of sufficient fissile material.

The most suitable coolants seemed to be liquid metals and proposals included lithium, sodium, gallium, lead, mercury, or a lead/bismuth alloy. Mercury had been used as a coolant in the USA 25KW fast reactor CLEMENTINE; sodium had been used in the USA submarine thermal reactor SIR. Trial combinations of coolant and cladding might have been arranged for testing in the Canadian NRX pile if a decision had been made quickly. The chairman, who preferred a more direct approach, insisted on restricting the

number of coolants to be studied and the choice was narrowed to mercury, lithium or sodium (or a sodium potassium alloy).

The coolant would become highly active but it was anticipated that, by using an intermediate fluid, a conventional steam generator could be used.

Hinton sought to make an immediate attack on what he perceived to be the main problems and, drawing on his experience with the Windscale piles, suggested at this first meeting that the design of the reactivity control system might prove difficult and asked for design work to be started immediately.

A second meeting was held in December 1951 and, instead of dealing at once with possible design problem areas, a very general paper by Rennie (Harwell) was considered. With fissile material being scarce, it was desirable to have a self-sustaining core in which fissile material would be bred at the same rate at which it was being consumed. For the immediate future, a lower power and hence smaller fast reactor would have to be tolerated although this would not permit the use of a self-sustaining core. The penalty of a shorter running time between refuelling would have to be accepted in the short term with the expectation that the fuel cycle would evolve from a U235-based system into a fully sustaining plutonium system.

The safety of all the various alternatives, reactor size, fuel and fuel element style was extensively debated but no significant safety difference between them was apparent. It was expected that the reactor would be built at Windscale. The choice of any other site would lengthen the project time scale.

The main uncertainties affecting the reactor design were listed. Only a small amount of the required nuclear data was available. Some information for the high neutron energy range was known from the wartime weapons programme but this was not immediately relevant to a power producing fast reactor. The extrapolation to conditions appropriate to the softer neutron energy spectrum had to be guided by application of theoretical models of the atomic nucleus, supplemented by experimental information gleaned from less than gram quantities of fissile material. Relevant nuclear physics data was beginning to emerge from the experimental programmes based on the Cockcroft-Walton set, a 30MeV synchrotron and linear accelerators. Theoretical treatments had to be relied upon where direct measurement of data was not possible. The ZEPHYR experiment, which was

expected to provide a measure of the adequacy of the current state of theoretical reactor physics prediction, was still under construction.

Apart from a lack of physical and nuclear data relating to the fuel, it was noted that there was no UK experience of liquid metal technology, or of the effect of irradiation on cladding or structural materials. There was also no data on which to base estimates of achievable burn-up or the cost of manufacturing the fuel. The long term effect of high energy neutron bombardment in structural materials was completely unknown. Finniston correctly forecast that displacements of atoms from structural materials would occur but, most unfortunately, he was only partially correct in forecasting that annealing would render the effect harmless.

At Harwell, the programme emphasis was to seek an understanding of the main features which would characterise the general development of the reactor whereas the industrial group under Hinton preferred to focus attention on the potential problem areas by drawing up a specific design.

This distinction surfaced at the third FRDC meeting in April 1952 when Harwell tabled a comprehensive programme for the development of the heat flow process from the reactor core to the turbo-alternator. The programme included basic studies of the properties of candidate materials, corrosion, liquid metal technology including electric magnetic pumping and heat exchange design, reactor design, steam generators, steam conditions, system control, instrumentation including coolant flow rate temperature and purity, and finally fire fighting.

Irradiation data was expected to come from Chalk River. Each of the above topics was to be closely examined for any safety implications.

This broad programme very clearly reflected the contemporary Harwell view that the responsibility for reactor design rested with them, and the responsibility for the production of fissile material was Risley's. Furthermore, the design process should not become specific until some of the many alternatives, eg liquid metal fuel, had been eliminated.

Hinton seems to have ignored this completely. He announced at this meeting that design, development and construction programmes must be produced within a month. These programmes would identify dates by which important design decisions must be settled.

An R&D programme must also be produced and this should be tailored to provide the best possible data by the dates specified on the engineering programme. The timing of the R&D work was to be subordinate to engineering design and production. Cockcroft stressed that the physics information then available might be in error because it was mainly based on theoretical modelling. He emphasised the importance of the ZEPHYR experimental programme which was planned to generate essential reactor physics data, albeit of a very preliminary nature. Hinton appreciated the point but felt that the main difficulties lay with the engineering. The overall reactor plant would be designed with sufficient flexibility to accommodate whatever the reactor physicists specified for the final core, though this might mean over-design in some features.

Hinton, having considered where the main design problems were most likely to appear, had identified refuelling as a critical feature and suggested that the successful techniques used in NRX and the proposed NRU piles should be closely studied with a view to adopting the same methods, using rotating shields. He also underlined the importance of reactivity control and, at the very first FRDC meeting, had wanted design work to be initiated immediately. He was clearly thinking in terms of the mechanical engineering of components in a hot liquid environment because, at that time, the method of reactivity control design had yet to be selected from a number of options.

It was expected that the design and operation of ZEPHYR would provide the requisite information on which to base nucleonic instrument development.

The theoretical possibility of cavitation erosion of components submerged in the liquid metal, emphasised the urgent need for a sodium test circuit, running under conditions which fairly realistically mirrored the expected reactor situation. It was necessary to "learn the trade".

The safety implications of these preliminary design options were constantly surfacing during discussion. With the design in such a nebulous state it is not surprising that by compounding pessimistically the many assumptions involved in estimating the consequences of an ill-defined accident in the vaguely defined reactor, an uncomfortably large upper limit to the energy release was estimated. Reservations over the siting of the reactor at Windscale began to emerge.

At the fourth FRDC meeting in June 1952, safety, including siting, was the primary discussion topic. It was recognised that there was a possibility of an accidental loss of coolant leading to fuel melting which, in the absence of a moderator, could lead to a more dense fuel configuration and, perhaps, prompt criticality. The calculation of the consequent energy release had to be based on extremely simplified models. The complexity of the reactor physics equations governing the hypothetical core failure plus the deficiency in information about the fuel element design and hence its mode of failure, made energy release calculations very uncertain. In this situation it was inevitable that the tentative upper limit of the consequences of a dis-assembly spanned a very wide range, depending on the assumptions made. The highest estimate was disconcerting.

The choice facing the committee was whether to continue the design and construction programmes in the expectation that further refinement would substantially reduce the upper limit value, or whether to adopt a more prudent policy by waiting until a more informed and improved explosion model resulted in a smaller calculated yield. The former view held but the choice of the Windscale site was seriously questioned.

Following discussions with the nuclear weapons experts, the upper limit for an explosion was reduced. At this level Hinton advised that an igloo-style containment was feasible. For anything larger, a deep cave might be necessary, with an attendant penalty of having to pipe fluid from the reactor to the turbo alternator. Small scale explosion experiments were proposed and the ability to contend with both the blast wave and missiles was recognised.

The first project programme was tabled in February 1953. The freeze date for a safe core design with suitable control gear and a complete thermal circuit, was set for August 1953, six months hence and less than two years after the first FRDC meeting. The programme was revised in 1954 and the completion date put back to January 1958. The site would be chosen at the end of 1953. An R&D programme had been agreed and this had been arranged to provide the requisite data as and when required by the master programme. There were some doubts expressed over the time available for development but Hinton emphasised that the present target was to develop the first reactor in order to establish the technique. Further development would be available for the subsequent reactors following quickly behind.

Fuel element designers considered the alternatives of using a weak fuel, uranium, in a strong can, or a strong fuel, uranium carbide, in a weak can. Risley was to be responsible for the development of the former and Harwell for the latter. The use of carbide fuel was pursued for about a year before being rejected.

To avoid stressing the cladding, the fuel elements were not sealed and coolant would flow over the uranium fuel surface; this proved to be a successful stratagem although it had implications for the eventual decommissioning of the plant.

In March 1953 Hinton reported the decision to go ahead with PIPPA (later to be called Calder Hall). Responsibility for PIPPA was given to the industrial group in spite of Cockcroft's wish for it to be built at Harwell. The decision meant that the Risley design team would have to cope with both reactors. A substantial reorganisation was necessary at Risley but when this was achieved Hinton felt strongly that both programme time scales could be met.

There was a slight hesitation when Hinton suggested and Cockcroft agreed that it might be preferable to build a smaller fast reactor with a lower heat rating than the proposed 100MW design. This would have been a test bed for the components being considered for the full size fast reactor.

However, the consensus of the FRDC was that the fast reactor at the full heat rating already agreed should be the first priority. The question of site selection had to be faced. It was noted that existing atomic energy sites fell into three groups according to population density. Windscale and West Milton (Schenectady) had a density of 100 per sq. mile; Hanford and Chalk River had 10 per sq. mile; and Idaho had 1 per sq. mile. At that stage, although explosions had been ruled out by design, this belief had not been substantiated by firm evidence. A panel was convened with the objective of defining the exclusion zone for a reactor which was provided with fission product containment.

Intensive theoretical work had reduced the estimate of fission product deposition and relaxed the siting requirement. A coastal site together with appropriate rock foundations was necessary to obtain adequate cooling water supply for the turbine. Several sites were considered and the choice was narrowed to one of two disused air fields in the North of Scotland, one being at Dounreay, near Thurso, Caithness. The latter option was examined in detail before being finally chosen.

The cost was estimated to be £15M. This included the reactor and the plant for fuel fabrication, fuel element production and the chemical separation of irradiated fuel. The estimate was approved by the Atomic Energy Council and submitted to the Treasury, who sanctioned it in March 1954 having considered the recommendations of a special panel to consider the reactor safety.

In January 1955 Sir (later Lord) Hinton addressed a public meeting in Thurso to introduce the subject of fast reactors. More than 500 people (15 per cent of the Thurso population) packed the Town Hall, the ante-rooms and the whole of the staircase approach. Having explained the technical basis of the reactor system, Hinton stated that no human activity is absolutely free from risk and that was one reason for choosing a remote site. He assured the audience that the risk was very remote.

At the outset the designers recognised that with no previous experience to provide guidance the design might well have to be modified as a result of the extensive R&D programme and it was conceivable that changes might prove desirable even before the reactor was physically completed. The core design was therefore considered as a unit for which substantial, if not complete, change might have to be considered.

The use of liquid metal coolant, on the scale required for the heat removal system, was also unprecedented. To set up very large test loops would have created its own problems and delays, and it was decided to use the reactor itself as the test bed for all components. The whole of the primary circuit was included within the reactor vessel, and was designed to be replaceable.

Outside the vessel, conventional engineering practice would be followed wherever possible, while efforts were concentrated on reducing to a minimum the risk of failure of the cooling system.

An economic steam generator with proven reliability eluded the designers. The scheme chosen used tubes carrying sodium and, separately, tubes carrying water or steam. Heat was transferred between the tubes via a matrix of close packed 3mm thick copper washers with holes to carry the tubes. A leak from either a sodium tube or a water/steam tube would be to air and readily detectable and a sodium-water reaction would not be a credible accident. It proved an expensive solution and only half the design capacity was planned, leaving the other half for future development. In the event, the expensive choice

was justified. The plant suffered a number of water-side leaks and one liquid metal leak, all of which would have been more serious had a conventional shell and tube design been chosen.

With the high thermal heat rating required in fast reactors, the fuel element had to have a large surface to volume ratio. Pins, plates and annular pellets were considered and the latter was adopted. Another imposed constraint was that the reactivity invested in any single assembly to be loaded into the reactor, should be less than the delayed neutron fraction. The risk of the reactor becoming prompt critical was thereby avoided even if an element were accidentally dropped into the core.

The choice of upwards or downward direction for the coolant was debated. No strong argument for or against either direction emerged and a choice of downward flow was made after finely balancing the arguments.

For the design of the coolant circuits the Designers adopted a strict policy of minimising extrapolation from known technology. By 1953, practical experience in the design, construction and operation of NaK filled circuits was limited to a few rigs using stainless steel pipework and powered by electro-magnetic pumps; this combination was used as a design basis for DFR.

The design policy of avoiding valves meant that non-return valves could not be used in the primary circuit. This could have created difficulties because flow reversal could have occurred in a failed pump circuit. While not a safety problem it would have required awkward maintenance to deal with the pump insulation. Fortunately, although normally run at temperatures close to the design limit, no insulation failures occurred

The limited size of the pump and pipework set an upper limit to the heat removal power in each circuit and so determined the need for twenty-four loops to extract 60MW from the core and breeder.

The crucial necessity to avoid accidental loss of core cooling was countered by surrounding the primary circuit vessel with a leak jacket, built to the same exacting standards as the primary vessel but subject to lower stresses since it had to support only its own weight. Sufficient NaK was available in the primary circuit to ensure that if the coolant emptied into the leak jacket the core would remain submerged and coolant circulation could be maintained. A further advantage of having many circuits was

diversity of coolant supply to the core; loss of pumping power in one circuit would not lead to a serious incident. To give effect to this diversity the circuits had to be fully independent and to achieve this they were grouped into twelve pairs.

Each of the 24 primary circuits comprised an electro-magnetic pump and an intermediate heat exchanger in the form of concentric NaK-to-NaK tubes; the latter transferred heat, but not radioactivity, from the primary to the secondary coolant circuits. An auxiliary bypass loop in each primary circuit fed an impurity trap and an expansion tank.

Another major change in core design, envisaged but not implemented before reactor construction was completed, arose when serious doubts crystallised over the burn up achievable with metal fuel. Although metallic fuel remained in contention, increased support developed for a ceramic or composite (cermet) fuel element held in sub-assemblies of pins or plates. At the same time consideration was being given to the next fast reactor - PFR - and it was evident that it would be a substantially different design from DFR. The primary role of DFR would have to change to being a test bed for the irradiation of fuel and materials rather than its original purpose as a power station prototype. To gain experience of sub-assemblies of pins, the fuel elements in the centre region of DFR were later replaced.

An important reason for keeping the relatively simple core arrangement for the initial loading was to provide an opportunity to compare fast reactor physics data measured on a real fast reactor, with predictions based on currently available methods and data.

The earliest experimental data relevant to fast reactors came from ZEPHYR, the first UK fast reactor critical experiment.

Operation of ZEPHYR generated confidence that the relatively untested calculation methods and data then available would give sufficient guidance for initial design work on DFR to proceed although extrapolation to the proposed uranium fuelled 100MW reactor was considered too large for generating reliable data for use by the designers, and a second low power critical experiment, ZEUS, was built.

ZEUS, which first achieved criticality at Harwell in December 1955, was designed to simulate as closely as practicable the size and composition of DFR. It soon served as an important source of reactor physics information for the DFR design and, later, for use in the early operation of DFR.

ZEUS could not model DFR in all respects. For example the liquid metal coolant was generally simulated by aluminium appropriately perforated to improve the simulation.

A conclusion from the ZEUS programme was that a similar low power experiment would be required for the fast reactor successor to DFR. At about this time consideration was being given to an AEA reorganisation which would have centred all fast reactor work at Dounreay, near Thurso.

The proposal was not implemented and the successor to ZEUS, ZEBRA, a more versatile design of experimental reactor, was built at Winfrith although the first capital expenditure proposal identified Dounreay as the construction site. A Dounreay physicist was seconded to work on the USA experimental reactor ZPR111 to gain experience of this type of reactor.

The DFR early commissioning programme included the insertion, into parts of the core and breeder, of thimbles and experimental fuel elements containing samples of materials chosen to provide information about the local neutron energy spectrum. These access facilities were used to make measurements of suitable reaction rates.

Wherever possible equivalent measurements were made in ZEUS to facilitate direct comparison with reactor measurements. Compositional and other physical differences between ZEUS and DFR were allowed for by calculation, the validity of the calculation methods having been an important feature of the ZEUS programme.

The construction programme prepared in 1954 was substantially adhered to and by 1957 the planned date for completion, January 1958, appeared to be achievable. However, in mid 1957 the demanded impurity level of oxygen in the NaK coolant was tightened. The installed cold traps were expected to reduce oxygen levels to less than 10 ppm. but to be sure that the corrosion rate of niobium and vanadium would be acceptably small, hot traps containing a zirconium getter were installed in place of seven of the cold traps; they were intended to bring oxide levels to less than 5ppm. This modification together with changes in the fuel dispersal arrangement below the core, led to a few months delay and the plant was handed over to the operators at the end of 1958.

A final assessment of safety at senior AEA level resulted in an initial power level limit of 1MW. Immediately after shut down from this power level, the decay heat in the fuel would have been sufficiently low for the fuel to be maintained below melting point even

if all the coolant had been lost. It was a cautious decision which was eased when initial experience of reactor operation showed that the reactor performance closely matched expectation; it was docile, easily controllable, and with no surprises.