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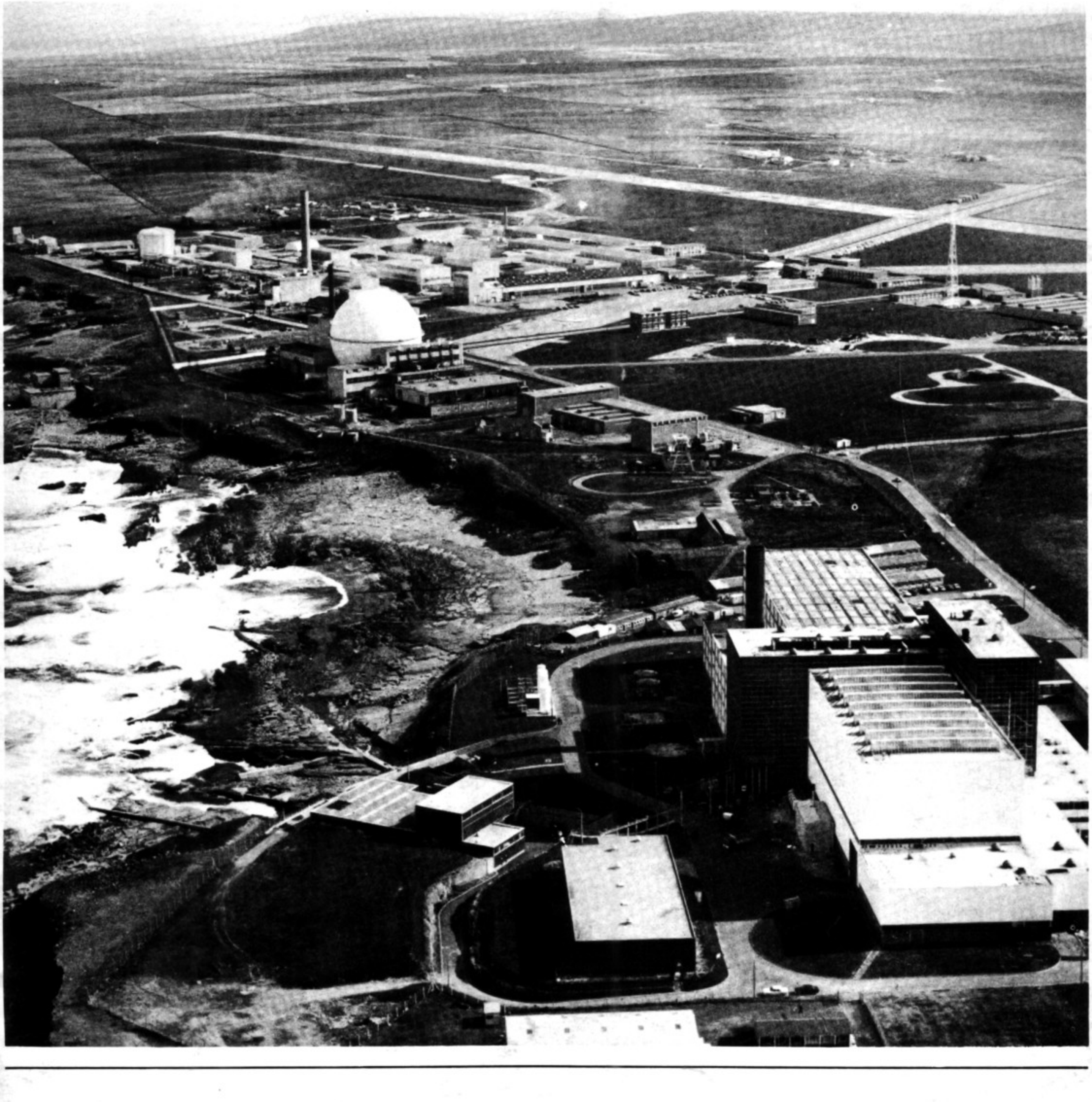
ATOM

THE FAST REACTOR: PERSPECTIVE AND PROSPECTS

X-RAY DIFFRACTION: ITS ROLE IN ATOMIC ENERGY



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ATOM contents

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Enquiries concerning the content and circulation of the bulletin should be addressed to the contributing editor,
Lesley Price
Information Services Branch UKAEA
11 Charles II Street
London SW1Y 4QP
Telephone 01-930 5454

Information on advertising in ATOM can be obtained from
D.A. Goodall Ltd., New Bridge Street House
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Front cover: A view of the Dounreay site showing the Prototype Fast Reactor in the foreground and the Dounreay Fast Reactor in the middle distance

THE FAST REACTOR: PERSPECTIVE AND PROSPECTS

Sir Peter Hirsch, Chairman of the United Kingdom Atomic Energy Authority, delivered the Sir John Cockcroft Memorial Lecture to the British Nuclear Energy Society on 15 September. His subject was the Fast Reactor. BNES has very kindly allowed ATOM to publish the lecture*.

It is some 33 years since Sir John Cockcroft, speaking on 'The Development and Future of Nuclear Energy' identified the long-term objective of the nuclear power programme "to build nuclear power stations which will produce power at a cost not very different from a coal-fired station. For this to be worthwhile we must have adequate uranium-ore reserves in sight to fuel our nuclear power stations for many centuries . . . For this we have to develop a new type of atomic pile known as the "breeder pile", because it breeds secondary fuel as fast or faster than it burns the primary fuel uranium 235 . . . These piles present difficult technical problems, and may take a considerable time to develop into reliable power units. Their operation involves also difficult chemical engineering operations in the separation of the secondary fuel from the primary fuel".[1]

The general case for the fast reactor has not altered since Sir John Cockcroft spoke those words in 1950. An expanding thermal nuclear power programme, itself determined by rising electricity demand and shortage of alternative fuel at economical prices, would place increasing pressure on uranium resources to the point where the fast reactor's dramatically greater uranium efficiency would dictate its commercial introduction for base load electricity generation.

Considering world uranium resources, the five million tonnes of currently known low cost uranium deposits (outside the centrally planned economies)[2] would be sufficient to fuel some 1 250 GW(e) of thermal reactors operating on the once through cycle (based on U235) for life. These deposits are likely to be fully committed early in the next century.[3] (The current worldwide installed capacity of thermal reactors is 183 GW(e)[4]; recent NEA projections suggest around 450 GW(e) for the world outside the communist areas by the year 2000).[5] Additional speculative uranium resources, if developed, might in principle support a thermal reactor programme perhaps three times as great, but there is no guarantee that such deposits will be located and developed to meet demand.[6] On the other hand, if uranium were used in fast reactors, the much more abundant U238 isotope would be utilised. In practice about 60 times more energy could be extracted from a given amount of uranium than if it were used in thermal reactors. The world recoverable energy resource of U238 in fast reactors is comparable to that of the world recoverable coal reserves (see Table 1).

In the UK, all U235 for thermal reactors must be imported. This introduces an additional element of uncertainty about future supplies, beyond that determined by the limited world resources. The oil crises and price excursions in 1973 and 1979 have demonstrated the vulnerability of industrial economies to disruptions of fuel supply or abrupt changes in fuel prices, and have drawn attention to the strategic importance of self-sufficiency and diversity of fuels.

The fast reactor offers the prospect of removing our dependence on imported uranium supplies. This can only be achieved gradually as fast reactors replace thermal reactors. However, the national stockpile of 20 000 tonnes of depleted uranium provides an indigenous energy resource equal to the estimated economically recoverable coal reserves in the UK. That is sufficient to meet electricity demand for current levels for some 400 years even without any other source of electricity. By the time existing nuclear power stations and those under construction are due to be shut down the size of the U238 stockpile will have been doubled (see Table 2). The depleted uranium stockpile would be sufficient for a fast reactor programme that would guarantee secure supplies of electricity, at current consumption levels, for nearly a thousand years.

While the case for the fast reactor on grounds of long term security and diversity of supply is clear, the date when fast reactors would be introduced on a significant scale for base-load electricity generation will depend on when, on reasonable assumptions, they can be expected to generate electricity economically. The oil crises of the last decade have not only changed irrevocably the world energy scene, but have also contributed, not least in the UK, to economic depression and low energy demand. Despite higher energy prices this has inevitably set back the timing of the commercial fast reactor (CFR) introduction.

During 1982, roughly one-third of total primary fuel consumption in the UK was for electricity generation. Roughly 255 TWh (255×10^9 kWh) of electricity were generated. Of this total, nuclear power stations contributed just under 16 per

Sir Peter in action

*The lecture will also appear, with additional illustrations, in the December issue of the BNES Journal.

cent. The great bulk of the rest was provided by coal-fired power stations, with oil, gas turbines and hydro stations together accounting for some 10 per cent of the total[7]. As a result of decisions already taken, and of nuclear power stations at present under construction and coming on stream shortly, the nuclear share of UK electricity generation will rise to 20-25 per cent over the next few years. This will be largely at the expense of older coal-fired stations which will be retired as they reach the end of their working lives.

Because of the large increase in energy costs experienced over the past decade and the current worldwide recession, projections of future energy and electricity demand have declined in recent years. Furthermore, there is such uncertainty prevalent over the future course of economic and energy prices that projections must incorporate vastly different future scenarios. This environment of recession and uncertainty is illustrated by the most recent projections of final energy demand produced by the Department of Energy and the CEGB, for the Sizewell Inquiry[8,9]. These projections are not policy targets but rather an array of possible futures, based on a range of assumptions. The projections illustrate our uncertainty about future events, but also indicate that only under the most pessimistic of assumptions is energy demand actually likely to decline over the next 30 years.

Projections

The projections produced for electricity demand also show a wide range of possible futures. It is important to note, however, that not one of the Department of Energy's growth assumptions leads to a reduction in electricity demand. This is because even if overall energy demand is stagnant it is likely electricity demand will grow. Electricity is a clean, versatile, and attractive form of energy that can be used with high efficiency—characteristics that have led to a progressive increase in its share of industrial and commercial markets, even during the recent recession. Conservation measures are taken into account in the CEGB and Department of Energy scenarios, both through allowances for continuing improvements in efficiency and through the effects of fuel prices on consumption. More vigorous conservation measures aimed at saving energy at any cost could further reduce demand (and economic activity and human welfare), but they would defer not remove the long term energy problem. Conservation measures, such as high levels of domestic insulation, will have their major impact on fossil fuel use and they and developing industrial technology are likely to make the use of electricity even more attractive in the future.

In planning an electricity supply system the generating boards have a number of objectives. One of the most important is to provide electricity at the lowest economic cost subject to the constraint that security of supply is ensured, taking due account of environmental considerations. Nuclear power has an important part to play in meeting the objective within the constraint. Compared with fossil-fuelled power stations, nuclear power stations such as our Magnox and Advanced Gas Cooled Reactor (AGR) power stations have higher capital costs but lower fuel and running costs.

The analysis of generating costs is complex and controversial. For present purposes, it seems fair to say that on a whole-lifetime basis our Magnox stations will generate electricity at more or less the same cost as contemporary coal-fired power stations. The AGR at Hinkley Point is generating the cheapest electricity on the CEGB system[10] and AGR stations as a whole are likely to show a reasonable cost saving taking into account the AEA's R&D (even though the number installed is less than might have been anticipated). It is well known that the CEGB's cost estimates for the Sizewell B PWR show that it is expected to generate electricity significantly more cheaply than a comparable AGR, and will allow older, less efficient fossil fuelled stations to be retired. Projected lifetime averaged generating costs are compared in Table 3. Provided nuclear power retains its expected cost advantage over coal-fired stations, nuclear energy is likely to provide an increasing share of electricity generation. This is true even if there is no growth over the next 30 years, during which time most of the existing coal-fired power stations will be retired.

Table 1 World recoverable energy resources (10^9 tonnes coal equivalent)

Coal		Uranium		Oil*	Gas
Total	10 795	in fast reactors	14 378	951	302
50% recovery	5 398	in thermal reactors	172		
10% recovery	1 080				

(Source: World Energy Conference 1981)
*includes natural gas liquids, bituminous sand and oil shale.

Table 2 UK recoverable energy resources (10^9 tonnes coal equivalent)

Coal	Uranium		Oil*	Gas
45	existing stocks depleted U for fast reactors	40	4	2
	depleted U from current operating and current committed power stations	100		

Source: 'Development of the Oil and Gas Resources of the UK 1982', and National Coal Board)
*includes natural gas liquids, bituminous sand and oil shale.

Table 3 Lifetime averaged generating costs (p/kWh, 1982 prices)

(5% Discount rate; 2% p.a. rise in real coal prices; 3% p.a. rise in real uranium ore prices)

Power stations commissioned 1965-1975		
Magnox	(25 year lifetime, Wylfa 20 year)	2·63
Coal	(40 year lifetime)	2·46
Oil	(30 year lifetime)	3·07
Power stations most recently commissioned		
AGR	(Hinkley Pt. B; 25 year lifetime)	2·39
Drax A	(40 year lifetime)	2·67
Power stations under construction		
AGR	(25 year lifetime): Dungeness B	4·18
	Hartlepool	3·15
	Heysham I	2·95
	Heysham II	3·14
Coal	(40 year lifetime): Drax B	3·38
Future stations		
PWR	(35 year lifetime): Sizewell B	2·61
AGR	(25 year lifetime)	3·15
Coal	(40 year lifetime)	3·84

Source: CEGB Analysis of Generating Costs

Table 4 Rate of change of world oil, coal and uranium prices (March 1982 $ price base)

	1980/1990	1990/2000	2000/2030	1980/2030
	per cent per annum			
High				
Oil	3·1	3·7	0·5	1·7
Coal	4·1	2·9	2·0	2·6
Uranium	3·3	3·4	4·0	3·8
Medium				
Oil	1·9	2·2	1·1	1·5
Coal	2·3	1·8	1·5	1·7
Uranium	nil	3·3	3·1	2·5
Low				
Oil	1·9	nil	0·4	0·6
Coal	nil	2·3	0·4	0·6
Uranium	−1·2	3·5	2·5	2·0

Oil – Saudi 34 fob Gulf
Coal – ARA steam coal cif
Uranium – lb U_3O_8
Source: CEGB Statement of Case Sizewell Public Inquiry

Timescale

Fast reactors will not be commercially introduced in the UK until they can generate electricity at prices roughly comparable to those of the thermal nuclear alternatives. On current estimates, a commercial fast reactor station would cost significantly more to build than a thermal station. Even with continued development, some capital cost differential is expected to persist indefinitely. Fast reactors will become economically desirable components of the UK electricity supply system only when the capital cost disadvantage is outweighed by the benefits of lower operational costs—principally lower fuel costs. Precisely when this point will be reached is very difficult to forecast. To some extent, it depends on progress in reducing the likely capital cost disadvantage of a commercial sized fast reactor station. Since the capital cost is a high proportion of the total, compared with fuel and operating costs, even modest progress here will have a significant effect on when the break-even date is reached. But the escalation of uranium price will of course be most important.

At present the world uranium market is depressed, with over capacity on the supply side. Spot prices, which account for only 10 per cent of the market, have been influenced by destocking and have fallen to unrealistically low levels—below the cost of extraction of uranium from many mines. Contract prices have not been nearly as volatile and are expected by some consumers to show a steady rise in real terms reaching some US $60 to US $90 by the mid 1990s[11]. CEGB projections in their Sizewell evidence[12], shown in Table 4 for three different scenarios, are most optimistic in the short-term but include steady rises in the longer term post 2000. The depressed market has discouraged exploration or mine development, has led to mine closures and to high grading, none of which augur well for future supplies, bearing in mind the long lead time from discovery to exploitation of new deposits. The expectation of rising prices, even in the stable market situation, is supported by the increases of real costs for base metal mining during the 1970s which have exceeded 2 per cent per annum almost everywhere[13]. These rises are due in part to the inevitable progressive move to more difficult and lower tenor deposits and partly to enhance environmental and worker safety standards.

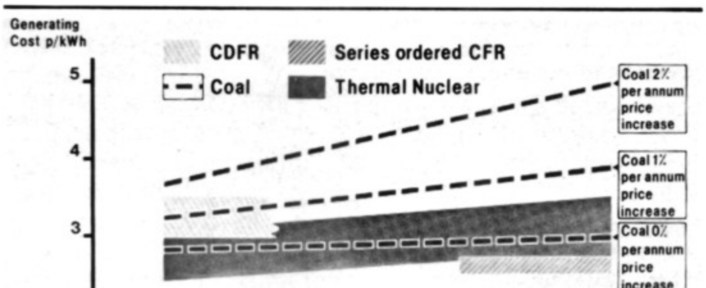


Fig 1 Discounted average generating costs against date of commissioning (70 per cent load factor.) A low rate of fuel price increases is assumed

We have carried out calculations on various assumptions to estimate the time when fast reactors may be economically attractive. Figure 1 shows the discounted average generating costs against date of commissioning for coal-fired stations, thermal and fast reactors. The main assumptions made in these calculations are given in Table 5. The following conclusions may be drawn:

- On the basis of a 3 per cent per annum dollar price escalation of U prices between now and 2030, which are close to the CEGB central estimates, and the basic assumptions listed in Table 5, series ordered fast reactors should become economic, compared with the PWR in the second decade in the next century. It could be earlier if uranium prices rise faster than expected or if thermal reactor costs rise more than we expect or if fast reactor capital and fuel cycle costs can be reduced more quickly. Alternatively it could be later if more low cost uranium is found, if fast reactors prove more expensive to build than expected, or if thermal reactor costs can be reduced. In practice, barring sudden rises in uranium prices, the cross-over is likely to be shallow with fast and thermal reactors having very similar costs for some time, possibly decades, not least because of the stabilising effect of fast reactors on uranium prices.
- The cost advantage relative to coal-fired power stations is very considerable, even if coal prices increase by only 1 per cent in real terms over this period. Even if there is no real increase in coal prices over the next 50 years, the cost of electricity from fast reactors is expected to be competitive with that from coal-fired stations.

Before series ordering can begin the Generating Boards are likely to want to be assured that they are investing in a proven and reliable plant to provide a secure supply of electricity.

Table 5 Assumptions for Fast Reactor costs and benefits—generation costs breakdown (1982 money values)

Comparative reactor assumptions

	PWR (2015)	CDFR (1995)	CFR (2015)
Output	1 100 MW	1 250 MW	1 250 MW
Central assumptions on capital, including IDC, contingency	£1 235/kW	£1 840/kW	£1 650/kW
Economic life	35 years	25 years	35 years
Load factor	70%	70%	70%

Additional assumptions

1. 3 per cent per annum real uranium ore price increases.
2. Costs and benefits discounted to 1982 at 5 per cent per annum.
3. Fuel costs for series ordered fast reactors per kWh are of the same order as the costs of enrichment, fabrication and spent fuel storage for once through PWRs.
4. Operations and maintenance costs for series ordered fast reactors and PWRs are comparable.

In comparing the estimates of capital cost of the different reactors, it should be noted that even for the fast reactor only around 50 per cent of the capital cost is due to the nuclear island and most non-nuclear plant is common to all reactor types.

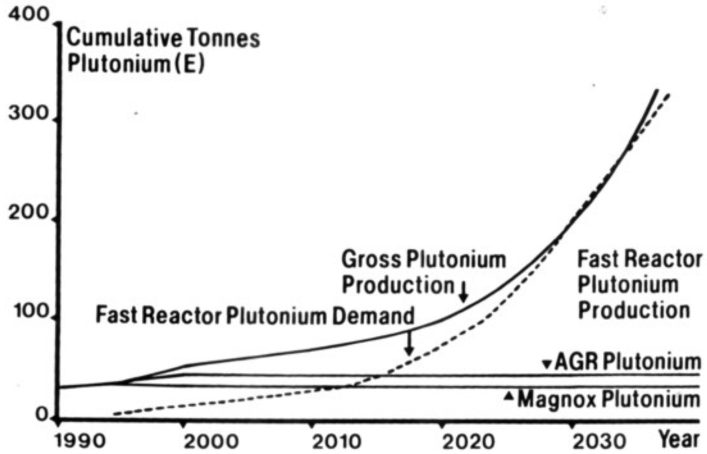


Fig 2 Gross plutonium supply and demand with only Magnox and 1 805 t of AGR reprocessing, CDFR in 1995 and series CFR ordering at 1·25 GWe per annum from 2015

Furthermore, since the fast reactor system depends on rapid and economic reprocessing and refabrication of plutonium fuel, reliable and economical fuel cycle facilities will have to be demonstrated.

The commercial introduction of the fast reactor will also involve considerations of safety and public acceptability. The Nuclear Installations Inspectorate will have to be convinced, before approval is given for a commercial fast reactor station and fuel cycle plants, that the designs are sufficiently safe, and that the construction, operation and maintenance procedures proposed are sufficient to keep the risk of harm, to members of the public and to operators, to an acceptably low level. None of this will be worthwhile if the general public, with understandable if sometimes misplaced anxieties about fast reactors and the use of plutonium, will not accept that the fast reactor system is safe, reliable and economic.

So a commercial size lead station (or CDFR) will need to be constructed well in advance of series ordering to demonstrate the basic safety and reliability of the system, and to give the data on which the economics of series ordered stations can be determined with confidence. (Such a station will probably not generate electricity at fully competitive rates when compared with that from thermal reactor stations.) Such a lead station is likely to be preceded by a public inquiry. The timing should be such as to give a few years operational experience before series ordering begins. If we assume that the first CFR might be commissioned in 2015, then a lead reactor should come into operation around the year 2000 to give some operational experience before the Generating Boards have to decide to order the first CFR in 2005. A Government decision to proceed with construction of a lead reactor would then have to be taken in the early 1990s, preceded by a Public Inquiry. Of course, the final decision to proceed with such a lead station would be taken only after thorough consideration by the Government of the day, in the light of the circumstances and updated energy projections.

Figure 1 compares the estimated cost of electricity (on the main assumptions listed in Table 5) from a lead station to be constructed in the 1990s with that from alternative systems. Generating costs for a lead reactor are likely to be lower than, or at least comparable to those for any coal-fired station built at that time. While the optimum timing of the introduction of commercial fast reactors must remain uncertain because of the difficulty of assessing the future fifty years ahead, for planning purposes it seems prudent to work towards commercial series introduction from around 2015, bearing in mind that it may be earlier or later by some years. It may be that the current recession persists into the next century and uranium proves to be more plentiful than anticipated. We will need to review our expectations from time to time in the light of changing circumstances.

We shall assume for discussion purposes a programme of 1·25 GW(e) per annum of fast reactors built from 2015 for 30 years. This is compatible with a steady state replacement rate for the electricity base-load stations. It should also be noted that, as shown in figure 2, such a programme is just sustainable with plutonium from reprocessed magnox fuel and that arising from the CEGB's commitment for AGR fuel reprocessing by BNFL by the year 2000. If all the fuel from AGRs in operation or under construction at the present time were reprocessed there would be more flexibility in the programme. A reduction in cost of the series ordered CFRs compared to that of the lead station (see Table 5) is to be expected on the basis of the benefit to be gained from experience and from repeat orders of very similar reactors.

On the basis of the assumptions in Table 5 we estimate that on the CEGB's central uranium price projections a programme of 1·25 GW(e) per annum of fast reactors built for 30 years from 2015 onwards could give net benefits (relative to an equivalent PWR programme) of some tens of billions of pounds (1982 money values) discounted at 5 per cent per annum to the start of series commissioning. Looking so far into the future we cannot be precise; for example we have to make assumptions about uranium prices up to nearly 100 years from now. We cannot hope to predict the future over such a time span. Judgements on the likelihood of events, particularly those dependent on world politics, must vary greatly and cannot take into account the unexpected. However, based on our present knowledge, the probability distribution of expected benefits from a series ordered programme of fast reactors will have the form illustrated on figure 3, on the assumption that the ordering programme will proceed only if the economics look sufficiently favourable at the time.

On the basis of a surprise free future, we would expect the most competitive alternative generating source when fast reactors are introduced to be the PWR. The figure illustrates the scale of benefits we could expect on the basis of the assumptions in Table 5. If PWRs should turn out not to be an available option in the UK, then the benefit of a fast reactor programme would have to be assessed against the cost of the next best alternative; on the assumption that this would be the AGR the scale of benefits could be considerably greater. Against a coal option if all thermal reactors had become unsustainable or very much more expensive, for example because of increased uranium prices, the benefits could be more extensive still. Major perturbations in the world's uranium markets or world fuel supplies could increase the benefits by an order of magnitude or more.

Thus although on our view of the most probable future we will derive the relatively modest benefit of tens of billions of pounds on the timescale indicated (assuming a commissioning programme extending from 30 to 60 years from now), the strategic importance of fast reactor development is that it would enable us to avoid the very extensive penalties which could arise if our expectations are upset. The cost of fast reactor development is therefore as much an insurance premium against these less likely outcomes as it is the cost of achieving the most likely benefits. The cost of the insurance premium to the UK would be the differential cost between the Lead Reactor and its fuel plant, and that of a conventional PWR which it would replace, in round terms perhaps £1 000 million including future R&D costs, discounted at 5 per cent per annum to the present time. (Note that on our central assumptions, this premium would be more than recouped with interest at 5 per cent per annum in real terms, by the expected benefits relative to the PWR option, of the order of £2 000 million discounted back to 1982 from the years of commercial operation up to the latter part of the next century).

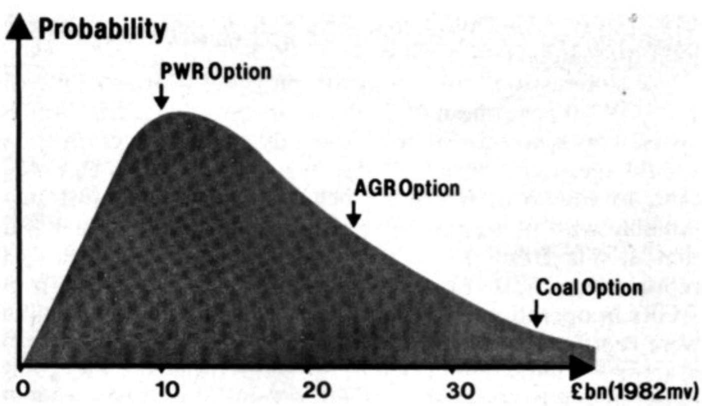


Fig 3 Benefit of 1·25 GW/year Fast Reactor programme (illustrative)

It would not be prudent to base national energy policy on the speculative hope that additional uranium resources will materialise, or that the future world will be free from political upset or the continuation of the pressures that have led to rising prices in the past. The fast reactor provides a means of reducing our dependence on external supplies and our vulnerability to disruption. If this assurance can be gained at reasonable cost it is well worth having. The economic benefits of fast reactors will also extend beyond direct generating cost effects, substantial though these should be. The availability of fast reactors will act as a restraining influence on other fuel costs, and in that way fast reactors will provide a wider economic benefit.

Present UK fast reactor policy

Following its review of UK fast reactor policy last year, the Government concluded that the series ordering phase will need to begin in the earlier part of the next century, i.e. on a longer timescale than previously envisaged, and that a substantial development programme for the fast reactor based on Dounreay should be continued and geared to this new timescale. While the precise timing for the introduction of commercial fast reactors must remain uncertain at present an R&D programme planned to make series commissioning possible from about 2015, preceded by a lead reactor constructed in the 1990s, should put the UK in a position to meet the Government's objective. The Authority's fast reactor development programme is therefore planned to meet these timescales, and in particular to put the UK in the position of ordering a lead station and associated fuel plants in the early 1990s. This will ensure that we will be ready for a public inquiry and to build such a plant when Government decides to do so. The design of such a lead reactor and associated fuel plants also provides a necessary focus for the whole programme, ensuring that the various strands of the development work are harmonised.

Collaboration

In its statement on fast reactor policy, the Government stressed the importance it attached to the involvement of the electricity boards and the nuclear industry, specifically British Nuclear Fuels Ltd (BNFL) and the National Nuclear Corporation (NNC), in the fast reactor programme. There has, of course, been close co-operation within the UK industry for many years. NNC have been working for some years with the Authority, on a CDFR design. In 1981 they produced a Design Concept Status Report presenting a compact design, with good prospects of a low capital cost, which is the basis for current work. The Authority also collaborate closely with BNFL on fuel fabrication through a joint development programme for standard and experimental sub-assemblies for PFR. For reprocessing, the Authority's approach is to involve BNFL as the development programme progresses from prototype scale towards commercial facilities.

During the last few months, and arising from the Government's statement on fast reactor policy, this co-operation within the UK industry has been extended and formalised. As a result of initiatives made by Sir John Hill when Chairman of the UKAEA we have a senior co-ordinating committee of the Chairmen of all the organisations involved. This has enabled us to give the Government co-ordinated and unanimous advice on the direction of the future programme. We have now also formed a series of joint committees to oversee the content and structure and progress of the future programme in a co-ordinated way by the industry as a whole. These arrangements demonstrate a new unity of purpose within the UK industry, and represent a significant advance.

The development of the fast reactor to the commercial stage will necessarily take a number of years and require a considerable investment of money and skilled manpower. There is therefore a great incentive to establish close collaboration with an overseas partner or partners whose objectives are similar or compatible with our own; table 6 lists fast reactor expenditure and some details about test or demonstration reactors in other countries. One obvious motivation for such collaboration is the possibility of reducing R&D costs; by eliminating duplication and sharing results, we should get better value for money. Another important advantage is that we should meet the required timescale for commercial introduction with much greater confidence in the technology and much reduced risk; each partner will in effect have the experience of having taken part in building two or more lead stations (one in each major partner country) before the commercial ordering phase begins. We should also be able to go further in reducing capital costs, bringing the date for commercial introduction nearer.

When the Government made its announcement regarding future UK fast reactor policy in November 1982, the then Secretary of State for Energy asked me to draw up, in consultation with the nuclear industry, a future programme for fast reactor development which would make the best use of the nation's resources. On the basis of that advice and encouraging preliminary discussions with relevant overseas bodies, the Government have agreed that pooling our efforts with our European neighbours will maximise the benefits from our own programme. On 5 September, the Secretary of State for Energy announced that the Government had decided to open formal negotiations to seek a collaborative agreement on fast reactors

Table 6 Fast Reactor expenditure and large test prototype and demonstration fast reactors outside the UK

Country	Station	Capacity	Date to operation or estimated date to operation	1981 expenditure (£m)
France	Phénix	250 MW(e)	late 1973	165**
		1 200 MW(e)	1984	
FR Germany	SNR 300	300 MW(e)	end 1985	80**
USA	*Fast Flux Test Facility	400 MW(e)	1980	300
	Clinch River	350 MW(e)	Not fully approved (1990 earliest)	
Japan	*Joyo	100 MW(e)	1978	105
	Monju	300 MW(e)	earliest 1990	

* Non-electricity producing
**Includes some contribution to Nersa for Superphénix

with France, West Germany, Italy, Belgium, and the Netherlands. Our choice of partners reflects a similarity of purpose and equivalent level of expertise within Europe. We are, of course, aware of developments elsewhere, particularly in the US and Japan, and are therefore maintaining the possibility of extending the collaborative venture outside Europe when the time is right.

We expect the collaborative agreements will favour and encourage links between manufacturers. It is hoped these links, in conjunction with agreements between utilities, design companies and development organisations, will assist the process of evolving the most economical designs of fast reactor. They will also help sustain collaboration into the commercial phase. Generally collaboration should give British firms earlier opportunities to get fast reactor business—albeit in a limited and competitive field—than if the UK goes ahead on its own. It may be noted that the UK line of development—pool type, sodium cooled reactors—is likely to be the 'orthodox' type. The UK will not be technically isolated as many have argued is the case with gas-cooled thermal reactors.

If such collaboration can be fully and successfully established, the UK will benefit from additional R&D work of some £200 million per annum and additional benefits from the overseas construction and operating experience to which we should also gain access. Collaboration should lead to lower capital costs for the UK lead station, reduce operating problems and allow harmonisation of investment with our partners in fuel plants. Having a commercially viable system available earlier rather than later could lead to great benefits to the UK economy if there should be a world fuel shortage which would otherwise inhibit UK economic growth.

The Authority's programme

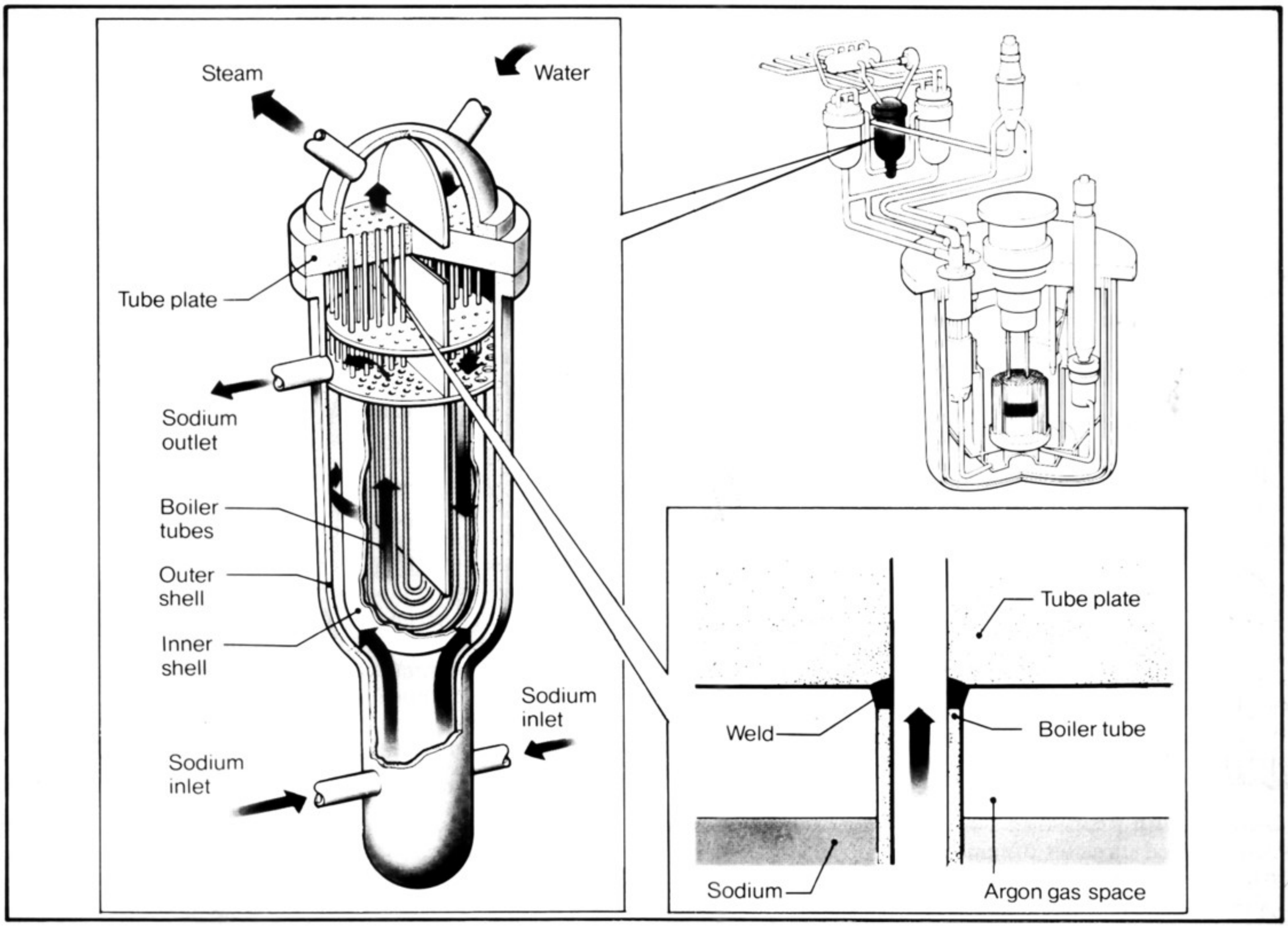
The Authority's programme has been under way, supported by successive Governments since the early 1950s. Technically it is focused on the development of the full reactor and fuel cycle system with a view to ensuring safety and reliability and to optimising the economics to the point where it could be commercially introduced as a proven, safe and economic component of the UK's electricity generating capacity.

We have already recorded a number of important achievements on the way towards achieving that objective. The construction and successful operation of the Dounreay Fast Reactor (DFR), which owed so much to the early leadership of Sir Christopher (later Lord) Hinton, demonstrated the feasibility of the fast reactor concept on a small scale with a very conservative design. This 60 MWth reactor, having operated successfully as an electricity generating station for nearly 20 years, is now being decommissioned and thereby providing further valuable experience.

DFR and the associated research programme led to the construction of the 250 MWe Prototype Fast Reactor (PFR) which started operation in 1974. The design of PFR was based on a conceptual design of a 1000 MWe reactor so that the components and systems in PFR would extrapolate readily to full commercial scale. For example, PFR fuel sub-assemblies are of a size appropriate to those in a commercial scale reactor. In addition it is well provided with equipment and instrumentation to make it a good test facility, particularly for the irradiation of fuel and materials under relevant conditions.

The operation of PFR is of great importance to the programme. With the exception of the evaporator units, the plant has operated with high reliability. Its continued operation will

Fig 4 A PFR evaporator unit



demonstrate the ability of engineering components such as pumps and heat exchangers and reactor structures to perform their duties reliably and routinely throughout the 30-40 year life required of commercial reactors. Further it will amass data on the safety and performance characteristics of the fuel, establish a lifetime experience of operating a fast reactor power station including maintenance of reactor components, and provide a fast reactor test facility particularly well equipped for experimental work.

Performance of the fuel continues to be extremely satisfactory with no fuel failures in the driver fuel which has now attained a burn-up of over 9 per cent: lead fuel has been taken to almost 12 per cent burn-up. Post-irradiation examination of driver charge fuel pins at burn-ups of up to 7·5 per cent has revealed no unexpected features and is giving confidence that the CDFR fuel burn-up target of 15 per cent can be attained. Indeed fuel designed for this burn-up is currently being manufactured for loading next year. Data from post-irradiation examination of control rod pins are confirming the ability to predict their performance and to design for substantially longer life.

A particular recent highlight is the successful performance in PFR of an under-sodium viewer (using 1 MHz ultrasonic signals). A number of scans of the top of the PFR core were made and excellent pictures obtained. In all, 22 out of 25 sub-assembly rigs have been seen by the viewer. Off-line analysis provides data and sub-assembly position (to within 1 mm), bow and relative height which are of value in core monitoring.

Safety analysis of the fast reactor system is a further area where we have learnt a lot. One potentially significant development derives from recent work on the role of natural circulation convection currents in removing decay heat from the reactor core. The safety design of the system after shutdown is based on decay heat removal by pumped circulation with a high degree of redundancy. However, calculations and experimental measurements indicate that even with complete failure of the pump systems, natural circulation of convection currents of the sodium in the primary tank would be sufficient to remove the decay heat and keep the core cool. Following this analysis, calculations we have carried out recently suggest similar mechanisms could be significant in cooling within sub-assemblies. It seems possible that after a shutdown, even if a sub-assembly inlet were completely blocked, natural circulation initiated by cool sodium flowing in through the top of the sub-assembly could provide sufficient cooling inside the sub-assembly to remove decay heat and prevent the sodium boiling. In both of these areas the detailed calculations are extremely complex and further experiment and analysis are planned to explore the phenomena more fully.

The PFR Reprocessing Plant plays an important role in the overall development programme. It is providing a demonstration at pilot plant scale of the reprocessing of a mixed oxide (PuO_2 and UO_2) fuel and has demonstrated the complete fuel cycle; that is, plutonium nitrate from the plant has been refabricated by BNFL into fresh fuel which has been reinserted into PFR. A total of 4320 kg of irradiated fuel (509 kg of Pu), equivalent to 46 sub-assemblies, has been reprocessed. In the last campaign the average burn-up was 6·6 per cent and one sub-assembly had a peak burn-up of 8·8 per cent. Four sub-assemblies with short cooling (4½ months) were indicated. The campaign was completed without incident. Sodium cleaning of the sub-assembly, dismantling and dissolution of the fuel posed no problems, and high product purity and low plutonium losses to solid and liquid waste streams were achieved.

Outstanding problems

Despite these successes a number of problems remain. The main area of concern, causing substantial loss of output since 1979/80, has been an unacceptably high incidence of small leaks in the tube to tubeplate welds of the evaporator sections (made from 2¼ Cr 1Mo ferritic steel) of the PFR boilers (see figure 4). Four such units were produced (3 operating and 1 spare). To overcome the problem three of the units will have sleeves fitted over each weld, using an explosive weld at the top of the tube plate and a braze joint to the tube below the tube plate; the fourth unit will be retubed with some minimal design alterations. The sleeving modifications have been under development in the Authority since 1977. At that time, they were envisaged for application to a relatively small number of tubes as an alternative to plugging faulty tubes. When the need to apply the process to all welds was recognised steps were taken to work it up for production line application by an industrial boilermaker.

The first unit has been completely sleeved (it takes about 6 months to fit approximately 1 000 sleeves). The second will be completed later this year. The third unit is still in service (providing an excellent test bed for a batch of about 60 sleeves fitted last year) but full sleeving of this unit will probably start towards the end of the year and will be ready for service about the middle of 1984 when PFR is expected to operate again at full power on its three secondary circuits.

In parallel with the adoption of these measures there has been a substantial amount of work to diagnose the cause of the defects in the welds and to seek operational solutions (e.g. changes to operating procedures of conditions). The cracks now giving concern in the evaporators all start on the sodium side of the weld and considerable development of ultrasonic inspection methods for detecting and sizing has been necessary, augmented by novel procedures for cutting out some welds for laboratory examination. From this work in Authority establishments it is clear that the lack of heat treatment of the original welds, together with some unanticipated ageing effects, have made the weld susceptible to cracking in the environment in the above-sodium gas space because of the ingress of small amounts of water. Thus a picture emerges of the large incidence of leaks being the aftermath of a small number of early leaks caused by manufacturing defects or of a waterside stress corrosion mechanism (recognised early on and eliminated by shot peening.) These environmental effects are still not fully understood and are clearly very complex; for example recent work is suggesting that the small amounts of impurities in the sodium may play a part as well as reaction products from water ingress.

Looking forward

The overall technical content of the forward programme and its priorities will remain uncertain until the international collaborative arrangements have been agreed, and a joint programme worked out. In the meantime, in the light of the Government's new extended timescale and a consequent reduction of Authority annual vote expenditure over the next 3-4 years, a revised programme has been formulated. This takes account of an associated design and proving programme, which will be funded largely by UK industry, but to which the Authority will also contribute.

In the revised programme the highest priority is being given to engineering and components (including Design Codes), the development of fuel, and the design of fuel plants. Selection of the high priority areas took into account the strengths of the UK's technical position, the opportunity for making most of the PFR and its fuel plants, and the interests of UK industry. When international collaboration has been established, the needs and strengths of the partners must also be taken into account to ensure the total programme covers all the necessary area.

One of the major objectives is to produce an NNC design for a commercial-scale lead station. In 1981 NNC produced a Design Concept Status Report that summarised their work and presented a compact design with good prospects for a low

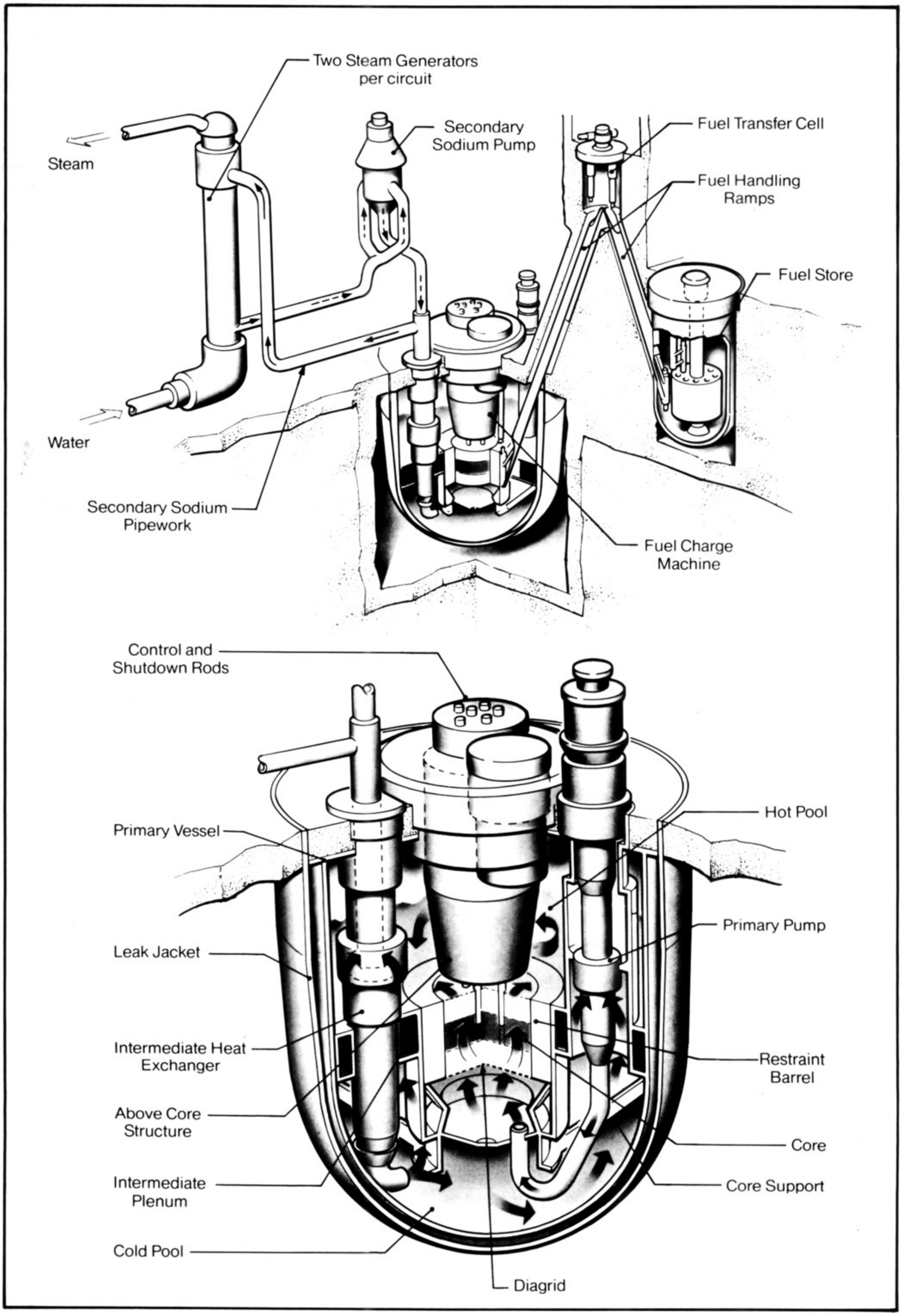

Two Steam Generators per circuit
Secondary Sodium Pump
Fuel Transfer Cell
Fuel Handling Ramps
Fuel Store
Steam
Water
Secondary Sodium Pipework
Fuel Charge Machine
Control and Shutdown Rods
Hot Pool
Primary Vessel
Primary Pump
Leak Jacket
Intermediate Heat Exchanger
Restraint Barrel
Above Core Structure
Core
Intermediate Plenum
Core Support
Cold Pool
Diagrid

Fig 5 CDFR

capital cost. The most important features of this design are illustrated in Figure 5. Basically the 1 250 MWe reactor is a sodium pool design operating once-through boiler units fabricated from 9Cr/1Mo steel (unlike PFR). The tubes in the intermediate heat exchanger for CDFR do not incorporate a bend (as in PFR) to deal with differential thermal expansion. Work is therefore required to assess thermal hydraulics and the resulting thermal stresses. A tube buckling rig will investigate the buckling characteristics of straight tubes under service conditions.

PFR experience has highlighted the importance during the design process of taking full account of the possible adverse effect of thermal stresses on the structural integrity of reactor components. This is especially important for the structures which support the core within the primary vessel. In PFR the core support structures also form the boundary between the hot and cold sodium pools and are therefore subjected to considerable thermal stressing. To avoid this in CDFR the primary core support structures, comprising the diagrid, strongback and the primary vessel, are entirely within the cold pool. The back-up, or secondary, core support system is *via* the pipework connecting the diagrid to the primary pumps and hence to the reactor roof. Both core support systems are protected from the interface between the hot and cold sodium pools by a novel feature known as the intermediate plenum (see Figure 6). This is an enclosed volume, about 3 m deep, crossing the reactor vessel at half height and containing stratified stagnant sodium. A further advantage of the intermediate plenum is that it establishes an extended vertical temperature gradient along structures passing through it, notably the intermediate heat exchangers and primary pumps. This reduces thermal stresses and strains that would otherwise

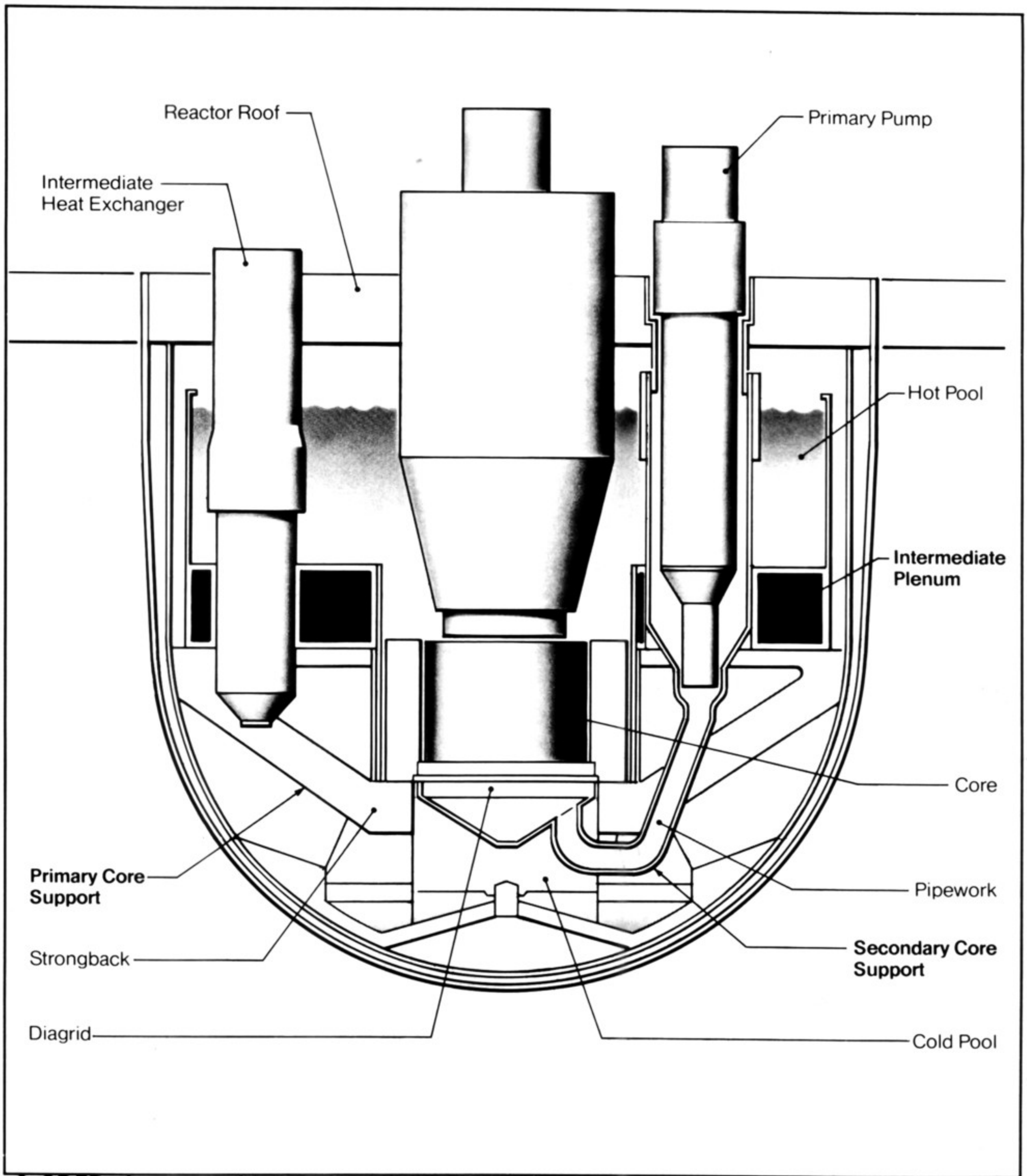


Fig 6 CDFR plenum and other essential features

be set up in these components.

The Authority have an extensive programme to validate the intermediate plenum design. This programme is studying temperature distributions and flow within the intermediate plenum, under a range of reactor operating conditions (steady state and transients) by carrying out experiments on scale models of the component using water and liquid metal, including sodium, rigs. This is coupled with the development of supporting analytical models to study the thermal hydraulics within the plenum.

The good performance of fuel so far in PFR has led to a decision to increase the target burn-up in CDFR to 15 per cent (about 150 000 MWD/T). Increasing burn-up from 10 per cent to 15 per cent is estimated to reduce generating costs by some 5 per cent. The major challenge this presents is the design of the overall structure of the sub-assembly to accommodate distortions such as bowing, differential growth and dilation caused by the swelling of materials resulting from irradiation in a fast neutron flux (this phenomenon was first discovered at Dounreay in the DFR reactor). A combination of engineering design (restrained core) and improved materials (resistant to swelling) is required. PFR is being used to assess alternative materials incorporated in full size sub-assemblies and in experimental samples followed by detailed post irradiation examination at Dounreay.

The experience with the PFR steam generators has highlighted the need to carry out extensive design and validation work on these critical components. A particular issue is the validation of the selection of normalised and tempered 9 Cr/1Mo steel as the reference material for the thick tube plate for the CDFR steam generators. It will be essential to demonstrate that the good creep/fatigue properties of this alloy found in tests on small specimens are maintained in the centre of a thick tube plate forging. Similarly it must be demonstrated that satisfactory welds between tube and tube plate can be produced, that these can be heat treated and inspected, and that their integrity is maintained over the lifetime of the plant.

When the collaborative programme with our prospective partners gets under way, the work on CDFR carried out up to that time will form an important input to the design of future reactors in the partner countries and in the UK. Priority will be given to design and development work in support of Superphénix II and subsequent reactors as part of the joint programme. A considerable part of the input to the joint effort will be on the development of the design and validation of a full-scale reprocessing plant. Efficient and economic reprocessing of the spent fuel elements is an essential feature of the utilisation of the fast reactor, and this is an area where the UK has a leading position. A joint BNFL/Authority programme will consider alternative design of plants, and the development programme will include *inter-alia* a study of the performance of improved solvent extraction contractors, for example pulsed columns rather than the mixer settler system in PFR which is difficult to scale-up.

Much progress has been made since the early days of Sir John Cockcroft. Many of the technical problems have been solved, for both reactor and reprocessing plant, and valuable operating experience has been gained. The goal of commercial introduction remains as important to long term energy security in the UK as it has ever been, although the time scale for probable commercialisation has, on economic grounds, now moved into the early part of the next century. The Government's commitment to the Fast Reactor removes the uncertainties of the last few years, and represents an important milestone in our development programme.

The proposed international collaboration presents the Authority, the Generating Boards and the Industry with important new challenges and opportunities. It will enable us to bridge the gap until commercialisation by taking part in an integrated programme of R&D, design and construction of lead stations. The operation of such lead stations and associated fuel cycle plants will, *inter alia,* play an important role in reassuring the general public that a system based on the fast reactor fuel cycle and the use of plutonium is safe. This is essential before series ordering begins and the proposed collaborative programme will enable us to do this. We now have a new spirit of co-operation within the UK industry, renewed confidence in the future role of fast reactor technology, and enthusiasm to collaborate with our partners. I have no doubt that the remaining technical difficulties will be overcome and that national and international collaboration will enable us to tackle successfully the final challenge of development to commercial introduction.

Acknowledgements

I am very grateful to my colleagues in the UKAEA who have helped me in the preparation of this paper.

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X-RAY DIFFRACTION IN THE DEVELOPMENT OF ATOMIC ENERGY

X-ray diffraction has been used since the earliest days of atomic energy and nuclear technology as a valuable tool. I F Ferguson from the UKAEA's Springfields Nuclear Power Development Laboratories traces the history of its development and some of its successes.*

The role of x-ray diffraction (XRD) in atomic energy is an interesting one. If we go back historically we find that in 1895 x-rays were discovered by Roentgen, whilst in 1897 J J Thomson measured the ratio of charge to mass for the electron. From these dates it can be seen that x-rays were closely associated with the very earliest steps towards the release of atomic energy. Indeed, this association had begun before any conception, or proof, of the nuclear atom existed. A little later, in 1912, Friedrich and Knipping, following a suggestion by von Laue demonstrated the diffraction of x-rays. In 1919, Hull demonstrated x-ray powder diffraction, then, in 1921, commercial x-ray diffraction apparatus appeared on the market. 1932, was a remarkable year; Cockcroft and Walton first split the atom by artificial means and the neutron was discovered. To continue the x-ray story, 1936 saw the introduction of the Dow Index by Hanawalt, Rinn and Frevel which was to prove the precursor of the JCPDS x-ray data file. In 1942, the Fermi pile went critical for the first time.

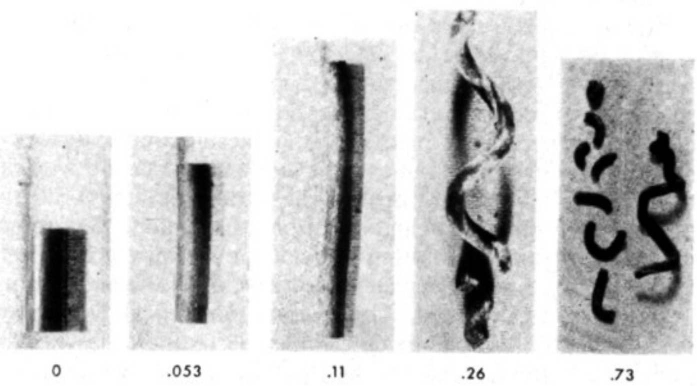
At this stage x-ray diffraction became entwined with atomic energy. It played a role in the British Tube Alloys project as is demonstrated by a Tube Alloys Debye Scherrer film number 1817 which still survives. This film, abysmal by today's standards, reached Springfields from Capenhurst and is probably the diffraction pattern of uranium dioxide. In these early days some work was done too at the National Physical Laboratory at Teddington.

X-ray diffraction played a part too in the war-time American Manhattan project. Thus we find 38 references to x-ray diffraction in 'The chemistry of uranium' by Katz and Rabinowitch, whilst in 'The transuranium elements' by Seabourg, Katz and Manning there are eight references to Zachariasen—the great war-time American exponent of x-ray diffraction—a number which exceeds those credited to Cunningham who first isolated plutonium metal. It is clear that the Russians also had an interest in this field for we also find a book by Makarov entitled 'The crystal chemistry of simple compounds of uranium, thorium, plutonium and neptunium'.

Why was x-ray diffraction linked in this way with atomic energy? The answer is clearly given in the National Nuclear Energy Series statement "In November 1943 Dr P Kirk submitted a sample of PuO_2 for x-ray diffraction study . . . the calculated density was $11 \cdot 44 \pm 0 \cdot 01$". The density of PuO_2 was needed to calculate its critical mass. Moreover, in this case of plutonium, an entire new chemistry had to be mapped out for this man-made element which was first seen and weighed in 1942 whilst the location of plutonium in the Periodic Table made for perversely difficult chemistry.

At first only very small amounts of material were available. As already noted density determinations were of vital importance, whilst the determination of crystal structures was also significant since, for example, the recognition that PuO_2 was of the same structure as UO_2 implied that it would prove to have a high melting point, as indeed it has. Crystallographically the problems presented by the development of atomic energy were formidable. For example there are 20 uranium oxides and 8 oxide hydrates, there are moreover 5 anhydrous uranium fluorides. It was necessary to understand the crystal chemistry of all these, as well as of the uranyl fluorides and their hydrates. (In a gaseous diffusion plant—another key point in the release of atomic energy—these latter compounds would form if water were to leak into the plant. Their densities, which can be calculated from their crystallographic unit cells, determine the critical mass of each compound and so set constraints on the operation of a diffusion plant. There was a section studying crystallography at Capenhurst in the 1950s.)

In addition, the uniquely complex phase/temperature diagram of plutonium had to be determined. Plutonium has the unique property that, over certain temperature ranges, some of its different forms contract as the temperature is raised. This must have had profound criticality consequences, and, doubtless, spurred the investigation of many plutonium binary systems in an effort to stabilise the phases with desirable properties. Consequently we find XRD work at AERE, Harwell in 1958 aimed at determining the thermal expansion of PuO_2—a fast reactor fuel.



Effect of irradiation on uranium specimens rolled at 300°C, in increasing order of burn-up

*Based on a lecture presented to the UKAEA Diffraction Analysis Conference 25th Anniversary and to the meeting at which the British Crystallographic Association was constituted.

Other studies in the Harwell Chemistry Division by Baynall and D'Eye in the late 1950s were concerned with polonium which could be used to prepare a gamma-free neutron source. At the same time Wait was working on the chemistry of UO_3 and its hydrates as well as developing micro XRD techniques for studying UO_2 irradiated to high burn ups. J S Anderson's group had examined UO_2 and related phases by XRD, work L E J Roberts was to extend to other actinide oxides.

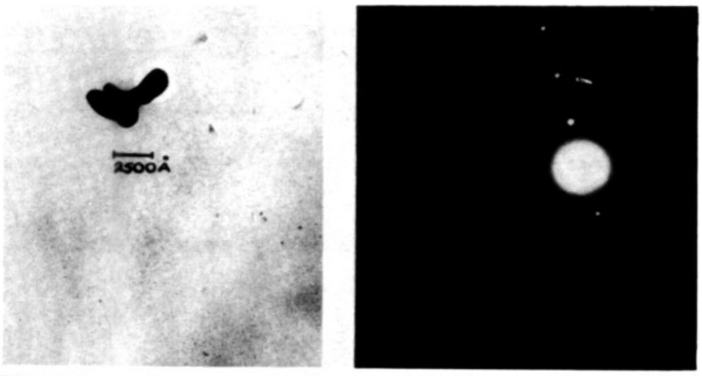
Meanwhile, in AERE's Metallurgy Division, Thewlis was studying the structure of uranium while Mardon *et al* were examining binary systems based on plutonium. Kinchin and Pease were working on irradiation damage in general and Smallman on irradiation damage in metals. In connection with this work Pease showed that boron nitride could exist in a modification with the diamond structure, Bacon was investigating graphite. Lee and Marples studied the crystal lattice behaviour of the actinides down to liquid helium temperatures. At the same time T W Baker was carrying out a great deal of routine service work, for example on reactor steels. Specialist equipment such as a diffractometer which could be used to investigate extremely $\beta\gamma$radioactive samples was being designed by J Adam. (This equipment has been used to study irradiated europia which was giving off doses of almost 1 000 roentgen on contact.)

In contemporary crystallographic literature there are many examples of the determination of the precise arrangement of the atoms in ligands coordinated about a central metal atom. It might have been thought that the various atomic energy projects would have produced many similar papers. However, the development of atomic energy does not need knowledge of the finer details of the structural chemistry of an element once the broad features of its inorganic chemistry are clearly understood. Consequently the UKAEA's Northern Division is little interested in either the coordination behaviour of uranium or precisely how ligands are disposed about it. Nevertheless, some work does go on along these lines.

Irradiation damage

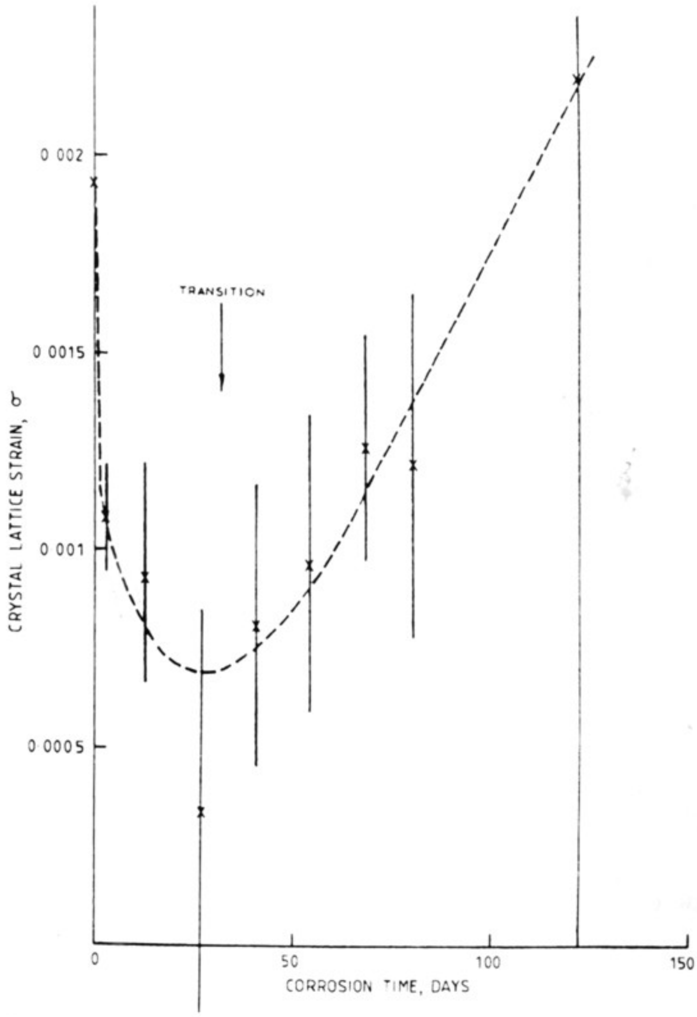
The study of irradiation damage is of considerable importance to the AEA because when a piece of ordinary (textured) uranium is irradiated it changes size and shape. When it is recalled that the first plutonium producing piles involved loading (canned) natural uranium metal into suitably arranged channels cut into a large mass of graphite, it will be clear that the uncontrolled irradiation growth of uranium could lead to difficulties. The piles of the US Manhattan Project would have ground to an untimely halt had they not contained overlarge channels! These problems were overcome by the production of randomly orientated α-uranium (as shown by XRD) and by making various additions to the metal.

But irradiation damage can be turned to good use. When β-silicon carbide is exposed to a neutron flux its lattice parameter expands to reach a limiting value which depends upon the temperature at which the irradiation was carried out. If the limiting value is determined by XRD using small fragments of β-SiC incorporated into an experiment in a reactor then temperature can be determined out of the pile after the experiment. Incorporating thermocouples into irradiation experiments can thus be avoided. A second way of determining the temperature is to heat the irradiated β-SiC to progressively higher and higher temperatures and to determine the lattice parameter limiting value at room temperature after each heating, since it begins to decrease once the irradiation temperature is exceeded. This method is used at Dounreay Nuclear Establishment to determine the temperature of experiments in the fast reactor. At sufficiently high post irradiation temperatures the limiting value reverts to the unirradiated value and at even higher temperatures falls below it, an unexpected and original observation. It is thought that this is because the interstitial atoms and the vacancies introduced by the irradiation anneal out at different temperatures—interstitial atoms annealing out first.



Electron micrograph of a particle from an unmilled uranium dioxide powder and the corresponding electron diffraction pattern which shows it to be a single crystal

Another area in which XRD has an inportant role to play is the study of corrosion mechanisms, although such studies are rarely made. It is well known that if the weight of a zirconium sample is plotted as a function of exposure time to steam, its weight gain follows a parabolic law, and oxidation becomes progressively slower with the passage of time. However, after a certain interval 'transition' occurs and rapid 'breakaway' oxidation recommences only to slow down as before. This process is repeated seemingly endlessly. The time to transition differs from sample to sample. At Springfields two Zircaloy samples were examined by XRD. Both of them had been pickled in a mixture of hydrofluoric and nitric acids, but one of them had been polished afterwards. XRD using CuKα



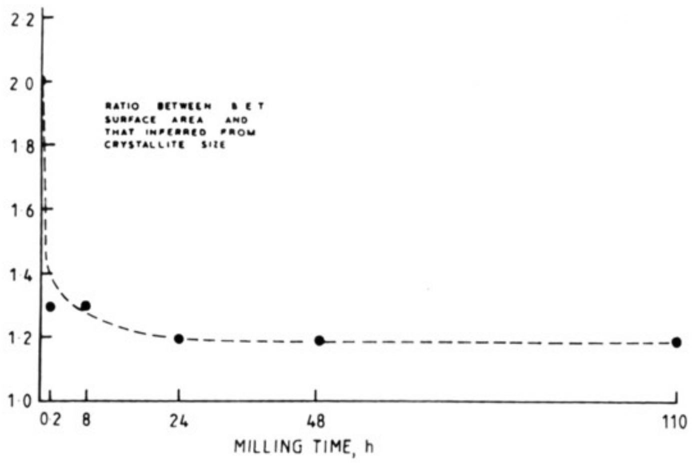
Crystal lattice strain in polished zircalloy substrate

radiation shows that the oxide film is predominantly monoclinic zirconia, although the use of progressively softer x-radiations i.e. those with longer, less penetrating wavelengths, culminating in the use of TiKα radiation ($\lambda = 2 \cdot 75$ Å) also showed that the outermost layers of the oxide film were much less crystalline than the 'bulk' oxide film. The oxide film is always so highly textured as to be unrecognisable in terms of the standard x-ray powder pattern of monoclinic zirconia. The degree of preferred orientation in this film can be measured and from such measurements related to models of the crystal structure of monoclinic zirconia it was found that the crystallographic planes which are richest in oxygen tend to lie parallel to the surface of the corroding Zircaloy. The XRD investigations were extended further to determine: the lattice parameters of the Zircaloy substrate and to show that oxygen dissolves in it as oxidation proceeds; the size of the crystallite in the zirconia corrosion film, and their crystallite strain; crystallite size of the Zircaloy substrate; and the crystallite strain in it. With the exception of the last property, the variation of none of these parameters correlated with the 'transition' to breakaway oxidation. 'Transition' is generally judged to be a function of strains and cracking in the oxide film, but these XRD results show that it may be the behaviour of the Zircaloy substrate that controls the rate of oxidation of Zircaloy rather than that of the oxide film.

Distinguishing materials

As atomic energy becomes more focussed in its interests XRD has been required more and more to distinguish and differentiate chemically identical materials. Uranium dioxide, for example, like many other materials in the ceramic industry exhibits variable sintering behaviour depending upon its precise origin, preparative route, and how it has been handled. A common method used to produce a powder of predictable sintering behaviour is to mill it. A major investigation was made to interpret and explain the behaviour of uranium dioxide powder upon milling based primarily upon XRD because transmission electron microscopy, a technique which might have been used, was handicapped by the difficulty of dispersing the power. X-ray line broadening showed that the crystallite size decreased as a function of milling time whilst at the same time there was a steady increase in the surface area as measured by the BET method. The behaviour of the ratio of the BET surface area to the surface area inferred from the crystallite size was interesting, for it decreased rapidly from 2 at the onset of milling to become steady at $1 \cdot 2$ after considerable milling. The crystallite strain behaved curiously, passing through a minimum at the beginning of milling but then increasing steadily as the power oxidised. These two phenomena can be explained in terms of the milling breaking strained necks in elongated monocrystallites present as basic particles in the unmilled powder, a fact strikingly confirmed by electron microscopy which showed the constituent UO_2 particles in the unmilled powder as elongated, necked, single crystals.

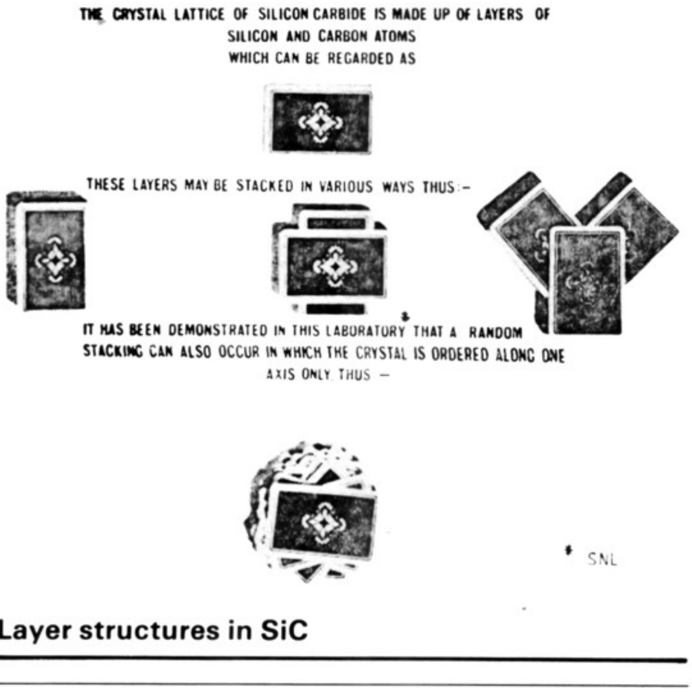
The second major class of examples where XRD was used to differentiate preparations of supposedly identical material is that of the investigation of silicon carbide made by the pyrolysis of trichloro-methylsilane in a fluidised bed. This material was intended to coat granules of nuclear fuel for use in a High Temperature Gas-cooled Reactor. In these investigations it was noticed that the 111 Bragg reflection of β-SiC, was accompanied by a feeble satellite. This reflection could *not* be attributed to the presence of one (or more) forms of α-SiC. Indeed its skewed profile, as shown by means of a diffractometer, was typical of disordered layer structure. If you consider a single sheet of atoms in the βSiC structure parallel to the 111 plane (or in the case of α-SiC parallel to the 100 plane) as being represented by a playing card, the various polytypes of SiC can be understood in terms of these playing cards being stacked in various regular ways.



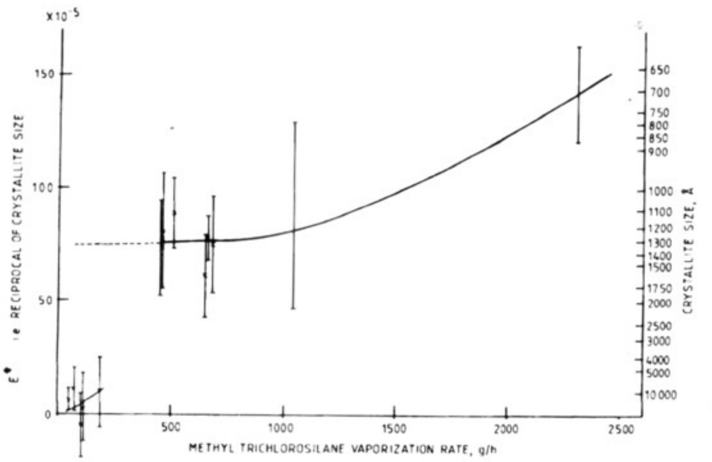
Relation between milling time for a UO_2 powder and its surface area as measured by BET

It is postulated that the observed reflection is due to a form of silicon carbide, termed δ-SiC, in which the playing cards are arranged randomly and only possess an order perpendicular to the layers. The amount of δ-SiC present in pyrolytic silicon carbide, which normally deposits as cubic β-SiC, is directly proportional to the coating rate, whilst it also depends upon the proportion of argon present in the fluidised bed coating gases.

An important feature of XRD in the UKAEA has been the introduction to the country of new techniques as well as the development of new methods and equipment long before they had become available commercially. The introduction of the Hägg design of focussing camera from Uppsala University to the UK and in particular Harwell by D'Eye in 1954 is a case in point. This camera enabled D'Eye to carry out significant work on the thorium and uranium fluoride hydrates, on zirconium analogues and on the extraction of beryllium from its ores. Meanwhile at Capenhurst 'ammonium diuranate' was characterised using a focussing camera, something which would have been quite impossible with the Debye Scherrer camera used previously. The particular advantages of the focussing camera are its low background, high resolution and freedom from angular errors at low Bragg angles (and, today, the short exposure times which are less than those of the Debye Sherrer camera and the ability to use absolutely pure monochromatic e.g. CuKα_1 radiation).



Layer structures in SiC



Variation of the crystallite size of β-SiC as a function of methyl trichlorosilane vaporisation rate

In a different vein at Harwell the collection of x-ray powder diffraction data on punched tape for subsequent computer processing was introduced by T W Baker in the late 1950s, and later came the APEX goniometer which enabled lattice parameter measurements to be made with unprecedented accuracy ($\sim$1 in 10^8). In this way Baker was able to measure the thermal expansion of magnesia over a 1°C interval of temperature. He also designed a high temperature diffractometer attachment which could operate at up to 2 300°C. This was redesigned by the author and subsequently marketed by Philips. The author was also responsible for the development of the first diffractometer attachment which could exchange rotating samples.

Beginning in the 1960s automation using computers has played an increasing role in XRD in the UKAEA. Without computers the crystallite size measurements referred to above could not have been made. Neither would it have been possible to carry out the numerous repetitive measurements made on Prototype Fast Reactor wrapper materials to prove their uniformity both along their length and between different manufacturers. Computers have also been used to describe unambiguously the position of Bragg reflections. This has been especially important in measurements on irradiated material, such as boron carbide, when the reflections become weak and diffuse.

In the 1980s, XRD is being used increasingly, in conjunction with other techniques, to solve problems. An early example at Springfields was the investigation of the high temperature (greater than 1 500°C) reaction between silicon carbide and uranium monocarbide. XRD was used, in conjunction with electron probe microanalysis and with the help of information provided by P L Blum's group at the CEA's Grenoble establishment, to characterise the presence of such unlikely ternary phases as $U_3C_3Si_2$ and $U_{20}Si_{16}C_3$ as well as the better known carbides and silicides. Today, in the 1980s, we are using XRD with other techniques to understand how aluminium reacts with Inconel when it is deposited to form a protective coating for fast reactor applications.

It will be seen that XRD has played many important and diverse roles in the UKAEA. Today other specialist techniques compete with XRD. An important role of XRD is that it can characterise phases (which may be toxic, extremely radioactive or sensitive to the atmosphere) over very wide ranges of temperature and pressure on a precise numerical basis, over large areas ($\sim$1 cm^2) of specimens—something no other method can do with so little restriction on where the equipment is located. At the same time, for those without immediate access to a range of instruments the use of complementary techniques can enormously enhance the significance of simple XRD data—as for example in forensic science. □

Important year for the Authority

In presenting the 1982/83 Annual Report of the UKAEA to the press, on 15 September Sir Peter Hirsch, Chairman of the Authority said 'The past year has proved to be a very important one for the Authority. Following its review of fast reactor policy, the Government concluded at the end of November last year that the fast reactor was of major strategic significance to the UK's future energy supply, that the commercial introduction of the fast reactor was likely to begin in the early part of the next century, and that a substantial development programme, based on Dounreay, should be continued and geared to this new timescale.

'The Secretary of State asked me to prepare proposals for the future development programme in consultation with my colleagues from the Generating Boards, BNFL and NNC, and to explore the possibility of international collaboration. Following our unanimous advice, the Government announced on 5 September its acceptance of our proposal that the future programme should be carried out in close collaboration with the other European countries—France, Germany, Italy, Belgium and the Netherlands—who have already joined together in a very successful European "club" for fast reactor development. . . . When the collaboration with Europe has been established, there is the possibility that Europe can extend, at the appropriate time, the collaboration to the US and Japan, who are also developing the fast reactor.'

Sir Peter pointed out that 'The fast reactor will enable the UK in due course to achieve independence from imported supplies of uranium. Fast reactors can extract up to about 60 times more energy from uranium than is possible in thermal reactors such as PWRs and AGRs. Our national stockpile of depleted uranium represents an indigenous energy resource, comparable in size to our economically recoverable coal reserves—sufficient to meet our electricity needs at present levels for about 400 years, when used to fuel a fast reactor system. The aim of the collaborative programme will be to develop safe, reliable and economic designs of reactor and fuel plants for commercial introduction, and the development programme will be focussed on the design of plant for lead stations for possible construction in any of the major countries of the enlarged 'club', i.e. France, Germany and the UK, when the respective Governments decide that the time is right to do so.'

The development programme will be worked out in collaboration with the Generating Boards, NNC and BNFL, and in due course in consultation with our European partners, Sir Peter said. The programme will use the extensive facilities at Dounreay, including PFR and the reprocessing plant. Development of fuel, plant and fuel cycle processes and joint efforts on station design and the establishment of the economics of the system will all be included.

During the year being reported on the fast reactor fuel cycle was completed successfully. The reactor itself has also worked well, Sir Peter said. 'It had completed 79 days of continuous power generation when it was shut down as planned on the September for fuel changing, maintenance and statutory inspection of the steam plant. There have however been recurrent problems with leaking welds in the boilers outside the reactor, which have reduced electricity generation. A programme to bridge these welds by internal sleeves is well under way. Much has been learnt about the mechanisms of failure, ultrasonic inspection techniques have made considerable advances, and the lessons learnt will be applied to avoid such failures in future designs.

'Whilst the development of the fast reactor is important for the future there is a good deal of work for us to do on the AGR system. The five stations now in operation or being commissioned and the two stations under construction, represent a considerable national investment and will provide most of our nuclear-generated electricity at least to the end of the century. There is an obvious national benefit in increasing the output of these stations and extending their lives. Our development work, which is closely co-ordinated with that of the generating boards, BNFL and NNC, has assisted the introduction of partial load refuelling at Hinkley B and Hunterston B and in enabling a steady upward trend in output and load factor to be achieved at these stations. Work on graphite life has given us confidence that it should not be a limiting factor in achieving station lives of 40 years or more.

'The proposal to construct a PWR in the UK is, of course, currently the subject of the Public Inquiry at Sizewell. The UKAEA is not a party to the Inquiry but we have made a substantial R&D contribution to the CEGB's safety case and some Authority senior staff have given evidence. Our principal objective in PWR R&D is to develop expertise in safety technology to assist the NII and the UK nuclear industry.

'A very important area is that of PWR pressure vessel integrity. The Authority have developed highly sensitive methods of testing these major components for small defects that might lead to fracture in service. To ensure that the new techniques will be reliable in practice, an Inspection Validation Centre, funded with CEGB support, is being set up at Risley. Its work will be guided by an independent advisory committee chaired by Sir Alan Cottrell, who has recently become a part-time member of the Authority.'

Media focus on the management and disposal of radioactive wastes was also mentioned by Sir Peter who reminded his audience of the formation of the Nuclear Industry Radioactive Waste Executive (NIREX).

'Deep ocean disposal is particularly suitable for certain types of low-level waste, for instance bulky but lightly contaminated articles and tritium—the radioactive isotope of hydrogen' Sir Peter said. 'The rules for disposing of this waste in the ocean were not devised by the nuclear industry but by

Computerising safety course

Computer applications in safety and radiation protection is the theme of a one-day symposium to be held at the University of Reading on Tuesday 20 December 1983. The morning sessions include a general introductory talk on computers and their uses, and detailed lectures on applications in the analysis of accident data, on-line information retrieval, and the storage of chemical hazard information. The first afternoon session describes applications in radiation protection involving isotope stock control and record keeping, personal monitoring and related topics, and quality control in isotope production. The second afternoon session relates the experience gained and lessons learned by one university in the application of computers to a variety of problems in safety and radiation protection. An exhibition of hardware and software will accompany the symposium.

The symposium should be of interest to safety practitioners in industry, local government and education who would like to consider using—but not necessarily understanding—computers for safety purposes. Overnight accommodation can be provided.

Further details: John Kibblewhite, Safety Office, University of Reading, Whiteknights, Reading RG6 2AB. Tel: Reading (0734) 875123, ext. 7948 oceanographers and marine biologists whose primary responsibility is a concern for the marine environment. We have made many appeals to the National Union of Seamen to discuss their concerns with us but without response. It would be very sad if the case for sea disposal in accordance with the procedures currently approved, which so many scientists find completely acceptable, should be overwhelmed by prejudices derived from emotion rather than reason. We hope that good sense will finally prevail in this issue.'

In the fusion field 1983 has seen the start of operations in JET (the Joint European Torus experiment sited at Culham in Oxfordshire). 'UK industry played a major part in the construction of this large tokamak machine. Its successful completion on schedule is a considerable achievement, on which we congratulate Dr Wüster and his team. We look forward to the experiments in JET to provide valuable knowledge, which could lead ultimately to the development of a major new energy source based on widely available fuels.' The Authority are providing a large proportion of the staff of the project and Culham Laboratory is doing important R&D work in support of the JET programme.

'But the Authority's activities are not confined to nuclear energy. We have for many years been passing the benefits of our expertise and advanced technology to British industry to help it to remain competitive in international markets.' The Authority's laser techniques have been brought into use by manufacturers of combustion engines and industrial robotics during the year, advanced computer simulations assist the exploitation of oil and gas resources; methane gas from landfill sites is in routine use, and systems reliability techniques developed for nuclear plant are being transferred to industry.

'Underlying all the Authority's R&D programmes is our fundamental nuclear and allied research work, which provides the essential base for the technology of nuclear power development and for our assistance to the UK nuclear industry. I attach great importance to this work, which is generally recognised by scientists outside the Authority, including those in Universities, as being of the highest quality. The Underlying Programme provides the Authority with its main interface with the universities and polytechnics, and it generates the seed corn for the technological developments of the future.

'All this R&D work adds up to an Authority programme which is carefully balanced between the more speculative, longer-term, work which we carry out on our own initiative and the contract work in support of the UK nuclear industry, with which our own work is closely integrated to yield the most fruitful results.'

Construction problems behind CEGB

Construction of the Heysham II AGR in Lancashire is running to time and budget. With a similar performance at the Drax coal-fired station in Yorkshire the Chairman of the Central Electricity Generating Board, Sir Walter Marshall could happily tell journalists visiting Heysham that "We now have a convincing demonstration of our ability as an organisation to manage effectively these very large power station building projects. This must strengthen confidence in the Board's ability to meet the construction targets for the proposed Sizewell pressurised water reactor power station." (In evidence to the Sizewell public inquiry CEGB witnesses have said that 72 months was a feasible target construction period for Sizewell B, although for appraisal purposes 90 months had been adopted.)

This new-found ability is in stark contrast to the delays and problems that have, in the past, afflicted the Board's construction sites, most notoriously Dungeness B. The reasons for the new order? Well there were seven main reasons Sir Walter gave for the happy state at Heysham II, most of which could be applicable to other projects.

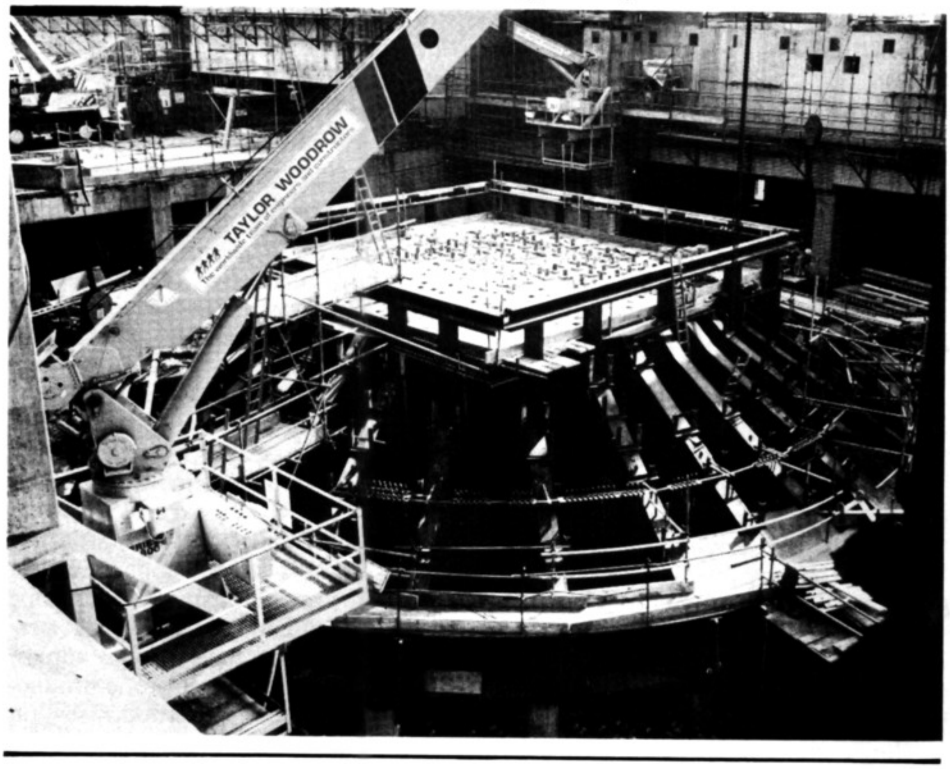
- The design is based on the successful design at Hinkley Point B, Somerset, modified only to take account of operating experience, and changes in safety requirements and technology since the original design concept.

The changes that were made included providing considerably more 'elbow room' and locating a diesel generator as emergency power supply on each of the four corners of the reactor complex.

- The basic design of the whole station was well developed before work started on site. Vigorous discipline had been imposed to control any subsequent changes in design.

Brian Powell, the Project Director pointed out that Heysham II was 'the most complete design and safety report the Board had ever submitted for a power station . . . the site had never been held up and nothing had had to be reworked because of design changes.' And this was a point Sir Walter was very forceful about, saying that alterations to the design and retrofitting had 'plagued AGRs, and PWRs in the United States.' He joked that, should there ever be a decision to build a further AGR in Britain, he, as Chairman of the Generating Board might, just possibly, agree to the paint in the

Roof of the first reactor pressure vessel liner, with temporary supporting structure ready for concreting at Heysham II



turbine hall being a different colour, but that would be a major modification and as far as changes would go!

- The overall management of the project was in the hands of an experienced and enthusiastic team of engineers and non-technical staff from the Board's Generation Development and Construction Division, led by one of its most experienced Project Managers. The team was supported by technical specialists based at GDCD's Gloucester headquarters.
- Within the overall management framework, staff of the National Nuclear Corporation, many of whom worked on Hinkley Point B, act as the Board's agents for work on the nuclear island.

They were responsible for reactor design and supporting systems, and managed the contracts which comprised the nuclear island works.

- All the major contractors involved in the project have had previous experience of nuclear power station work, and were stimulated to meet key programme dates by penalties for shortfalls in performance

This ensures that 'every company on site has a direct interest in sticking to the timetable' as Sir Walter said.

- Site work was co-ordinated by the Board and NNC, with all major contractors working together to establish and maintain consistent employment policies on the site.

The Board and NNC staff cooperated excellently with good personal relationships as well as a sound contractual understanding, Sir Walter claimed. The project involved the largest number of people that the Board had ever had on a power station; there were over 120 contracts on the nuclear island side, all on a firm price basis.

- Of the 4 000 workers employed on the site, 800 in key electrical and mechanical engineering trades were engaged in double day-shift working.

The double day-shift working has had a considerable payoff since 'paid overtime is a problem' acknowledged by the Board.

These seven points have paid dividends. According to the Project Director Brian Powell the bulk of the work on the first reactor is '2-3 months ahead of the programme. On the second reactor all the work is ahead of schedule by 3-4 months.' Current spending runs at £1 million a day, which is on target!

The Board appear to have every reason to believe that they have found the formula for building power stations on time and to cost—inflation apart of course! □

Construction progress at Heysham

Work started on the Heysham II site during 1979 when the ground was cleared, the sea wall strengthened, roads constructed, temporary offices built and the area of the main building excavated down to rock level (−20 metres).

In August 1980 the first 'permanent' concrete was placed in the area of the reactor foundations. In parallel with construction activities at site, work began in various manufacturers' works on the design and fabrication of plant components.

The project is currently on programme (mid-September) and the present state of the job is as follows:

Reinforced concrete structure of the reactor hall raised to final height of +52 metres.

Erection of charge hall (reactor hall) roof steelwork commenced in December 1982 and now virtually complete over the first reactor (final height +74 metres).

First reactor steel liner, weight approximately 1 000 tonnes, moved into position in January 1982.

First reactor gas baffle, weight approximately 1 000 tonnes, lifted into position in December 1982.

First reactor steel liner roof, weight approximately 1 000 tonnes, lifted into position in May 1983.

Second reactor liner moved into position in January 1983.

Substantial areas of thermal shield applied to first reactor pressure vessel liner and gas baffle ready for boiler loading in October/November 1983.

Installation of core support and restraint structures well advanced in first reactor in anticipation of commencement of core laying in November 1983.

Turbine house roof steelwork erected by December 1982 and cladding and roofing now almost complete.

Turbine house cranes erected and first turbine condensers positioned in August 1983.

Two essential supplies buildings completed, the second pair now approaching completion.

Four of the eight diesel generators installed.

Four 11 kW switchboards, twelve 3·3 kW switchboards and 40 lower voltage switchboards erected, together with various batteries, chargers etc.

Installation of cable supporting steelwork commenced in July 1982 and 1 200 cables laid since January 1983.

Second reactor gas baffle waiting to be lifted into position.

Control room nearly ready to receive desks and panels.

Circulating water pumphouse has been constructed within a circular cofferdam some 70 metres in diameter and approximately 20 metres deep. The reinforced concrete structure has now been brought up to ground level and the associated tunnels driven through the rock approximately 30 metres below ground level are complete. The pumphouse forebay will shortly be flooded.

Construction of circulating water pumps is in hand and erection of screens is about to start.

The fire fighting pumphouse has been commissioned and the first station transformer is about to be energised by a 132 kV cable connection from the nearby 400 kV substation.

Over a million tons of concrete containing more than 30 000 tons of reinforcement have been placed and 6 000 tons of steel erected since work began on the site.

The site labour force is now 4 100 and is expected to reach a peak of about 4 500 during 1984.

Expenditure to date is nearly £600 million, and is continuing at the rate of about £1 million per day.

Courses on micros

Harwell's Education and Training Centre are running a couple of courses during the next few months for those with a bent towards microcomputers. The first, *Interfacing the Z80* on 21 and 22 November, is to familiarise the student with the electrical characteristics of a microprocessor and its peripheral devices to a level where the student can design and 'debug' a microcomputer system. Emphasis is placed on interfacing devices to the Z80 processor.

On 9-11 January 1984 is a course entitled *Micro-computers: an introduction,* which is intended to give a general understanding of the structure, operation and potential of microcomputers. The first part covers the principles of computer operation, and the architecture and organisation of microprocessor based microcomputers. The second part centres around the structure and function of the microprocessor and the supporting chips which make up a microcomputer. Programming comes next, an overview of general techniques for microcomputers being followed by examples of machine code, assembly language, and high level language programming.

The final part of the course covers the build-up of microcomputer systems, extending from small single-board computers to large development systems. Selected case studies of microcomputer applications are included and the course concludes with a survey of second-generation microcomputers and current development.

Fee for the first course is £180 + VAT: the second is £270 + VAT. Further details from: Education and Training Centre, AERE Harwell, Oxon. OX11 0QJ. Tel: (0235) 24141, ext. 2422 or 2350.

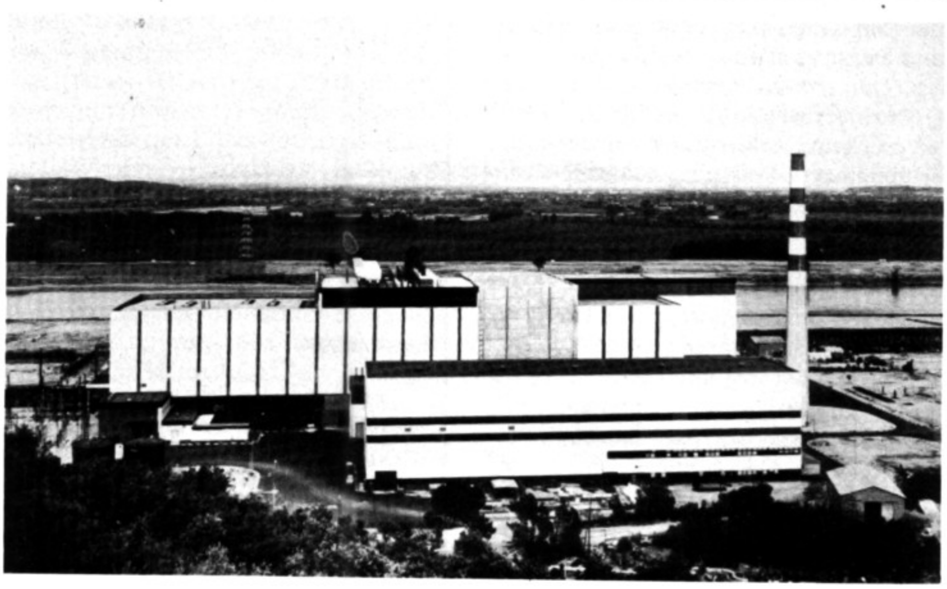
World Energy Congress — Mrs Gandhi

The 12th World Energy Congress was held recently in India. The Indian Prime Minister, Mrs Indira Gandhi delivered the inaugural speech:

Energy is at the heart of contemporary living. For agricultural and industrial development, for hospitals and other institutions, for homes, for entertainment, we are all dependent on energy of one kind or another.

Indian civilisation has had an intuitive regard for the inter-relationship of all phenomena. The mind which sees connections and similarities also sees the divisions and differences. Giant intellects have sought panoptic explanations of matter and energy, life and non-life, space and time, but taken as a whole, modern scientific thrust has been towards specialisation and compartmentalisation. Now science is humbler. It no longer rejects what is not immediately explicable. It realises that all answers pose new questions. The current debate on entropy is abstruse, but interesting. It is good therefore to find that your own Conference is linking energy, development and the quality of life, and that apart from problems of more efficient production and utilisation, you will discuss also the social, political and ecological aspects of energy.

It is ten years since the tempestuous spurt in oil prices so adversely affected the world's economy. Each country was compelled to find its own ways of dealing with the difficulties thus created. For the affluent, who had margins that could be cut, this meant economising on consumption. Many of them were compensated by investments from the oil-rich nations. The non-oil producing poor countries were much harder hit in every way. For a time it looked as though developing countries would have to give up their development plans. Fortunately, development has not stopped, although the pace is slower, the cost much higher and the toil more exacting.



The French fast reactor Phénix, which first went critical in August 1973, has generated about 11 000 million units of electricity. The station has been working commercially since July 1974 but its output was affected for nearly a year from April 1982 because of problems with the steam generators. It has been working at full power again since 14 August this year.

During its life it has bred more plutonium than it has burned and most of the fuel being used at present has been made from reprocessed material.

Our national movement had decided to have planned development and to take advantage of modern science in the fight against poverty and its attendant ills. After independence we have viewed development as involving the modernisation of our agriculture and laying the foundations of industry and, simultaneously, the building of a scientific base. Our planning gives priority to energy, next only to agriculture. In 1947 the total installed capacity in India was about 2 000 MW. Today it is 36 000 MW. Nearly a fifth of the power we produce goes to our farms and has contributed to our self-sufficiency in grain. Of the 560 000 towns and villages in India only 3 000 had electricity in 1947. Today the number has risen to more than 300 000.

Three decades ago a dynamic leader of science, Dr Homi Bhabha, pointed out that to meet our growing energy needs we could not remain dependent on the expansion of hydroelectric and thermal sources. He initiated our nuclear energy programme. This aroused opposition from many countries, who accused us of imprudence and impracticality. The opposition continues and we are obstructed at every step. But Indian technology has acquired the capacity to design, fabricate and build nuclear power stations.

India looks to science as a way out of economic backwardness. We shall not deny ourselves anything that will help us in this objective. I hope you are all aware that our nuclear programme is prompted not by military objectives but by developmental necessity. It is dedicated to agriculture, medicine and meeting our energy needs. We are opposed to nuclear weapons and do not have any.

Nuclear energy is new to India, oil is not. The first oilfield was dug in Assam in 1867 but growth was negligible until some fifteen years ago. Foreign companies advised that our search in other areas was futile. However our persistence has been worthwhile. Compared to the oil giants, our production is modest. But every barrel produced at home saves foreign exchange. In the last two years our domestic production has doubled from 10·5 million tonnes to 21 million tonnes. We are able to produce 50 per cent of our needs and are trying to be self-reliant in oil by 1990. Our energy strategy has three components: (1) in the short-term, to reduce the consumption of oil and increase efficiency in the use of energy in all sectors of economy; (2) in the intermediate range, to supplement oil with other primary forms; and (3) in the long-term, to develop nuclear power, solar and wind energy, biomass and other renewable resources, so as to conserve fossil fuels.

Nations are sovereign but the world is one. National boundaries can prevent some goods from coming in, but not ideas. There is apparent asymmetry in the problems of oil-exporting and oil-importing countries. In the long run the interests of the two converge. I believe that energy could be the focal point of international cooperation. Reserves of oil and some other fuels are finite; hence science is turning its attention to the possibility of harnessing the ampler and renewable resources like sun, wind and tides. Industrialised countries should so recast their economic processes that they reduce their offtake of oil and other depletable resources. Oil-exporting developing countries should utilise this breathing time to invest their export earnings in socio-economic development.

Coal and oil are the most important non-renewable resources of energy. The shift will have to be first from oil to coal and then to other forms of energy, which need to be developed rapidly. We do not have more than 25 to 50 years for the overall transition. For the advanced countries the problem in this area was never urgent. Just how marginal it was is indicated by the wholesale abandonment of renewable energy projects in USA and Western Europe at the decline of oil prices last year. For oil-importing developing countries, this question is one of life and death. The crisis will become even more acute with the depletion of forests, which today meet the most basic energy needs, that of fuel for cooking. There is immediate need to increase the availability of energy *per capita* in the developing countries, taking into account the likely increase in population.

Two of the many reasons for the rise and fall of nations are the discovery of new resources and the emergence of new technologies. Economic power is employed to buttress existing advantages, rarely caring for others. Developed countries control enormous industrial production systems. Based on this current affluence and control over technology, they regulate world trade and investment in directions that strengthen their own authority but make the others more dependent. The world needs long-term vision, not short-term calculations. I hope that this Conference will suggest some mechanism to monitor the use of depletable resources, and give guidance and even signals of danger to all countries.

All known strategies of development and of raising the living standards of the poor are energy-intensive. So long as they are dependent on centralised energy systems, people's needs are not likely to be met in full measure. Decentralised systems are necessary to promote regional self-reliance and help the further utilisation of materials such as the animal and plant wastes which

Mrs Gandhi

are available in villages. Such processes could be managed and maintained even by those who do not have much education. I cannot understand why rural problems do not interest scientists and technologists. What can be more satisfying and exciting than ameliorating the conditions of millions? This is one of my constant refrains. We want technology which will reduce drudgery and improve output without displacing the labour technology that will use locally available materials. So far the entire approach in technology has been based on cheap and abundant energy. There should be rethinking on all processes in chemical, metallurgical and similar energy-consuming industries. Whole new areas of technologies are to be developed. The long-range energy problem is far more acute than we think. The world's complacency is totally unjustified.

Your Conference is exploring the relationship between development and the quality of life as it relates to energy. Affluence is marked by higher *per capita* incomes leading to higher *per capita* consumption of everything—food, energy, water, minerals. The higher a people's standard of living, the more their drafts from the world's resources. Higher energy consumption does not necessarily improve the quality of life. For example, North America consumes *per capita* roughly twice the energy that Western Europe does, without any great difference in standards. Thoughtful people have begun to worry whether affluence is not exacting too high a price. We should be good guests on our Earth, neither too demanding nor disturbing its delicate balance. We should allow it to renew itself for those who are to follow. For this, technology has to be reviewed and be given new direction, different from that of the First Industrial Revolution, and the Second Technological Revolution. Technology must create work, wealth and satisfaction without exhausting the finite resources of our planet and of the atmospheric layer enveloping it. The conservation of energy for a better future for humankind must be the concern of your Conference and of policy-makers everywhere. Urgent action is needed in the following areas:

- The application of new biological advances on biomass production, e.g. tissue culture, protoplast fusion, genetic engineering, nitrogen fixation, improved photosynthesis, etc., particularly on lands not suitable for agriculture.
- Photochemical techniques to produce hydrogen (basically from water) to be used as mobile fuel.
- Energy storage devices to make transportation less dependent on oil.
- Photovoltaic devices to provide electricity directly from sunlight costing 10 to 100 times less than today.
- Integrated energy systems to optimally meet a variety of needs.

All living forms, from the smallest micro-organism to the largest mammal, depend on the energy of the sun. They have myriad complex mechanisms to gather energy, store and use it. The smallest cell of the tiniest organism holds an enormous magnitude of information, and of programmes of learning and application which are as yet unmatched by the largest of computers. Modern biology is trying to understand the chemical and physical basis of these extraordinary functions. Genetic engineering and biotechnology give hope for transferring and combining many capabilities into convenient life forms. Tiny microelectronic devices are also making rapid strides to provide reliable modes of process regulation. The combination of these two separate streams of science and technology may provide new routes for very high utilisation of solar energy through natural and newly designed photosynthesis. The hydrocarbon of the future need no longer be fossil fuel to be unearthed and processed but might well be one available continuously from our rooftops or gardens. While we wait for the day when we can simulate controlled fusion that generates the energy of the sun and stars, we might also find new ways of harnessing solar energy.

On behalf of the Government and people of India, I greet the technological and managerial specialists who are gathered here from various parts of the globe. I am glad to inaugurate this Twelfth Congress of the World Energy Conference. I give it and you all my good wishes. □

SDP energy plan

While coal should continue to be the major fuel for electricity generation, it would be imprudent to rule out other options, including nuclear power. This is the view of the Social Democrats' Working Party on Energy, expressed in their open forum paper 'An Energy Strategy to the 21st Century'.

The paper, published on 26 September, continued: 'Existing nuclear power stations should continue in operation and research, development and engineering capability in this area should be maintained. Building further nuclear power stations should only be considered when they are economically justified. Policy towards nuclear power should be guided by the need for stations to operate safely, to dispose of radioactive waste safely, and to be decommissioned safely.'

The working party did not feel that nuclear power, any more than any other source of electricity, warranted a 'grandiose programme of construction.' However, they felt that existing Magnox and AGR reactors should continue to be operated until the end of their useful lives and the nuclear power stations currently under construction should be completed.

The working party would await the outcome of the proposal to construct a PWR at Sizewell before 'a final view is taken.'

The paper does not distinguish between reactor types but in discussion the members felt that Britain should continue to take part in international collaboration on fast reactors. Working party member Tom Burke, who wrote the nuclear power section, said it would be 'foolish to shut down any option.'

The highest priority in the working party's proposals was given to improving energy efficiency. An important part would be a programme, similar to that of the Association for the Conservation of Energy to create 155 000 jobs, by insulating housing stock. These jobs would be distributed over the whole country in contrast to centralised energy production. They claim this programme would be cost-effective with immediate returns.

The working party also favoured a major programme to reduce industrial energy consumption by 20 per cent at an investment cost of £2·4 billion with a claimed pay back time of only four years. □

Correction

On page 196, in the September issue of ATOM, the sentence immediately above the first cross-head should read 'The nuclear industry therefore devotes considerable effort to the **prevention** of such accidental chain reactions'. We apologise.

Health and Safety report

The 1982/83 report of the Health and Safety Commission was published on 28 September introduced by Bill Simpson, its Chairman who is retiring after nine years in office. His place will be taken by Dr John Cullen, who at one time worked for the UKAEA.

In the nuclear safety field, the report says that 'the HSC has maintained close liaison with its Advisory Committee on the Safety of Nuclear Installations. Its involvement has ranged from close consideration of the issues connected with the development of a pressurised water reactor (PWR) to giving evidence on nuclear safety to the Select Committee on Employment. . . .

'The Advisory Committee's work culminated in the publication, in December, of its report *Some aspects of safety in pressurised water reactors,* which was discussed fully with the HSC before submission to the Secretary of State for Energy. The report included contributions by three study groups concerned with the pressure circuit, operator/plant interface, and fuel processing. . . . The *Loss of Coolant Accident Study Group,* was established with the task of considering the scientific and technical basis of methods of analysis used in the prediction of coolant accident conditions in PWRs.

'In addition, the Committee paid visits during the year to the SSEB's Torness site to witness construction work on the advanced gas-cooled reactor . . . and to Sellafield to discuss decommissioning of an AGR.'

The HSC's interest in the Sizewell B PWR Public Inquiry has been maintained primarily *via* the Nuclear Installations Inspectorate (NII). In this context the NII has devoted a major effort to the assessment of the CEGB's safety case for the PWR and to preparations for giving evidence at the Inquiry, and there has been considerable discussion within the HSC of the safety issues involved.

'A major review of the CEGB's pre-construction safety report was published in July 1982 by the NII followed by a series of supplements. These supplements covered degraded core analysis; safety analysis; external hazards – aircraft crash, fire, and earthquake; steam generator tube integrity; fuel clad ballooning; and reactor protection systems. The safety case has been carefully looked at and this has resulted in a number of major safety issues being identified, which still remain to be resolved by the CEGB to the NII's satisfaction.

'Apart from generally keeping abreast of the Inquiry, witnesses from the NII have formally presented evidence and will be appearing again towards the end of 1983 for detailed cross-examination on those aspects affecting safety.'

The NII has continued its surveillance of the fuel reprocessing and waste storage facilities of British Nuclear Fuels Limited at Sellafield and the work connected with radioisotopes at Amersham International. The BNFL response to the HSE review of safety management at the site has been monitored and improvements noted. The design and construction of new reprocessing and waste storage facilities have also been assessed. This has included an assessment of a preliminary proposal of a central dry storage facility.

Emergency plans

During the year a review of emergency plans was undertaken by the NII in consultation with other responsible bodies, resulting in the publication of a booklet *Emergency Plans for Civil Nuclear Installations* to help provide an overall appreciation of the consequences of accidents at nuclear plants and the plans made to deal with them. The aim was to set down the HSE's arrangements and make clear that detailed, well rehearsed plans exist for the protection of the public in the unlikely event of a major emergency. The booklet also outlines the applicable radiation and protection standard, the roles of other authorities, e.g. health and water, the importance of the media and the purpose of local liaison committees.

The Magnox stations which were shut-down whilst undergoing repairs, owing to the defects found in their main gas ducts, are now being allowed to return to power as and when the NII is satisfied. An overall safety review of those commercial stations which are coming up to twenty years of operation has been commenced.

'The NII has been heavily involved with the three advance gas-cooled reactor (AGR) stations, Dungeness B, Heysham 1 and Hartlepool, which are expected to raise power during 1983 and are now being commissioned. It has also assessed the safety of the proposed arrangements for the on-load refuelling of the two operating AGR stations and has agreed to the refuelling of these reactors at part load under specified conditions.'

Another HSC publication during the year was a consultative document on the Ionising Radiations Regulations (see ATOM March 1983, p53). □

*Available from HMSO.

REVIEW

Europe's nuclear power experience by E N Shaw, published by Pergamon, Oxford. 338pp. £12·50. ISBN 0 08 029324 7

The Dragon reactor still sits on its knoll at Winfrith, Dorset, dominating the view from the entry gate of the Atomic Energy Authority's establishment—a monument to the 17 years collaboration of 13 nations. In *Europe's nuclear power experience* E N Shaw records the history of the project.

For much of its 17 year life the Dragon project was regarded as one of Europe's most successful collaborations in applied science and certainly one of the most important in the field of nuclear energy.

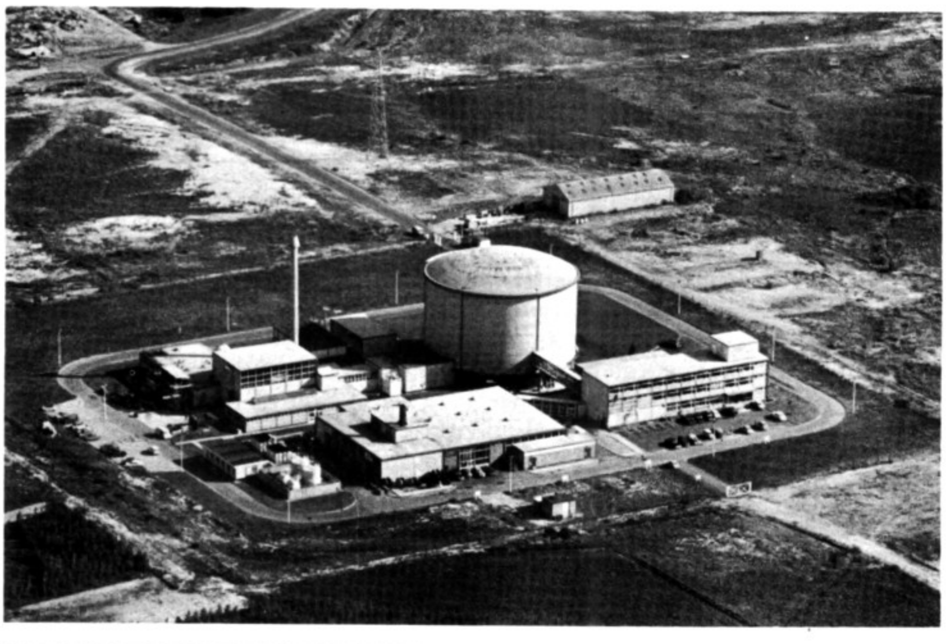
It was created in 1959 under the *aegis* of OEEC's European Nuclear Energy Agency (now the Nuclear Energy Agency of OECD) when desire for a more politically integrated Western Europe was running strongly and nuclear energy was seen as the technical key to a better world.

The project was concerned with the design and construction of a new high temperature gas reactor (HTR) using helium and designed to produce higher temperatures than could be achieved with the first generation of reactors. The project produced a promising operating system and research in the USA, following the European, lead led to the construction of a demonstration plant. However, this was not followed by full commercial exploitation and the work in the USA was effectively abandoned.

By this time—the early 1970s—it became clear that at ministerial level Britain, France and Italy were happy for the project to end and Germany was at the best apathetic. Britain had given up the HTR, France had become discouraged by the collapse of the General Atomic Company (GAC) contracts and Italy had abandoned interest in gas cooling. Germany had been thrown into confusion by GAC's deficiencies and was gathering its resources around the pebble-bed once more. With the exception of Switzerland and to a lesser extent Sweden, no country in Europe wished to pursue the system.

This contrasted with the position at the working level. Dragon was unique and its forward programme was well supported. New rigs and experiments were ready for installation, the materials programme had extensive backing, as did studies on physics, safety and fuel cycles. But this was irrelevant. Dragon's role was to serve the 13 countries and three of the biggest countries had decided Dragon no longer supported their national programmes. No other country was prepared to assume added financial responsibility to keep the project in being. So termination was logical.

The Dragon reactor, Winfrith



The end for Dragon was untidy. The untidyness arose principally from a general unwillingness to see a successful collaboration come to an end. Countries preferred to let procedural delays in Brussels take their course during negotiation for an extension to the project, instead of coming to a clear decision to close. Had Dragon been a failure, either technically or politically, its demise might have been cleaner and kinder.

In the current climate the cost of the project, £47 million, would not be considered large. In the words of the author Dragon demonstrated three cardinal virtues desirable in any international venture: "It was a successful political venture, it was a successful technical development and it was not immortal."

Reevaluations of dosimetric factors—Hiroshima and Nagasaki Technical Information Center, US Department of Energy, pp296, 1982. $15·75

It is always so much easier to identify better decisions with the benefit of hindsight. The physicists at Oak Ridge National knew that the tentative 1965 doses, designated T65D, for the Hiroshima and Nagasaki survivors needed further refinement, even though they were a substantial improvement over the earlier estimates. But other priorities were pressing, the budget was tight and good progress could be made with the T65D values; so the programme of refinement effectively stopped. That was a mistake.

It was inevitable that the mistake would be revealed as the passage of time unfolded the epidemiological results from the population of bomb survivors. The group from Hiroshima were the only human population exposed to substantial neutron doses, and much attention therefore focussed on the differences between the two cities. Perhaps the chequered history of the BEIR III report best illustrates the confusion and uncertainty in interpreting the so gradual accumulation of sparse data. The resolution of these problems was bound to include a critical examination of the dosimetry, but it was not until 1980 that the Lawrence Livermore National Laboratory showed that improving the estimates of radiation dose could have a substantial effect on the interpretation of the evidence provided by the bomb survivors.

It will be a year or two yet before all the components of the revised analysis are in place. Those who wish to follow the detailed process of revision will find the proceedings of the symposium held at Germantown in September 1981 a fascinating example of the scientific method at work. Following a review of the early work eleven papers were presented on all aspects of the problem: the yields of the two weapons; the attenuation of the consequent radiation in air; the delayed radiation from the fireball; the effects of buildings, self-shielding, and radiation quality; and the inferences that can be drawn.

The symposium made it very clear that much evaluation remains to be done so that it is too early to reach any firm conclusions. There are indications that the revision will tend to bring the results from the two cities into closer agreement, and that the neutron dose at Hiroshima will become less significant. This latter point is of considerable practical importance, since the Hiroshima survivors have been the only substantial human population exposed to neutrons. If the effect of that exposure becomes invisible under the revised dosimetry then neutron protection standards will have to be derived entirely from non-human evidence. There was widespread agreement that the risk factor for gamma rays would not be changed by more than a factor of two, a factor within the uncertainties of the present risk estimates. This is consistent with estimates based on the available data excluding that from the bomb survivors.

With that tentative indication the world of radiological protection will have to be content until the calculations in hand are completed.

Dr Brian Wade
Nuclear Environment Branch
AERE Harwell

NRPB research and development report

Over one hundred research and development projects carried out during the period 1979 to 1981 by the staff of the National Radiological Protection Board are described in its Research and Development Report*. They include the dosimetry and assessment of exposures to all forms of radiation, the consequences of routine and accidental releases of radionuclides into the environment, epidemiological studies and aspects of radiological protection policy.

The report lists over two hundred papers published by NRPB staff during the period. It also describes how the involvement of NRPB staff with the International Commission on Radiological Protection led to an established capacity for the calculation of doses per unit intake of a wide range of radionuclides in various forms, and hence of Annual Limits of Intake (ALI) and derived limits; it has been supported by experimental work on the gastro-intestinal uptake of radionuclides in animals from foodstuffs and drinking water. Particular attention has been given to the assessment of internal doses to young persons and the age-dependence of committed dose equivalents.

The importance of exposures to radon and thoron daughters in mines and poorly ventilated houses resulted in the development of models for the deposition of these radionuclides in the human respiratory airways. Experimental and theoretical studies designed to investigate the doses received by critical cells in lung tissues were undertaken and the relationship between absorbed dose and the measurement parameter of "Working Level Month" defined.

A knowledge of the mechanisms by which actinides cross the lungs into the blood and are deposited in tissues is highly desirable if rational approaches to accelerating their removal from the body are to be developed. Projects designed to increase this knowledge and the techniques that are being developed for optimising therapeutic procedures for removal are described in the report.

Chromosome damage observed in cultured lymphocytes is still the only sensitive and reliable biological indicator of absorbed dose following human exposure to ionising radiation. The Board has continued to provide a dosimetry service for the UK based on the yield of dicentric aberrations. Over the years a comprehensive set of dose relationships has been built up for a wide range of radiation qualities. Although the method is only of use in detecting the exposure of individuals to comparatively high levels of exposure, one of the projects described demonstrates that elevated levels of aberrations may be detected in groups of workers routinely exposed over many years at less than the permitted dose limits.

The requirement for improved accuracy in the measurements at occupational levels of exposure, together with the need for convenient, inexpensive personal monitoring services on a large scale, have motivated research and development projects in this field. The development of dosemeters to measure the exposure of the public to natural radiation is also described.

Dose from the environment

The magnitude of the doses to human beings from radioactive material discharged to the environment depends, among other things, on the manner and form of the discharges and the way in which the contaminants are transferred through the environment until they reach man. The pathway may be straight, as with the inhalation of radioactive material emitted to air from a stack, or it may be tortuous, as with the discharge of radioactive liquids to sea that are partly blown ashore, cause contamination of grassland, are ingested by cattle, and finally appear in milk and meat. It is essential to be able to trace these pathways to man and to be able to describe, in a quantitative way, the processes by which radioactive material is transferred through the environment. The main reason for doing so is to be able to predict the radiological consequences to the local and the national populations of routine or accidental discharges from nuclear and similar installations. Two strands in work of this nature, the experimental and the mathematical, are illustrated by projects described in the report.

Observational studies on radiation-induced malignancies face the problem of the detection of small excesses against large fluctuating backgrounds of the same malignancies present even in the absence of radiation. Occupationally-exposed groups provide the best study population, because their exposures are routinely monitored and recorded and because the radiation doses some of them incur are significantly higher than the background radiation experienced by the whole population. As a basis for such studies the Board is attempting to record data on exposure and mortality for occupationally exposed groups of workers in the UK with the National Registry for Radiation Workers.

In Great Britain, medical procedures contribute around 95 per cent of the average annual effective dose equivalent from artificial sources of radiation and it is obviously important that this particular source is carefully monitored. The medical uses of ionising radiation may be classified into three groups associated respectively with the practice of diagnostic radiology, therapeutic radiology and nuclear medicine. The radiation dose received by the patients has two components, somatic (concerning the patient) and genetic (concerning the patient's progeny). Projects designed to assess both dose components are described.

One section of the report describes projects concerned with effects of non-ionising electromagnetic radiations, particularly radiofrequency and microwave radiations, low frequency electric fields, and the magnetic and radiofrequency fields associated with medical uses of nuclear magnetic resonance. □

*HMSO, £10·50. ISBN 0-85951-199-5.