TECHNICAL AND COMMERCIAL POLICY ASPECTS OF THE U.K. NUCLEAR FUEL CYCLE

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Received 5 October 1971.

The paper reviews the main aspects of nuclear fuel cycle services which are essential to the economics of any nuclear reactor programme. It also examines the need for industrial concerns to change their basis of operations from a national to an international environment involving collaboration with other companies, in order fully to utilise resources and to maintain viability as the industry develops, especially with regard to the development and exploitation of new reactor systems. The influence of technology on the general development of the industry is considered as well as examples of procedures adopted for tackling specific technical problems.

1. Introduction

In his paper to the Geneva conference on the Peaceful Uses of Atomic Energy (held in Sept. 1971) Sir John Hill, the Chairman of the UKAEA, gave an account of the reactor development programme that has been followed in the UK. I do not intend to recover this ground but rather to concentrate upon various aspects of international nuclear fuel and nuclear fuel cycle services which are essential and economically important adjuncts of any reactor programme. Before leaving the general subject of reactor development programmes and policy I should like to comment that I do not believe that during the next decade it will be realistic for a single European country to undertake an independent reactor development programme. It may be possible for Western Europe to have such a programme. If so, as W.K. Davis of Bechtel said recently, in a lecture to the British Nuclear Energy Society, such a programme must be related to the fast reactor [1]. In his view the main issues of thermal reactor development are already settled, and what remains is the determination of the international structure through which the sodium-cooled fast reactor will be developed and

exploited. I think that there are many in the United Kingdom who would agree with the general philosophy which he expressed.

Returning to the question of the nuclear fuel cycle, I shall divide my presentation into sections dealing with the commercial policy which may be expected to emerge during the next decade, the technical policy and the treatment of outstanding problems associated with technical developments in this area, and finally, I shall give two examples from our own experience in the UK since 1960 — examples chosen to illustrate the considerations which I intend to bring forward in relation to technical policy. By adopting this route I hope to demonstrate that some of the problems faced by those involved in the provision of nuclear fuel cycle services are, to an important extent, dependent upon an understanding of the problems which are the subject of many of the papers to this conference. At the same time, however, I will be drawing attention to the need for those involved in the work reported in these papers to have in mind the practical application of their conclusions and the business context in which, finally, they will be considered.

2. Commercial policy and the nuclear fuel cycle

Predictions as to the course of events during the next decade cannot reflect the commercial objectives of the individual parties who will be concerned in Europe and elsewhere. Experience to date suggests that a number of the trends which can be foreseen are more or less inevitable and that the commercial objectives of firms in individual countries will have to be modified to take account of these external factors if the firms are to survive into the 1980's. The most important single conclusion is that, as with reactor development and exploitation, the scale of operation for the next ten years is not national but, except in the case of the United States of America, multinational. This conclusion is true in different degrees of the various sectors of the nuclear fuel cycle industry and, because the subject is of sufficient economic importance, I shall review the position in the individual sectors.

The fuel cycle business can be divided into four main areas, each of which has ancillary industries: uranium supply, enrichment, reprocessing and fuel fabrication.

2.1. *Uranium supply*

The production of uranium concentrate must of necessity take place in those areas which geology has favoured with uranium deposits capable of being exploited for sale at a price within the range of \$5–10 / lb U_3O_8 . Internationalisation of the exploitation of uranium involves the operations of major mining houses and the national interests of the countries fortunate enough to have high grade uranium deposits. But it seems likely that such countries will not be content at the end of the 1970's to export uranium in a form in which the added value is restricted to that deriving from the production of concentrate. It is to be expected that they will seek a forward integration of their operations to the stage where they are selling pure intermediate products such as uranium hexafluoride, either as natural uranium or as enriched material. The relative economics of this course of development, by comparison with the purchase of uranium concentrate by individual or groups of consuming countries for purification, the manufacture of uranium hexafluoride and subsequent enrichment, are far from clear. The

operations up to the stage where purified natural uranium hexafluoride is available do not require a scale of manufacture beyond a few thousand tons per year in order to be economically competitive, and a few thousand tons of natural uranium hexafluoride corresponds to about a thousand tons of uranium enriched to the level required as fuel for typical thermal reactors. This level of demand is associated in the early years of the 1970's with groupings of two or three countries the size of the United Kingdom, and by the later 1970's will typify the requirements of the larger individual European countries.

2.2. *Enrichment*

The line of commercial development is likely to be heavily influenced, however, by the next stage in the nuclear fuel cycle where economies of scale are dominant. It is generally believed that the development of the fast reactor will not prevent the installation of a substantial capacity of thermal reactors throughout the world before 1990 and there are various forecasts as to the consequent demands for capacity for uranium enrichment. Most of these relate to needs at the end of the 1970's because the existing American enrichment capacity, reinforced by engineering additions and modifications to existing plants, are likely to be capable of meeting the needs of the world until the late 1970's. Beyond that time, however, it has been forecast that additional capacity of a few thousand tons of separative work may be required annually to meet world needs.

The existing process depends upon gaseous diffusion and enjoys the advantage, from the viewpoint of commercial investment, that it is well demonstrated and that some countries have experience over 25 years of the long-term characteristics of such a process. On the other hand, two of these characteristics involve a requirement for investment in relatively large increments of production capacity and the availability of cheap electric power because about a half of the total cost of separative work produced by a diffusion plant is the cost of the electrical power. New processes are being sought and developed. In some cases, notably the development of the gas centrifuge, the commercial objectives are clearly to produce an intrinsically cheaper process than gaseous diffusion but, in practice, the relative merits

of the two processes in a given location will depend upon the cost of power and the scale of demand increases which can be associated with that location. It is for this reason that Europe, where power is relatively expensive and where the pattern of demand changes have the nature of a ramp rather than a step function, is the area in which development of the gas centrifuge is being most vigorously pursued. Other processes may have a different balance of characteristics. It is conceivable that a process could be sought for a region where power was inordinately cheap but where capital investment was to be minimised and where ruggedness and simplicity of operation might be at a premium, and there are processes which, in these particular circumstances, might be more suitable than either gaseous diffusion or the gas centrifuge.

The investment decisions in the field of uranium enrichment will, nevertheless, be the most important ones which have to be taken in the whole of the fuel cycle field during the 1970's. Not all of the considerations involved can be simply expressed in terms of costs. The pattern of international trading; the diminution or increase of tariff barriers; the desire of nations or groups of nations to have an independent supply of a commodity so vital to their programmes as separative work; all of these factors will be involved in decisions on an investment which on the world scale is likely to be of the order of hundreds of millions of dollars per year at the end of the decade. For the investor demonstrated long-term reliability of the chosen process will also be important, both intrinsically and because customers are unlikely to be willing to place the necessary long-term contracts with an organisation operating a process which they consider to have been inadequately demonstrated. It may be that more than one enrichment process will be the subject of substantial capital investment starting in the later years of the 1970's. It does not seem likely that these decisions need to be taken for two or three years but, in the interim, those who are developing processes alternative to gaseous diffusion may be expected to invest large resources in development and demonstration work. The ability to develop such a process is possessed by many of the more advanced countries. The major investment of resources is required to bring the process to a stage where it can be demonstrated to have sufficient commercial

viability to merit major capital investments. The resources required for such a step are considerable, being comparable with those required for the development of a reactor system. Accordingly, it is to be expected that individual countries will seek to act as part of international groupings in the development stage of new enrichment processes and in the subsequent stage of capital investment.

2.3. Reprocessing

Although it is not in the natural sequence of the overall fuel cycle flow sheet, I shall deal next with commercial policy on reprocessing because it has features in common with the enrichment problem. The reprocessing of nuclear fuel and the recovery of the contained values is an operation where economies of scale and high levels of plant utilisation are of great importance because the majority of the costs associated with the operation of such a plant once it is built are independent of the throughput, but these same costs do not rise in proportion to the capacity of plant installed on a given site. On the other hand, the feed materials, irradiated fuel, are difficult items to transport. It might, therefore, be thought that the economic balance could favour plants of moderate size with short transport distances, but in practice it is not a great deal more difficult to make arrangements to transport irradiated fuel for a few thousand miles than to make arrangements for much shorter transport distances, except insofar as the short distances may avoid the crossing of national boundaries. The UK and other countries have already considerable experience of transporting irradiated fuel over distances of many thousands of miles, and it seems likely that the typical reprocessing plant for thermal reactor fuels in the future will have an optimum scale of the order of a thousand tons of fuel per year. It will therefore be capable of providing a service to, say, 30 000 MW of typical thermal reactors and the number of such plants which can be economically justified throughout the world will be small. Outside the United States it is likely that multi-national groups will be formed in order to achieve a rational investment in facilities, each of which may involve \$ 100 M and for each of which an adequate capital return will be crucially dependent upon achieving good plant utilisation during the early years of operation. There are kindred problems in the

reprocessing of fast reactor fuel but the scale of operation required to service existing fast reactors will be modest until the 1980's. It may be expected that by that time the multi-national commercial structure which will have evolved to deal with the thermal reactor fuel problem will extend its interests to achieve a similar rationalisation of fast reactor reprocessing.

2.4. Fuel fabrication

The area of commercial exploitation of the fuel cycle to which I have not so far referred is that of the development and manufacture of nuclear fuel. The product from this process is specified in engineering terms rather than as a chemical material, and it has economic characteristics different from those associated with the major process operations of uranium production, enrichment and reprocessing. The process of development and demonstration of the product is both lengthy and costly. The customer may be expected to place stringent demands on inspection and procurement methods and upon the guarantees which the manufacturer is required to offer, because the potential economic loss to the customer by inadequate performance of even a limited proportion of the nuclear fuel which he purchases is so much greater than the minor economies which might be achieved by highly competitive purchasing. The economics of scale of uranium fuel manufacture are also complicated. In the first place, the product is fairly specific to a given type of thermal reactor by contrast, for example, with enriched uranium which is an intermediate material of universal application. In addition, the total operations of fuel manufacture contribute no more in added value to the fuel than does the single operation of uranium enrichment, but the value added by the fuel manufacturer is contributed at a number of points ranging from the procurement of materials for cladding to the fabrication of these materials into cans and components and inspection, and the production of fuel elements incorporating uranium usually as UO_2 , which has itself been the subject of a sequence of shaping operations carried out to very high standards of inspection. The economics of scale are different for these different phases of fuel manufacture, but viewed solely as a manufacturing operation, it is possible to operate commercially with a volume of no more than a few

hundred tons of such fuel per year. The problem here is that the fuel element is an intrinsic part of the viability of a reactor system from both the economic and the safety viewpoint. Whilst, therefore, it is possible to operate at a modest scale as a licensee dependent upon another agent for the design, development and demonstration work, and relying upon this agent to produce the information necessary to satisfy both customers and safety authorities, there has to be at some point a group which operates on a scale sufficient through sales and royalties to cover the large costs associated with the non-manufacturing phases of the operation. It is difficult to assemble the true costs of development of a reactor system, but W.K. Davis offered \$1 000 M as an order of magnitude figure. The division of recovery of this expenditure between fuel and reactor sales is, of course, a matter of selling tactics, but on an assessment based upon turnover or upon the attribution of development costs so far as this is possible, it is reasonable to suppose that up to half the cost of developing and demonstrating a reactor system may be associated with the nuclear fuel. The development costs for most thermal reactors have been spent and can be recovered only so far as the market will bear the additional charges, but the recognition of their volume may be an additional factor leading to multi-national development and exploitation of future reactor systems, of which the sodium-cooled fast reactor is undoubtedly the most important and may in practice prove to be the only one.

In the case of fast reactor fuel, qualities are being sought which are not dissimilar from those associated with the more highly rated of existing thermal reactors but the demands are more severe. In order to achieve a satisfactory economy it is necessary to have relatively high ratings per kilogram of contained plutonium, and given the requirements of neutron economy and breeding characteristics, this leads to high volumetric ratings on the contained uranium-plutonium mixture, to fuel elements consisting of small diameter pins fabricated to very high standards, and to cans and components which are themselves high cost and precision items. The costs of development both of the fuel and of its components, and the cost of availability of prototype fast reactors and the associated rigs and loops in which the demonstration of the fuel performance can be undertaken, are major items in

the determination of policy. National considerations aside, it seems reasonable to suppose that there will be an increasing trend towards multi-national groupings designed to share these costs.

Fast reactor fuel production differs in another important respect from what has gone before. It involves the utilisation of plutonium and the associated safety precautions. It may seem to be conceptually simple to design a plant for the manufacture of fuel elements which is to be separated from the operator by contamination and radiation barriers, but practical experience shows that in uranium fuel production plants, even if they are automated, there is a good deal of operator intervention both for maintenance and to remedy minor quality defects. When such intervention is denied or can be carried out only with special dress and breathing provision, and perhaps after emptying the plant the basic design conditions are much changed and the ancillary costs associated with factory operation are increased.

Practical experience over 20 years in the U.K. in the handling of plutonium leads one to conclude that the production of fast reactor fuel will be a process in which there are substantial economies of scale and perhaps even more economies of standardisation both of the process and of the fuel design. This must surely point the way to multi-national manufacturing operation.

3. Technical policy

The boundaries between commercial and technical policy cannot and ought not to be clearly defined. Insofar as it is possible to abstract general conclusions concerning technical policy from the experience of 1950–1970, this is in part a consequence of the financial and commercial experience of those decades. The depth of technology required in the nuclear power industry in general, and the fuel cycle in particular, has proved consistently to be greater than had been anticipated in the early years. This is due in part to an understandable failure to foresee all the problems which would arise but also to a change in the standards set both by environmental and safety considerations and in the degree of sophistication which would be applied by those responsible for these considerations in exercising their statutory responsibilities. Together with other factors, these

have often led to delays in procurement or construction of nuclear power reactors and to difficulties in operation which have themselves produced reduced availabilities and poor economics.

Engineering design in a developing field is inevitably a compromise between the advantages of repetition of well established practice and the postulated savings of novelty, and within a particular project it is a matter of great difficulty to decide the time for which diversity of development should be allowed to continue and, by contrast, the time when concentration on a particular line of development is justified, either by what is already known or by the apparent indifference of the economic outcome to the choice of alternatives available. I believe that in the field of nuclear power the balance has swung significantly during the last few years towards conservatism and standardisation.

It would be possible to take the individual areas of the fuel cycle one by one and investigate this change in attitude in each of them, but in this lecture the matter must be treated by consideration of particular examples. As far as fuel design and demonstration is concerned, the general observations which have been set out already can all be seen to apply.

3.1. *Fuel performance and quality*

I shall describe later some examples of technical problems which illustrate the U.K. experience in this field, but so far as the technical policy of the situation is concerned it has clearly come to be appreciated that the safety and satisfactory operation of the nuclear reactor is very much dependent upon fuel performance and quality, and that whilst for some performance characteristics it is sufficient to deal in terms of the mean property of the assembly, there are many for which tolerance limits in the statistical sense have to be applied or corresponding assurances have to be given to the operator or to those responsible for safety assessment. It is recognised that the inspection of components or assemblies to an acceptance standard of 1 in 10^4 is possible but expensive, but that higher inspection standards are not practicable if only because the demonstration that they have been achieved is impossible.

In practice the designer's concept of a fuel element goes through the development laboratories and becomes a subject for process development and manu-

facturing plant design, but ultimately it comes to rest upon the manufacturing operations and the procurement of supplies of components, for example forgings, tubes and small machined items. The consequent inspection and purchasing operations are in general carried out by individuals who are now of increased specialisation but who, in their interactions with the suppliers, have a human rather than a mathematical relationship. Inevitably, therefore, from time to time materials and supply problems will arise and it is essential for the senior designer to take account (in formulating acceptable design policy) of the special safety and operational considerations associated with quality in nuclear fuel and, so far as is possible, to arrive at a design concept which is not unduly sensitive to the inevitable variations in production. One could instance many cases from the past where the contrary has been true and where, as development has proceeded, the intensity of the quality and uniformity requirements in fuel elements has been made more and more severe. The designer has solved his problems at the expense of the difficulties posed to the development worker and the latter, in turn, by intensifying the standards which have to be met by the fuel manufacturer. Costs have inevitably increased.

3.2. *The gas centrifuge*

The same general observation could be made in relation to the development of the gas centrifuge. The nature of the gas centrifuge is such that the economic design of machine will probably have a separative work output within the range 1–10 kg per year, and a well established plant with an output of, for example, 2 000 tons of separative work will therefore involve something between 200 000 and 2 million gas centrifuges. Partly as a consequence of experience with nuclear fuel problems it has been possible to recognise at an early design stage that to be economically satisfactory a concept must not require freedom from failure in every machine from advantageous causes, nor must the economy of the plant, and therefore the willingness to invest in its construction, be unduly dependent upon long term life characteristics which would not be capable of complete demonstration at the time when the investment decision came to be made. It is inevitable in a field such as gas centrifuge development, which, like

nuclear fuel is dependent upon the availability of materials having special qualities, that the technology will advance rapidly with time and that the conflict between established practice and novelty will be particularly severe. If the designer chooses a concept which through its sensitivity to individual component failure leads to conservatism either in design or in the choice of materials he will only be able to use at a given instance that which has been well demonstrated, and in so doing will deny himself the economies which may be available from stronger if less well proven materials.

Fortunately, in the case of the gas centrifuge the facilities required for life testing are an order of magnitude less expensive than those required for corresponding tests on nuclear fuel and the facilities for post mortem examination and interpretation of failure are not as difficult to provide or to operate, but in both cases the economics of the system drives the designer to make the maximum possible use of the properties of the materials which he chooses to employ with the consequence that accelerated tests are either impossible or of limited value. In the absence of design concepts which are robust against small numbers of failures the designer must use as his basic material property not the mean property but some low percentile in a multi-variate frequency distribution, the nature of which may not be well known and which may change with time owing to modifications in production technology which are external to the designer's control and of which he may only become aware when the consequences are apparent in the production lines.

The manufacture of fuel elements and of enrichment have been chosen to illustrate the balance of considerations in technical policy because these are areas in which there exists perhaps the strongest economic pressure towards the use of new designs or materials. In the remainder of the fuel cycle field conservative design seems more likely to be established because in most instances a stage has been reached at which the economic advantages of technological advance have been largely realised, and what remains seems at present to be small by comparison with the commercial risks involved in novelty. No doubt this observation has been made in many fields only to be proved wrong, but I suspect that they were not fields which had already received the intensity of

development which has been devoted to the nuclear fuel cycle industry.

4. AGR and HTR fuel — Examples of structural-mechanics problems

I shall conclude my lecture by turning from forecasts about future policy to examples of experience from recent years which will, I hope, combine an explanation of the basis from which the foregoing forecasts have been made with an interest to those who are concerned with structural mechanics in reactor technology. I hope that the examples will serve to illustrate the way in which what is apparently a specific and determinate technical problem becomes in practice more and more a statistical exercise as the realities of manufacture and supply and of the uncertain nature of material properties are incorporated in the problem.

4.1. *In-core stability*

I should like, first, to take the problem of in-core stability in the AGR which relates to the fuel assembly as it rests in its design position in the reactor channel. The components are deliberately loosely coupled so as to enable them to negotiate the unavoidable bends in the charge path and to conform to the reactor channel distortions incurred in service due to both thermal and radiation effects. The fuel assembly is subject to both gas flow forces and acoustic excitation over its lower half. The fuel stringer experiences both radial and transverse axial gas forces on its external surfaces due to the moderator coolant flow and direct axial forces on its internal surfaces due to the main coolant flow. Acoustic excitation is superimposed both from below the core via the main coolant stream and at the level of the dome above the core. The plug unit also sees the direct internal coolant flow but experiences little external flow except for the discharge port region which feels the cross flow of the reactor hot box. These forces mix in a variety of proportions, the internal channel forces being a maximum near the middle of the reactor core where the cross flow is minimal.

The fuel assembly may respond to these forces in a complex variety of ways. For convenience in discus-

sion, the movement of the complete assembly as an assembly is separated from that of the smaller components: the assembly movements being usually referred to as "instability", and the movements, say, of the fuel pins separately within a fuel element as 'vibration'.

Theory predicts that, depending on the conditions assumed for end restraint and fuel element to fuel element coupling, up to 12 discrete frequencies could appear in the fuel stringer instabilities. In practice about four of these can be separated from the complex responses measured by displacement transducers, typically in the range 2–10 Hz. The plug unit movements are not necessarily related to those of the fuel stringer, either one may be moving when the other is stabilised and either movements may be simple, ie planar, or precessional. The plug unit frequencies are found to cover the same range, i.e. up to 10 Hz, but are more often broad-band responses. The fuel pin vibrations are essentially higher frequency, viz. 50–100 Hz. Fuel movements of this magnitude could create fatigue failure of components or cause excessive wear, which in its turn could lead to fatigue over the fuel life of up to 70 000 hours.

The second part of the problem is to decide what is acceptable. Impact, fatigue and wear criteria have been determined using unirradiated components in accelerated furnace tests. These results then need to be scaled to allow for the effects of radiation and long-term corrosion, the scatter in material properties and, above all, the scatter in fuel component response to nominally identical conditions. Any failure in the fuel element assembly can be a cause for the removal of the assembly from the reactor. Under these circumstances a statement of the probability of failure involves a long chain of scientific or engineering inference, in which many of the steps are essentially probability statements or are at least dependent upon the performance of individual items sampled from distributions which are not well known. The outcome can therefore be regarded as dependent upon a multi-variate distribution and, having this in mind, and the long sequence of human judgments which will have been involved in the manufacture of the fuel, it is well to be sure that our theoretical analyses are not allowed to carry one too far from the practical realities of the situation.

4.2. Fuel endurance

A second area requiring extensive theoretical treatment involves fuel pin endurance because of the difficulties of repeating tests in rigs to obtain sufficient information to be of statistical use and because an AGR fuel element will involve of the order of 200 fuel pins which are on average subject to a range of conditions according to their position in the fuel channel.

The design of the AGR fuel pin is based on the thin can concept; that is, the can is sufficiently thin to deform plastically at operating temperature under the pressure of the reactor gas. The purpose of this is to ensure good thermal contact between the can and fuel pellets and so minimise fuel temperatures and fission gas release, as well as to minimise the parasitic neutron absorption of the can. As a consequence of this design feature the can wall is stress cycled.

When the reactor power level is reduced the temperature of the fuel drops more than that of the can; the fuel contracts more than the can and the can creeps down. On the subsequent return to full power greater expansion of the fuel strains the can both elastically and plastically. This process is repeated at every reactor power cycle and the can undergoes fatigue. The axial strains are, of course, smaller than the circumferential ones and, in addition, the anti-stacking grooves provide convolutions which absorb a larger proportion of the strain elastically. In practice, therefore, only the hoop strain becomes a problem.

The strains are small provided they are distributed round the full circumference. But the fuel pellets crack radially on initially going to power and the cracks provide discontinuities at the circumference into which the can may become locked. Also, the pellet fragments pivot under the changing temperature distribution during a power cycle, so effectively concentrating the total pellet expansions into the cracks. The fatigue strains in the can are thus locally enhanced. Reactor experience confirms that the can always splits longitudinally and that the split originates over a pellet crack. Other random and systematic factors, eg variations in can wall thickness and across-pin temperature gradients, determine which of the pellet cracks shall be the one to initiate the failure.

Theories have been evolved and incorporated in computer programmes which broadly support the

preceding explanation of the failure mechanism and which enable fair quantitative predictions to be made, particularly for the Windscale AGR prototype reactor which provides the basic experimental data.

In practice, however, fuel pins, and therefore fuel cans, are subject to a spectrum of cycles and the method of addition which ought to be applied to the consequential strains is not well known. Furthermore, there is a substantial statistical element in the material properties which are involved, and in the detailed conditions applying to individual pins by virtue of variations in heat transfer characteristics, the results of deposition or associated gas flow phenomena. The interpretation of the limited failure experience which can be accumulated even in a prototype reactor is difficult because the number of effective observations hardly exceeds the number of variables which are or may be important in the analysis, leaving very little information to be used to offset the effects of the random factors. The theoretical interpretation, therefore, even if it appears to be substantiated by the available data, can at best be used to indicate the directions of improvement in materials or manufacturing methods or the possibility of ameliorating or improving the conditions to which the fuel is subject.

4.3. Graphite components

Similar problems to those already mentioned are encountered with graphite components which are frequently used in gas-cooled reactors, in particular the HTR. The variations from specimen to specimen in mechanical properties of graphite are much greater than is usual in metals and great care is required to ensure that during routine manufacture certain minimum requirements will be met. In addition to the normal mechanical tests involved in each heat of graphite, proof testing of certain components is included to ensure that the minimum value of each component can be guaranteed. It will be seen from the examples quoted that in some cases the most difficult problem is to predict the long term behaviour of the components following exposure to the environment of a number of years. Irradiation effects in many cases are difficult to estimate and require extrapolation of shorter term tests. There have been cases where the theoretical analysis devoted to a prediction of mechanical behaviour has been far in

excess of that justified by the mechanical properties data eventually fed into the final analysis. It is clearly important for the theoretician to bear in mind the possible uncertainties in respect of materials behaviour when assessing the degree of sophistication required in the analysis.

Equally, if the requirements for materials data are made known early in the development programme, then the appropriate tests may be mounted. In fuel element engineering where large factors of safety do not exist, then mean data of properties are inadequate. The analysis must always be weighted in the direction of minimum behaviour.

5. Conclusions

It would be wrong to conclude my lecture on a note which suggested that I discounted the value of the type of analysis which is represented in so many of the excellent papers to the Conference. When those responsible for technical and commercial

decisions in the fuel cycle industry are obliged to proceed without the benefit of an established theoretical understanding of the mechanisms which are involved in processes, their position is indeed difficult. On the other hand, there is sometimes a danger when this type of analysis is being considered at a conference, that insufficient thought is given to the environment in which it will have to be applied and the practical application in production of conclusions drawn from it. I hope that in my lecture, in addition to giving what are personal opinions upon the commercial and technical policy of the nuclear fuel cycle in the next decade, I have been able to comment upon the role of engineering analysis and experience in forming opinions upon which such policy judgments have to be based.

Reference

- [1] W.K. Davis: International nuclear power; Brit. Nucl. Energy So. 10, 4 (1971) p. 269.