PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Future Trends in Nuclear Power Generation [and Discussion]

John Hill, A. B. Lovins, John Hill, K. E. Zimen and Edward Eisner

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Future trends in nuclear power generation

By Sir John Hill
United Kingdom Atomic Energy Authority, London

In the 20 years since the Calder Hall reactors were ordered, the U.K. has accumulated wide experience of building and operating nuclear power stations.

Early stations proved expensive because of technological novelty and infrequent orders, but the economics of nuclear power stations where regular orders can be assured are increasingly favourable. Other factors do not provide fundamental limitations to nuclear power growth.

Trends in fossil-fuel prices suggest that most utilities will look mainly to nuclear plant to meet their electricity requirements. The substantial savings of fossil fuel already achieved will thus grow rapidly on a world-wide basis. Though it would take quite unexpected shifts in relative economics for nuclear stations completely to supplant conventional stations, particularly for peak demand situations, a high nuclear share of new capacity may begin to throw some strain on uranium reserves in the 1980s.

The fast reactor, prototypes of which after long and careful development are commissioning in France, Russia and the U.K., can provide a huge increase obtainable from uranium resources, pending the successful introduction in the long term of fusion reactors.

Twenty years ago construction started of the nuclear reactors at Calder Hall and in October 1956 the first reactors there delivered electricity from a full-scale nuclear power station into a national distribution system for the first time in the world. Since then nuclear power has spread and grown in importance all over the world, particularly in the United States and Western Europe. Moreover, it is now clear that this growth will continue, at an accelerated rate.

In the European Community there is currently nearly 11000 MW (e)† of installed nuclear capacity, 22000 MW (e) under construction, and a further 11000 MW (e) on order and at the planning stage. Estimates of future capacity vary, but some Community officials have called for a total capacity of 200000 MW (e) by 1985 (E.E.C. 1973). Such an expansion, though justified by the energy trends already discernible, is probably not feasible, but there can be no doubt that a period of substantial expansion is beginning.

The United Kingdom is well placed to participate in this expansion. Since the inauguration of her nuclear power programme, this country has accumulated wide experience in the construction and operation of nuclear power stations. Following the construction of the four Calder Hall reactors and a similar set of four reactors at Chapelcross (all of which are currently operated by British Nuclear Fuels Limited with an output considerably in excess of the design figure) a series of nine commercial magnox stations were built, and have been operated by the Electricity Boards. Two further magnox reactor power stations were sold abroad, one to Italy and the other to Japan.

All these magnox reactors were of the thermal type. In a thermal nuclear reactor a moderator surrounding the fuel reduces the kinetic energy of the neutrons, increasing their chance of capture by a fissile uranium-235 isotope. In the resultant atomic fission heat is produced, and further neutrons are released which maintain the chain reaction within the reactor fuel.

These early stations have in general proved to be successful technically. Although other

† The power measured is the electrical output.

countries have in recent years been developing their nuclear power programmes at a far greater pace, this country has still generated more electricity from nuclear reactors than any other country (see, for example, Nicholson 1973), and this has been achieved almost entirely by the magnox reactors. The first Calder Hall reactor has now run without interruption, except for routine maintenance, for over 17 years, with a cumulative load factor of 88%. Several of the commercially operated magnox reactors, as indicated in Dr Broom's paper, have achieved impressively high cumulative load factors, together with high availabilities.

The magnox stations were succeeded by the advanced gas-cooled reactors (a.g.r.), which have many features in common with them but use slightly enriched fuel in stainless-steel cans, which permits operation at higher temperatures. A small experimental reactor of this type has been operating successfully at Windscale for over ten years, with a cumulative availability of 84% and a cumulative load factor of 71%. Five commercial stations will come into operation over the next few years. There have been problems and delays in their construction, but in many cases these have not been specific to the reactor concept. Delays have been experienced all over the world in the construction of generating plant, both conventional and nuclear, mainly stemming from the rapidly increasing size of the plant units. For example, while the first U.K. reactors had capacities of only 35 MW each, the a.g.r. have capacities of 600 MW or more each, and in America and elsewhere individual units of up to 1200 MW are being constructed. Similar increases have taken place in the size of associated plant such as turbines and alternators, and in that of conventional power units.

Table 1. Forecast growth of nuclear power in the principal Western European countries – GW (e) (from O.E.C.D 1973)

	1970	1975	1980	1985	1990
Belgium	—	1.7	3.0	5.5	10.0
France	1.5	3.8	13.4	32.5	67.0
Germany (W.)	0.8	4.9	19.0	38.0	75.0
Italy	0.6	1.4	6.0	18.0	44.0
Spain	0.1	1.1	8.0	12.0	24.0
Sweden	—	3.2	8.6	13.0	24.0
Switzerland	0.4	1.0	4.0	8.0	16.0
United Kingdom	3.4	8.8	13.8	35.0	75.0

The constructional problems with the a.g.r. are now being overcome. The good record of the magnox stations and the continuing encouraging performance of the Windscale reactor justify confidence that the a.g.r. stations will prove to be very valuable components of the country's generating system.

In the rest of Western Europe the nuclear reactors have predominantly been of the water-reactor type, although France for some years developed a gas-cooled graphite-moderated line of reactor development. The reactors have, in general, been built by national firms utilizing American technology under licence, although in some cases they have been constructed by an American firm directly or through a European subsidiary. While slower to start constructing nuclear power stations than the U.K., several nations in Western Europe, particularly France and West Germany, have since the late 1960s been constructing nuclear plant at a faster rate. The forecast programmes for these countries, and others such as Spain, Sweden, Italy and Switzerland, are ambitious, as table 1 demonstrates.

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The early nuclear power stations proved to be relatively expensive for a number of reasons. The novelty of the technology, the special engineering machinery required, and the fine tolerances demanded, were all reflected in the high capital costs of nuclear stations. Capital costs have also been pushed up by sporadic ordering patterns, the fluctuating size of total programmes, and more recently by difficult problems associated with scaling up (by factors of up to 20 in some cases).

These differentially high capital costs have been emphasized by the steep increase since the mid-50s in the test discount rate used in the U.K. public sector. The 1955 White Paper on Nuclear Power was based on a public sector rate of 5%; Generating Boards are now required to use 10% in real terms (i.e. with constant money values).

In the future, given a steady and regular programme of orders, the economics of nuclear power stations will become increasingly favourable. Nuclear capital costs should fall in constant money terms. The use of bigger-sized plant, associated together in groups of, say, four units, should enable the advantages of economies of scale to be realized, and also enable savings through 'doubling-up' in the use of facilities and staffing. With a sufficient flow of orders there can be savings gained through replication. As more nuclear stations of each type are built, the high costs associated with the launching of a new reactor will be eliminated, and the costs of further reactors of that type will fall as more is learnt of their construction and operation.

This process of reduction in nuclear capital costs will be much more pronounced than any that can be expected in the capital costs of fossil-fuelled plant. This is largely because the technology of fossil-fuelled stations is older and most of the improvements possible have already been made. As a result the difference between the capital costs of nuclear stations and the capital costs of fossil-fuelled stations is expected to diminish, although nuclear stations will probably remain rather more expensive.

A second factor which should keep the costs of nuclear power down for this country is the existence now of an efficient British nuclear industrial organization to construct commercial nuclear stations, provide fuel, improve the performance of existing types of station, and develop new systems for the future.

On the construction side, it at one time seemed appropriate for there to be five nuclear consortia competing for orders to build magnox stations both in this country and overseas. But, particularly with the increasing size of individual reactors, domestic orders were insufficient to maintain so many consortia, and none of the consortia was able to call on sufficient resources to compete overseas with companies which either had the advantages of tendering in their own countries, or had the huge resources of the American firms. The number of consortia reduced progressively from five to four, then to three and finally to two, the last reorganization taking place in 1968/9, when British Nuclear Design and Construction Ltd and the Nuclear Power Group Ltd were formed. But even at the time many of us would have preferred a single-company organization, and there has been a growing realization that further rationalization of the industry was indeed necessary. The government has recently presided over a restructuring of the industry into a single reactor construction company, which is designed both to meet the domestic demand for nuclear stations and to compete and, equally important, collaborate, effectively overseas. Such collaboration is highly desirable, especially between the countries of Western Europe.

The opportunities for fruitful international collaboration and the advantages of a single strong organization have been demonstrated by British Nuclear Fuels Ltd, which was set up in

1971. The main activities of this company are reactor fuel element design and manufacture, irradiated fuel reprocessing, UF_6 conversion and uranium enrichment. In addition to supplying nuclear fuel and reprocessing services to the home generating boards, B.N.F.L. has secured a good deal of export business, particularly in the fields of UF_6 conversion and reprocessing. For example, reprocessing contracts have been obtained in Canada, Germany, Italy, Japan, Spain, Sweden and Switzerland.

The performance of the fuel elements has been exceptionally good and any delays in reactor operation have certainly not been attributable to late deliveries of fuel.

Two areas which particularly illustrate the benefits of international cooperation are those of uranium enrichment and fuel reprocessing. Both involve considerable capital expenditure and it is essential to ensure that installed capacity matches the available market. The development of nuclear power requires an assured supply of uranium enriched in the 235 isotope. The bulk of the western world's supply of enrichment at present comes from the gaseous diffusion plants in the U.S.A., but these do not have sufficient capacity to meet the firm demands foreseen in the 1980s. There is the further point as to whether it is politically acceptable for Europe to rely on a monopoly supplier in the U.S.A. The diffusion process is one that requires a very large plant before it becomes economically viable, and it consumes very large amounts of energy. Following independent studies of an alternative method of enrichment using the gas centrifuge which were carried out in Britain, Germany and Holland, the three Governments signed in 1970 a treaty concerned with the exploitation of this process. Two international companies were set up: Centec, with headquarters in Germany, for the development and manufacture of enrichment plants, and Urenco, whose headquarters are in this country, for the operation of enrichment plants and the marketing of enrichment. B.N.F.L. is the British shareholder in both these companies, which have recently been brought under a united senior management.

In the equally important field of fuel reprocessing, the existing plants in Britain and France have sufficient capacity for the immediate European needs with a margin for overseas business. In the not too distant future, however, additional plant capacity will be required and, so that this may be developed in an orderly way, an international company – United Reprocessors – with British, French and German partners has been set up. B.N.F.L. is also the British partner in this company. Transport of irradiated fuel from the reactor sites to the reprocessing plants is another area in which B.N.F.L. is cooperating with French and German partners.

All these collaborative arrangements were facilitated by the existence of a single company concerned with all aspects of the nuclear fuel cycle.

The Atomic Energy Authority provide the third component of the nuclear industry – the research and development organisation. The Authority work on the improvement of the performance of existing reactor designs and advise on their safe and efficient operation. For the immediate future, development work is devoted to new systems such as the steam-generating heavy water reactor (s.g.h.w.r.) and the high-temperature reactor (h.t.r.), the latter partly on a collaborative basis in the O.E.C.D. Dragon project. The largest component of the Authority's programme is, and has been for some years, the work on the fast breeder reactor, which, as I shall explain later, holds the key to a balanced nuclear system for the foreseeable future.

The single reactor construction company, the single nuclear fuel company and the single research and development organization are all closely interlinked to provide a potentially very strong nuclear industry. Shortly it will have the task of designing, constructing and fuelling

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the next round of nuclear power stations. It is not yet clear what type of reactor will be chosen for this round. There are four main contenders, namely the a.g.r. (the type now under construction), the s.g.h.w.r. and the h.t.r. (both the subject of development work by the Authority), and the light-water reactor, largely developed in the United States. The balance of choice between them is fine; the small differences in generating costs means that the options will remain open even if engineering or safety problems arise for a particular line of development. Once the choice is made, and a sustained programme of construction started, the industry's position will be firmly established.

Certainly only such a programme, affording scope for replication and a fair degree of continuity, will give the industry the opportunity to provide the experience and quality control essential for timely completion and close control of costs. Moreover, while such a programme should include exports of reactors as a major objective, the initial impetus can only come from the domestic market. The history of nuclear marketing both here and overseas demonstrates unequivocally that only a secure and adequate home demand can provide a base strong enough for marketing overseas and for sound international arrangements.

But perhaps the most important factor favouring the development of nuclear power in the next 15 years is the status of alternative sources of energy. Prices of these alternative sources of energy, particularly oil, have risen rapidly recently and seem likely to continue to rise for the foreseeable future. At the same time, several of these alternative sources have a discernible exhaustion point which in some cases appears to be relatively near. Both in the short and the medium term this is likely to bring about limits in supplies by the producing countries which will seek to conserve part of their resources for the future. Again this will be particularly true for oil.

Even with North Sea oil, the European Economic Community (including the United Kingdom) could depend on imported oil for some 50% of its energy needs in 1985, according to an official estimate made earlier this year, and the price of North Sea oil will almost certainly be determined by world prices.

Similarly, with the other principal conventional fuels used in Western Europe – hydro-electricity, natural gas and coal. Although there is some scope for expansion of *hydro-electricity*, this is insufficient to meet increases in energy demand. Indigenous resources of *natural gas*, even with recent discoveries, are limited and restricted to premium uses. Supplies of liquefied natural gas and synthetic natural gas are likely to be obtainable only at prices high enough similarly to restrict their use. *Coal* mining must remain essentially a labour-intensive industry despite increasing mechanization. If the men employed are to maintain a standard of living compatible with the task they are being asked to undertake, the labour costs of the industry will rise, which will be reflected in the cost of coal. Therefore, even if the price of power-station coal relative to oil becomes more favourable, that price will nevertheless rise. This is especially true for the non-British Western European coal industries, which face particularly severe problems of recruitment, rising costs and exhaustion of the resources.

In the longer-term there is a general problem of demand outstripping supply for all these fuels. To gauge the extent and urgency of this problem the likely future demand for energy must be set against the resources available to meet that demand.

By A.D. 2000 and assuming only modest rates of growth there could well be a short-fall of the order of 40% of world energy requirements. It is unreasonable to expect acceleration of production from traditional sources plus the exploitation of non-traditional sources (such as oil shales and tar sands) to fill more than half of this gap, and even this much implies the acceptance of real price increases in traditional fuels by factors of 2 and 3 (Brookes 1973).

The remaining requirement, of the order of 20% of total world energy needs, must for all practical purposes be met by nuclear and hydro-electricity. Because of the limitations on further development of hydro-electricity, some 90% of this requirement has to be met by nuclear power. On this basis a world installed nuclear capacity of some 5000 GW (e) would be required in the year 2000.

Western Europe's share of this capacity would be some 800–900 GW (e) (compared with 12.3 GW (e) in 1972). This is a daunting increase, but should not be impossible. And failure to meet it would severely strain fuel resources, with consequent setbacks for national economic growth-rates. If the target is to be attained it is necessary that a good start on the process of nuclear power expansion be made as quickly as possible.

Power stations installed now and fuelled by traditional fossil fuels commit the country to a significant long-term demand for an increasingly expensive and economically unfavourable energy source. A substantial delay in starting the build-up of nuclear capacity may lead to difficulties later in providing the necessary economic resources for the delayed expansion, which would come at a time when increased fossil-fuel bills were already straining national economies. The need for many users of energy to adapt themselves in the next decades to electricity instead of other fuels will in any case be a call on resources. Certainly, there will be an interim period before the large-scale installation of nuclear plant can cushion the effects of fossil-fuel price rises on economic activity. But if the interim period was prolonged the electricity production and many other industries would have no alternative but to face substantial fuel price increases, with adverse consequences for economic growth. Such a setback would in turn hamper the delayed expansion in nuclear power, thereby precipitating a further period of rising energy prices and energy shortage. To avoid such a situation, the expansion of nuclear power at a steady and controlled pace, with well-defined targets in the longer term, must start as soon as possible. Western Europe should coordinate its plans for this expansion, to ensure the best use of skills and resources.

It is worth pointing out that this target implies an increased role for electricity in meeting energy needs, with an increase in the proportion of world useful energy supplied by primary electricity from the present figure of $12\frac{1}{2}$% to a little over 20% (using the energy coefficient devised by Adams & Miovic 1968). This should be attainable.

It is particularly important that the countries of Western Europe make the necessary effort to achieve these targets. In 1985, even with North Sea oil and gas, the annual oil imports of the Nine will be over 900 million tonnes at a time of great pressure on supplies from other oil-importing nations. It is clearly desirable that Europe should have alternative sources of supply as soon as possible, and of these alternatives nuclear power is currently the only practical contender. The various energy policies put forward both by individual European countries and by the Community recognize this by envisaging a rapid expansion of nuclear power.

Nuclear power, then, is now poised on the brink of a major expansion. Its capital cost disadvantages are becoming less marked at the same time as its undoubted running cost advantages are increasing. Moreover, a large increase in nuclear power is necessary if an 'energy shortfall' in 20–30 years time is to be avoided, and this country now has a nuclear industry capable of meeting the challenge of such an increase. Finally, we must not forget the advantages of an

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increased nuclear power programme for the balance-of-payments situation and in economizing altogether in the use of oil.

At present, nuclear plants account for about 7% of this country's electricity generating capacity, and by 1977/8 when the a.g.r. have all come into operation this proportion will rise to about 15%. Over 10% of Britain's electricity is currently generated by the nuclear stations, and this proportion is expected to rise to over 20%. By 1978 our power-stations will be saving the equivalent of 15×10^6 tonnes of oil a year (17.5×10^6 m^3), and even a modest nuclear programme would double the nuclear capacity by 1985 to give a saving of 30×10^6 tonnes of oil a year (35×10^6 m^3). On a conservative estimate of an increase in oil prices to £15/t in 1985, this is unlikely to be worth less than £450 million a year. The comparable saving in oil from a European Community nuclear programme of even 140 GW by 1985, which is very much lower than some of the most recent official targets of desirable capacity, would be of the order of some 210×10^6 tonnes of oil a year (250×10^6 m^3). The offsetting cost of uranium is relatively small, certainly not more than an eighth of the cost of the oil required for an equivalent programme, and expenditure on separative work should by then predominantly be at 'home'.

Can nuclear power fulfil the role I have described, or are there constraints on its development? In the short term there are no resource restraints; the existing problems are institutional or political. The nuclear industries of Western Europe are able, indeed keen, to tackle increased programmes of work.

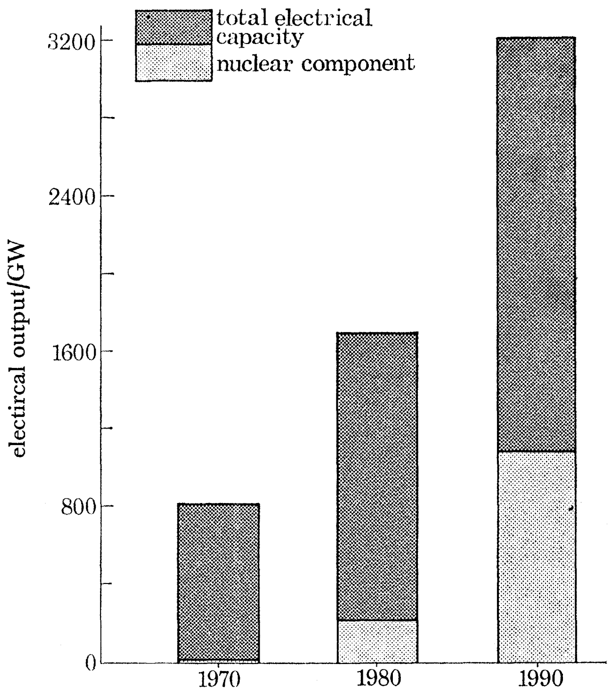

FIGURE 1. World nuclear capacity relative to total electrical capacity.

The thermal reactors already in use and under development could be used to meet the capacity targets called for and are a proved, safe and efficient way of producing energy. But in the longer term, if only thermal reactors are used, problems can be foreseen in providing sufficient reasonably priced uranium to fuel them. This problem has to be seen in a wider context than just Western Europe. A forecast of the growth of nuclear capacity, relative to total electrical capacity, in the non-communist world is given in figure 1 (O.E.C.D. 1973). This forecast assumes that while the rising cost of fossil fuels and their future supply position will make nuclear plant steadily more attractive, the shift in relative economics is not likely to be so radical that all existing coal- and oil-fired stations will be shut down before the end of their working lives. However, the trends in fossil-fuel prices will be sufficient to induce utilities to meet their growing demands for electricity from nuclear plant as far as possible, with fossil-fuel plant being used predominantly as low-merit order and peaking plant to provide capacity at times when system demand is high. By 1990 up to three-quarters of total new capacity ordered each year will be nuclear, with the remainder being divided between the most efficient fossil-fuelled plant, hydro-electricity and specialized peaking plant such as gas turbines.

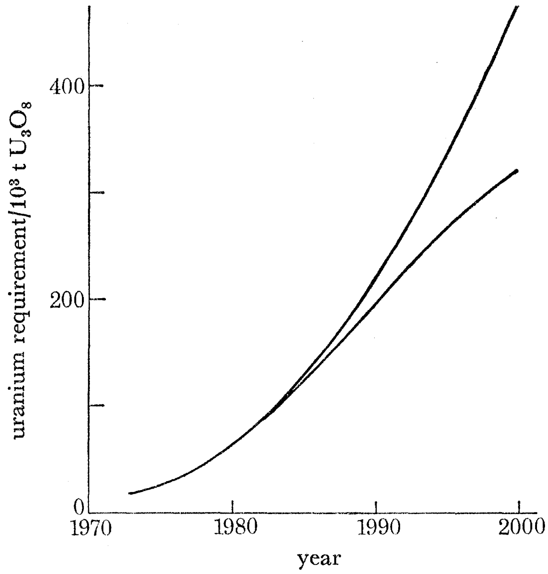

FIGURE 2. Annual uranium requirements for O.E.C.D. area.

If the nuclear capacity was installed at the rate shown in figure 1, and it was all of the thermal type, then the annual uranium fuel requirements would be as shown by the top line in figure 2 (based on O.E.C.D. 1973). The uranium requirements of the various thermal reactor systems do not differ significantly between types of the same size, and the precise mix is therefore not important in assessing the total demand. There is no reason to believe that insufficient uranium exists to meet this demand. But, as Dr Bowie's paper suggests, it may increasingly be available only as a result of more extensive world-wide prospecting and at higher prices. The cost of uranium is only a very small part of the cost of nuclear power, and would increase several times without destroying nuclear power's competitiveness for base-load generation. But the cost of uranium must rise as the lowest-cost resources are exhausted, and there is therefore an obvious incentive to economize in its use if possible.

Such economy will be possible with increasing utilization of the fast breeder reactor, which offers the solution to the world's fuel supply problems for centuries, even if no other solutions are found. The most exciting trend in nuclear power generation in the 1980s will be the increasing introduction of fast breeder reactors into commercial use.

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A fast breeder reactor is designed to operate entirely with fast neutrons (i.e. with no moderator), thereby making it possible to convert more than one atom of non-fissile uranium-238 into fissile plutonium-239 for every atom of fuel which is fissioned. To improve the probability of capture of neutrons by ^{238}U atoms, and hence the amount of plutonium produced, a 'blanket' of fertile material surrounds the core of mixed plutonium and uranium fuel. Waste uranium, depleted of its ^{235}U content, is used as the 'blanket' material. Thus, in addition to producing electricity, the fast reactor breeds more new fissile material than it consumes in maintaining the fission chain and this bred material can be used to initiate new fast-reactor stations.

Thus a fast-reactor system utilizes uranium much more efficiently than a thermal-reactor system; typically 60–70% of the uranium is utilized in a succession of irradiations and recoveries compared with the 1–2% which can be attained with thermal reactor systems. The fuel cycle costs of the fast reactor are, as a result, even more insensitive to variations in the price of uranium. For example, an increase of \$44/kg in the cost of uranium ore, would result in an increase of less than 0.1% of the total fast-reactor generating cost. The world's resources of uranium will be used more efficiently when fully developed fast reactors are installed on a substantial scale and more expensive uranium resources can be exploited thereby ensuring a continuing supply of cheap electricity.

The potential importance of this economy in the use of uranium was soon realized in this country, and led to feasibility studies in the early fifties. It was then clear that the system would require careful and cautious development, but the large potential benefits seemed sufficiently assured for work to start on the construction of the Dounreay fast reactor, completed in 1959. Major fast-reactor programmes have also been started in several foreign countries, most notably France, Russia, the United States, Germany and Japan. Work has continued in this country and a 250 MW (e) prototype fast reactor is being commissioned at Dounreay, which will start delivering power to the grid shortly. Similar-sized prototypes in France and in Russia are at about the same stage of development.

These three countries plan to have their first commercial fast breeder reactors in operation by the early 1980s and to install them steadily from the mid-80s. The other countries too, plan to catch up by then. By the end of the 1980s appreciable numbers of fast breeder reactors will be installed. Figure 3 (based on O.E.C.D. 1973) shows a prediction of the rate of installation of fast breeder reactors in relation to the total build-up of nuclear capacity already shown. Such a rate of fast breeder installation would modify the uranium demand as shown by the lower line in figure 2. The difference between the requirements of the two programmes increases with time as more breeders come into operation, as shown by the illustrative extrapolation of the two lines to the year 2000. The assurance of long-term supplies given by the breeder reactors removes the worry which would otherside exist if only thermal reactors were available. Moreover, this fuel economy is reflected in large savings in the fuel cycle costs. When fast-reactor fuel-cycle costs are compared with light-water reactor fuel-cycle costs, the early commercial fast reactors should have savings equivalent to over £15/kW over the life of the reactor (discounted at 10%) (Marsham 1973). Later fast reactors will use improved fuels, while the fuel-cycle costs for thermal reactors will probably rise; as a result the saving from fast-reactor fuel-cycle costs, relative to thermal, will increase to over £20/kW.

As far as they can be assessed at present, capital costs will be only marginally higher for a fully developed fast breeder reactor than for a comparable thermal reactor. The higher capital costs would offset part of the benefit from the reduced fuel-cycle costs, but nevertheless there should still be a net discounted saving, on a single-reactor basis, of some £10/kW, and rather more if the effect on system costs of the extra plutonium produced is included. As further improvements are made, the savings should increase. Of course, the corollary of the double promise of fast breeders – that they will ensure adequate supplies of fuel *and* reduce the costs of the fuel cycle, is that the longer the delay in introducing the fast breeder, the more concern there must be over fuel supplies and the price of the fuel cycle, as more expensive uranium resources are tapped. The fast breeder is a sophisticated concept, and some degree of caution is essential in the rate at which it is developed. But there is now great confidence in it all over the world, following a long period of painstaking experimentation and development. The first fully commercial reactors of this type will be in operation by the early 1980s. When these first reactors have demonstrated their reliability and economy they will be joined by others as quickly as is practicable, to meet the power needs of the last decades of the century. Design, testing and planning should continue without delay, so that potential problems will have been identified and solved before they can inflict serious or expensive delays.

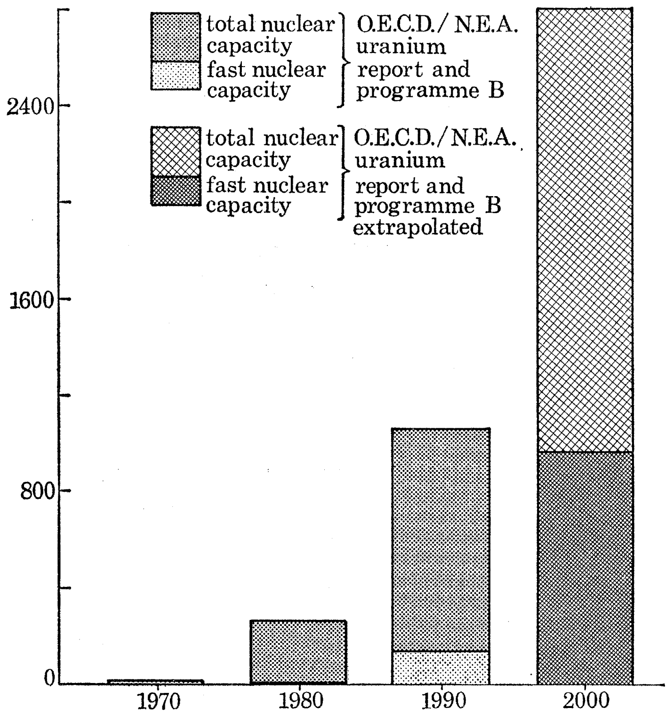

FIGURE 3. Fast-reactor capacity relative to total world nuclear capacity (excluding communist countries).

This is why the leading industrial nations are now intensively developing the fast breeder reactor. So far these developments have been largely on national lines, but there have recently been moves towards international collaboration. The Germans are collaborating with the Belgians and the Dutch in the construction at Kalkar of a 300 MW (e) prototype fast reactor. In the longer term the French plan to build the successor to their prototype in collaboration with Germany and Italy, this proposed reactor being a fully sized commercial breeder of 1250 MW (e).

This sort of international collaboration is a pointer to the future. Only collaboration in

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assessing the performance of the various prototype reactors will ensure that the maximum benefit is obtained from those reactors. There must be full collaboration in safety programmes and in formulating commonly accepted safety standards. Furthermore, international collaboration is desirable to ensure the most efficient and economical manufacture of components and fuel and to avoid an uneconomic proliferation of under-used facilities. This country must be ready to play its part in such collaborative programmes especially with her Western European neighbours.

The question of safety in nuclear installations is always uppermost in the public mind and I hardly need add is the first consideration of the designer, builder and operator. Most countries with significant nuclear programmes now have some form of independent Nuclear Inspector, as this country has, whose responsibility it is to inspect, licence and authorize the operation of nuclear plants and to advise Government on nuclear safety matters.

But nuclear safety is international and it is most desirable that standards be accepted internationally. Much good work has been done in the field of radiation protection by the setting of standards by the I.C.R.P. (International Commission on Radiological Protection). In the field of reactor design this international approval has been extended within the European Community by the setting up of a Fast-Reactor Working Group in which all the major nuclear interests are represented. This Working Group has made significant progress in establishing a common understanding of matters relating to safety, and in ensuring that the efforts in all E.E.C. countries make an effective contribution to the E.E.C. fast reactor safety programme.

No attempt will be made here to go into the detail of reactor safety philosophy. However, many ill-informed comments have been made recently in relation to the hazards of 'plutonium reactors' and the transferral of plutonium fuel and a short discussion of this subject seems appropriate.

Plutonium is produced in all existing types of nuclear reactors; fast breeder reactors produce no more plutonium than many thermal reactors per unit of electricity generated and in any case its separation for military use is still a formidable industrial undertaking. The complete elimination of risk of diversion would require the world to abandon nuclear fission altogether as a source of electrical power and to depend entirely on the diminishing fossil-fuel reserves for an unpredictable period, certainly the rest of this century, until alternative sources of energy could be commercially developed.

The extraction of plutonium from irradiated fuel, whether from fast or thermal reactors, and its conversion into a form in which it could be used to make a bomb, requires complex and expensive plant and considerable knowledge. International safeguards are applied to ensure that countries other than those already possessing nuclear weapons do not divert plutonium or other fissile materials from civil to military use and governments impose tight security arrangements for such materials. As regards the physical protection of fissile materials, arrangements are kept under constant review and strengthened as necessary in the light of changing circumstances.

Concern has also been expressed about the problem of disposing of the waste materials produced by the nuclear fission process. The extent of this problem is frequently exaggerated. To a first approximation, the amount of such waste is the same whatever the type of fission reactor used. Such differences as do exist between waste products from fast and thermal reactors do not change the nature of the waste management. Low active liquid waste can safely be released to the sea. Levels of activity are carefully controlled within limits authorized (and monitored) by the appropriate government departments. Small amounts of solids of comparatively low activity accumulate over years. Most of it is stored for long periods in drums in specially provided silos. Its bulk can be reduced by incineration, the ash being retained in the silos; or it can be disposed of in concrete drums in the ocean depths. Highly active fission products are currently stored in liquid form in specially designed tanks and these tanks take up only a small part of each processing site. The safety of the storage (which must be for hundreds of years) would be improved if the fission products were in solid form. Processes for doing this are being developed for introduction when required.

Table 2. Current radiation doses to U.K. population

	mrad/year
natural background	100
medical exposure	20
fall-out	2
occupational and miscellaneous	1.5
nuclear industry (radioactive waste disposal)	0.012

Finally, to place the levels of radiation from nuclear plant in perspective, table 2 shows that the U.K. population receives from nuclear waste an annual dose of the order of one-hundredth of 1% of that which is present naturally. Moreover, this proportion will not change significantly even with a substantial increase in nuclear power. Therefore, although there must always be great care involved in the operation of the nuclear-power industry, with rigid observance of the high standards set by international and national safety regulations, I believe that in matters of the environment and safety there are sufficient factual grounds to allow the expansion of nuclear power which, as I have tried to show, is so desirable on other grounds.

This paper has been predominantly about the ability of existing nuclear technology to make a growing contribution to meeting the increasing energy demands of Western Europe in the 1980s in the most economic way possible. It has also indicated the need to plan ahead during this period if longer-term energy needs are to be met. In this connexion it is appropriate to conclude with a few words about fusion power. For the more distant future, fusion power offers the promise of almost unlimited energy with very little in the way of environmental disadvantages. Because of the complexity of the technology, development of controlled fusion has proved inevitably to be a lengthy process, but recently progress has become increasingly encouraging. Fusion scientists in Britain and other parts of the world are now reporting steady progress towards achieving the minimum values of key parameters necessary to achieve a sustained thermo-nuclear reaction. The prize is a great one. Even if we confine ourselves to considering what is believed to be the easiest reaction to achieve (the deuterium/tritium reaction with heavy water and lithium as, effectively, the input fuels) the new source of energy opened up would last the world for thousands of years at a rate of electricity production ten times the present world rate. If deuterium only is needed, the world's seas offer virtually limitless supplies. Most attention so far has been given to fusion involving the magnetic containment of plasma; recently, work has suggested the prospect of controllable fusion using lasers. It is too soon to be certain of the ultimate potential of this method, but it is sufficiently promising to justify continuing study and there is already commercial interest in this approach. A further advantage of a fusion reactor is that there would be few of the environmental problems of radioactive

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waste disposal; although the central structure of the reactor itself would present problems of disposal at the end of its life its treatment would be similar to that of fission reactors.

It is very hard to say in the present state of knowledge just how fusion power would compare with fission power in terms of the cost of the electricity produced. Fuel costs would almost certainly be an order of magnitude lower even than the very low fuel costs of the fast fission reactor. Perhaps the best way of putting this difference in perspective is to say that it permits the capital cost of the reactor to be about £10 to £12/kW higher than that of a fission reactor while still breaking even with it on total electricity production costs.

In fusion research, however, large experiments may be beyond the existing capacity of any one nation to build, and accordingly the United Kingdom Atomic Energy Authority have recently signed a contract with the European Atomic Energy Community, Euratom, to advance collaboration in research into controlled nuclear fusion and plasma physics. This contract integrates the Authority's fusion programme into an existing coordinated Community programme the aim of which is to construct large experimental installations and, subsequently, prototype fusion reactors for the generation of electrical power. One proposal examined during recent Euratom discussions on future programmes has been the setting-up of a large joint European experiment, the Joint European Tokamak (J.E.T.), to try to establish conditions close to those needed in a power-producing thermo-nuclear reactor. Culham Laboratory will act as host to the Community team which is carrying out the initial design of this experiment. Through these arrangements, the Authority are joining in the furtherance of fusion research in the European Community on a scale comparable with fusion programmes undertaken anywhere else in the world.

Fusion power, when fully developed, will supplement fission power to a growing extent in meeting the energy needs of future generations. But between now and the end of the century it is to fission that Western Europe can turn with confidence to ensure that an increasingly important part of her power requirements is met in a safe, clean and secure manner.

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Discussion

A. B. Lovins (c/o *Friends of the Earth*, 9 *Poland Street*, *London*, *W*.1)

I agree that rapid proliferation of thermal reactors would lead to a shortage of low-cost uranium in, as you say, a time of the order of decades. But is it not right that because the cost of uranium is such a small fraction of the sent-out cost of nuclear electricity, the cost of uranium could rise by an order of magnitude (giving us several centuries' supply) without raising the sent-out cost of nuclear electricity by more than a few tens of per cent?

Sir John Hill

The price of uranium could indeed rise by an order of magnitude without significantly affecting the cost of nuclear electricity provided that fast reactors were to be installed in substantial quantities by the time that the envisaged uranium price increases were effective. In thermal reactors an order of magnitude increase in the price of uranium would about double their generating cost.

K. E. Zimen (*Hahn-Meitner Institute of Nuclear Research, Berlin* (*West*))

The limits to fission energy production will probably be set by the environmental effects of the extremely long-lived isotopes of certain transuranium elements (Np, Pu, Cm) in the radioactive waste from reprocessing plants. Do you agree, or do you think there will be a practicable solution to this problem in the year 2000?

Sir John Hill

It is recognized that it will be necessary to solidify high-activity liquid wastes (which will contain the large majority of the trans-uranic elements) in order to make their containment less dependent on human surveillance. Development of a suitable solidification process has been in hand for some time and it is planned to begin waste solidification in the mid-1980s by means of vitrification. It is, therefore, reasonable to say that by the year 2000 there will indeed be a practicable solution to this problem, and future generations will not find it unmanageable.

K. E. Zimen. In my opinion we cannot leave this problem to future generations for two reasons. (1) As a chemist working in reactor chemistry I am convinced that it will be practically impossible to meet the extreme requirements for keeping, for example, Pu away from the biosphere. (2) If this is right and fission energy cannot be used for more than – say – 50 years, then we have to ask: do we really need breeder reactors? For 50 years or so we have plenty of uranium. – I apologize for going beyond the 1980s, but we need to foresee what could happen to the human environment in the next century to be able to make appropriate decisions in the near future.

Sir John Hill

Discharges of radioactive wastes to the environment are regulated by law. These regulations apply of course to plutonium and therefore any discharges of this substance are, and will continue to be, carefully regulated and the standards regularly reviewed.

It is only true to say that we have sufficient uranium for the next 50 years if the breeder reactor is introduced on a substantial scale. Already the world-wide programme of thermal reactors is such that those installed by 1981/82 will require all the known resources of cheap uranium to ensure their fuel supplies for the first twenty years of their lifetime.

Professor Edward Eisner (*Department of Applied Physics, University of Strathclyde, Glasgow*)

Safety in a power system based on nuclear fission: sabotage

It seems to me that the safety of nuclear power systems is usually discussed in terms of accidental failures, and the standards achieved certainly look very impressive. However, I suggest that, in the modern world, an enormously greater risk is that of sabotage. Here a nuclear-fission system differs from a fossil-fuel system in that the sabotage not merely disrupts the system, but could cause widespread danger by release of radioactive material. Could Sir John please give us his thoughts on this?

Sir John Hill

The possibility of sabotage, leading to the release of radioactive material, is, of course, recognized and security arrangements for the protection of nuclear materials have been drawn up in consultation with all interested Government departments. These arrangements are constantaly reviewed to counter this threat as adequately as possible.

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