Community Topics 7

# Euratom's second five-year research program 1963 - 1967

european community
information service

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# INTRODUCTION

Although there is still some way to go before nuclear power in Europe becomes competitive with electricity generated by conventional means, there is every prospect that this will be achieved before 1970. Sooner or later, nuclear power will be needed on a large scale to meet the continent's rapidly increasing energy requirements, and solutions to the many remaining technical problems of producing electricity in nuclear power stations must therefore be found quickly. Likewise, much research has still to be done before the manifold uses of nuclear technology in industry, medicine and agriculture can be fully exploited.

Euratom, the European Atomic Energy Community, plays a dual rôle in promoting the research needed in these two fields. Its executive body, the Euratom Commission, must on the one hand coordinate research undertaken in the six member countries and, on the other, it must supplement national efforts "by carrying out the Community's own research and instructional program" (articles 4 and 5 of the Euratom Treaty). Euratom's rôle of coordinator is exercised formally by means of surveys of national research programs (article 5), through the work of a Scientific and Technical Committee and of the Council of Ministers' Consultative Committee for Nuclear Research, and, informally, at meetings on various subjects where experts from the Commission, national authorities and industry, exchange information. These formal and informal exchanges of information also help the Commission in drawing up Euratom's own research program – carried out at its Joint Research Centres and under "association" and other contracts with industry – and in ensuring that this program effectively supplements and dovetails with national research programs.

The broad lines of Euratom's first five-year research program (1958-62) were laid down in Annex V to Article 215 of the Euratom Treaty. Under this Article, a total of $215 million was allocated for the initial research program, and all but $20 million of this sum had been earmarked by the end of the five-year period. This period saw the launching of the Euratom program, the recruitment of some 1,900 research staff, the setting up of the Euratom's four Joint Research Centres, and the signing of well over 300 research or "association" contracts.

On June 19, 1962, the Council of Ministers approved the Commission's proposals for a second Five-Year Research Program for the years 1963-67, providing for expenditure of $425 million, or nearly double the outlay for the first period. The second program aims at continuing and expanding the work already under way: to improve existing types of reactor, to develop new types, and to carry out research on a wide variety of subjects related to the peaceful uses of nuclear energy.

The table opposite clearly shows the emphasis to be laid in the second research program on research into the production of nuclear power, to which 54% of the total expenditure will be devoted. The total number of research staff required to carry out the second five-year program will be raised from slightly over 1,900 at the end of 1962 to roughly 3,200 by the end of 1967.

## Summary of Euratom research budget, 1963 - 1967

| | | $ million |
|---|---|---|
| **Reactors and associated research** | "Proven" reactors and their industrial development | 29·5 |
| | Advanced gas reactors | 25 |
| | ORGEL | 57 |
| | Fast reactors | 73 |
| | New reactor types | 9 |
| | Ship propulsion | 7·5 |
| | Operation of BR2 (Belgian) materials test reactor | 12 |
| | Treatment of irradiated fuel | 14 |
| | Treatment of radioactive waste | 5 |
| | Total | 232 |
| **Fusion** | Thermonuclear fusion studies | 31 |
| **Radiation** | Radioisotopes | 5 |
| | Health protection and biological research | 17·5 |
| | Total | 22·5 |
| **Joint Research Centres** | Ispra | 72 |
| | Petten | 19 |
| | Geel | 11 |
| | Karlsruhe | 25 |
| | Total | 127 |
| **Training** | | 3 |
| **Dissemination of information** | | 9·5 |
| **Grand Total** | | 425 |

# THE ORGANIZATION OF EURATOM RESEARCH

Under the second program, Euratom is organizing its research in the same way as it did under the first: directly in the Joint Research Centres and indirectly through contracts with other establishments.

## The 'direct' approach

A total of $127 million will be spent on building up the Joint Research Centres, and about half the total expenditure of $425 million under the program will be allocated to work carried out at the Centres.

The Joint Research Centres are:

**Ispra** (at the southern end of Lake Maggiore, Italy), the largest establishment, both in terms of personnel and equipment. Although the equipment of this general-purpose centre is well under way, it will undergo substantial development during the five-year period, for which it has been allotted $72 million. The staff at Ispra already exceeds 1,000: by the end of the period it will have risen to 1,700.

Ispra is the location of the Orgel project (see page 5), to which its laboratories are largely devoted; a critical assembly, ECO, part of the Orgel program, is now under construction. The Scientific Information Processing Centre (CETIS), equipped with high-performance computers, is also located at Ispra. CETIS, which includes in its equipment IBM 1401 and 1090 ordinators, is one of the most advanced organizations of this type in the world, and serves the Brussels Headquarters and other research centres in the Community. Apart from straightforward calculations, the equipment can undertake grammatical analysis, automatic documentation and automatic translations. Further equipment will be installed to enable the centre, *inter alia,* to undertake translations between all four Community languages as well as English.

**Petten** (on the Dutch coast, 40 miles north-west of Amsterdam), currently under construction. The centre-piece of this general purpose establishment is the high-flux reactor (HFR) built by the Dutch and handed over to Euratom. Altogether 350 people will be installed at Petten, which has been allotted $19 million under the new program. Apart from the use of the HFR, this establishment will be concerned with technical coordination of the work performed under contract in the field of advanced gas reactors (the Dragon project in the UK and AVR "pebble-bed" reactor in Federal Germany) and with research into liquid fuels.

**Geel** (in Belgium, near the Dutch frontier), the location of the Central Nuclear Measurements Bureau (CNMB), a highly specialized laboratory for standardizing and perfecting fundamental nuclear measurements. The CNMB program covers, amongst other things, the improvement of standards and of measuring instruments, the preservation of primary standards and the distribution of secondary standards for use in science, industry, commerce and medicine.

Among the most important items of equipment at the CNMB will be a van de Graaf particle accelerator, a powerful linear accelerator and a laboratory for the preparation of samples. The sum of $11 million will be devoted to the CNMB and the number of staff will be raised from its present strength of 100 to 180.

**Karlsruhe** (Federal Republic of Germany), the European Transuranian Institute, now under construction. This institute will study transuranium elements in general and plutonium-based fuel elements in particular – the latter in view of the promising prospects for plutonium as a nuclear fuel for future power reactors. Karlsruhe will be the Community's headquarters for transplutonium work, coordinating the work performed directly by Euratom with that done under contract. An important part of the work will consist of studying the recycling of plutonium in reactors. The sum of $25 million has been allocated to this institute, whose staff will eventually total 300.

### The 'indirect' approach

The Commission's "indirect" approach to research is either by means of ordinary contracts for specific research assignments which are farmed out to industrial organizations or other research centres in the Community, or by association contracts under which Euratom and a national concern form joint research teams for long-term assignments. In the latter case the two parties share the expense.

In this way work by a large number of public and private organizations is encouraged and coordinated and the best possible use is made of available resources. So far, some 300 contracts have been concluded within the framework of the first five-year program. Nearly half the work under the second program will be done under contract. The contracts are principally for work on "proved" reactor types and the development of new types (Orgel, Dragon fast reactors, the Halden boiling heavy-water reactor, the Dutch Suspop homogeneous suspension reactor, etc.).

At the present stage of equipment of the Joint Research Centres – which do not necessarily undertake research themselves on all the reactor types selected by the Community – these contracts play an indispensable rôle in the Community's power reactor development program, as they do in consolidating work in other fields of research.

Association contracts are used for long-term research projects undertaken by private or public research organizations. Euratom's rôle, apart from the financial contribution, is to widen the scope of the project, to contribute up to 50% of the personnel and, through a mixed committee, to join with the organization concerned in drawing up and executing the research program.

## THE REACTOR PROGRAM

### 'Proved' reactors

There is still appreciable scope for improvements to the "classical" types of nuclear reactor (boiling-water, pressurized-water-cooled, or gas-cooled), of which 6,000 MW of capacity are already in operation or under construction throughout the world (2,000 MW in the Community countries). This type of research, the subject of nearly 100 contracts under the first five-year program, is important in view of the possibility that "proved" reactors may, even in the short term, be improved sufficiently to have become fully competitive with conventional power stations. Moreover, the Community will need to increase the number of technicians proficient in the operation of such reactors.

Euratom's research on "proved" reactors will be carried out in liaison with the national program, mainly under contract. Among the fields of research are:

- improvement of reactor parts, including automatic equipment and heat exchangers;
- improvement of structural materials, especially steel;
- development of metallic and ceramic fuel elements, and cladding materials;
- improvement of reactor performance, particularly as regards thermodynamics, increasing power output, and control instrumentation.

Euratom will also continue the studies already under way on the technico-economic aspects of nuclear energy production, the cost of nuclear kilowatt-hour fuel cycles, the transport of radioactive materials and so on.

The sum allocated to the proved-reactor program is $29·5 million.

### Orgel: heavy water-moderated, organic liquid cooled reactor

The Orgel program involves research on natural uranium-fuelled reactors using heavy water as a moderator and an organic liquid as coolant. This formula offers a number of potential advantages:

- natural uranium is an atomic fuel which can be obtained with relative ease in the Community, and industrial enterprises already process it for use in reactors in a large variety of ways;
- heavy water is an effective moderator when natural uranium fuel is used;
- an organic liquid tolerates both relatively high temperatures (of the order of 400° C) in low pressure circuits and allows the use of conventional structural materials.

Apart from solving the many problems which still remain before power stations can be equipped with this type of reactor, the Orgel R. and D. program is expected to provide research experience relevant to other types of reactors in the heavy-water group. Among the subjects to be studied under the program are metallurgy (sintered aluminium, uranium carbide), chemistry and reactor physics. The equipment for the Orgel studies includes the ECO reactor ("Orgel critical experiment"), now under construction at Ispra, which will enable precise studies to be made of techniques for obtaining the best neutron economy in Orgel-type reactors.

A further stage in the Orgel program (a large proportion of which will be carried out at Ispra) will be the construction of a 25-MW test reactor (ESSOR), which is likely to be completed in 1965. The design for the ESSOR reactor which will be built by private industrial groups, was recently completed. The sum of $57 million has been allocated to the Orgel program.

## High temperature reactors

Advanced gas reactors, featuring higher temperature, and higher rates of fuel consumption, offer important potential advantages over the natural uranium, graphite-moderated, carbon dioxide gas-cooled (graphite-gas) reactors.

The Dragon project, conceived by the British, involves the study and construction of a pressurized helium-cooled reactor (the outlet temperature of the gas being at least 750° C). Instead of using natural uranium, the fuel elements will consist of enriched uranium (U235) mixed with thorium (a cheap and plentiful mineral). The latter is convertible by irradiation into uranium 233, which can also be employed as a reactor fuel. Euratom is not only covering part of the Community countries' share of the reactor construction costs and of the associated research on the Dragon project, but has also sent some thirty engineers to work on the project at Winfrith (U.K.). The initial five-year agreement on Dragon which was due to expire on April 1, 1964, has now been prolonged until 1967.

Euratom will also be associated with the pebble-bed reactor of the BBC-Krupp concern, now being built at the German centre of Jülich. In addition to participating in the operation of this reactor, Euratom will undertake an associated research and development program covering reactor materials and fuel elements in particular. Euratom will also make a study of a 400-500 MW high-temperature thorium-fuelled reactor, the construction of which could start before the end of 1967.

The Petten establishment has been allotted the task of technical coordination between the Dragon and pebble-bed projects, and its own research activities will include studies of thorium and graphite, the development of liquid fuels, and the technological study of active circuits. This will involve building such items of equipment as dismantling cells, and very high and medium-activity laboratories. A total of $25 million has been allocated to the advanced gas reactor program.

## Fast reactors

Fast reactors are perhaps the most promising of all, and are one of the second program's principal objectives. Studies in this field, begun during the first program, will be greatly expanded.

Earlier reactors rely on moderators to slow down the neutrons and ensure that they bring about fission in the fissionable material employed. Fast reactors, on the other hand, lack a moderator and rely on fast neutrons to bring about fission. At the same time they breed plutonium from a blanket of natural uranium which surrounds the fast reactor core; in this way additional fissile matter is bred, which can later be used as fuel for another core. "Breeder" reactors can thus produce as much or even more fissile material than they consume. Once they become suitable for large-scale power production, great economies in nuclear power costs should be possible. Most of Euratom's fast-reactor research is being performed under association contracts. One such contract has been signed with the French *Commissariat à l'énergie atomique* and another is in view with the German *Kernreaktor Bau- und Betriebsgesellschaft,* with the active participation of the Transuranian Elements Institute at Karlsruhe. An Italian project may later be added.

Euratom at present plans to:

- participate in the construction and operation of the Rapsodie sodium liquid-cooled test reactor at the French Cadarache (Provence) Centre;
- participate in the construction of two large-scale critical assemblies, one at Cadarache and the other at the German Karlsruhe research centre;
- undertake research and development aimed at the design of a 100-MW fast reactor, the construction of which could begin towards the end of the five-year period.

Euratom will thus have an important coordinating rôle to play in European fast-reactor research. Cooperation in this field with the U.K. and the U.S.A. is also likely to be intensified.

A total of $73 million, the largest sum for any single item, will be devoted to this sector.

## New types of reactors

Work is already under way on new reactor concepts and will be continued under the second five-year program. One project is the SUSPOP reactor, which is being studied under an association contract with the Dutch KEMA concern at Arnhem. SUSPOP is a homogeneous suspension reactor in which fuel is suspended in a liquid moderator instead of taking the form of bars surrounded by a moderator.

Another project is for research on the development of "two-phase liquid coolants" (so-called "fog" reactors using a mixture of water and vapour); eventually it is intended to build a specialized test reactor operating on this system. Other studies to be undertaken include such new concepts as nuclear superheating, the sodium-graphite cycle and ultra-high temperature operations. $9 million will be spent on these programs.

## Material-testing reactors

It is essential for the development of new types of reactors and for the improvement of existing types that there should be facilities for testing the behaviour of construction materials under radiation. The ideal instrument is a reactor with an extremely high neutron flux, enabling the long-term behaviour of these materials to be tested rapidly after submission to intense neutron bombardment. Euratom has already concluded an association contract under which the Belgian Government has put its BR2 high-flux materials-testing reactor at the Community's disposal for twenty years. This reactor, which produces the highest neutron flux of any in Europe, entered into service in 1962 and is operated in association with the Belgian *Centre d'Etudes de l'Energie nucléaire*. It will be available for experiments both to the Joint Research Centre and to other national or private concerns in the Community. Alongside BR2, a very high-activity "hot" laboratory will enter into service in 1964.

The materials-testing facilities of the Community will be reinforced by the HFR reactor at Petten.

The allocation for materials' testing reactors is $12 million.

## Retreatment of irradiated fuel

Spent fuel withdrawn from a reactor retains fissile elements which can be recovered for further use. The material becomes partly "poisoned", however, in the sense that by-products are formed which obstruct the smooth functioning of the reactor. The process of eliminating these poisons still leaves wide scope for improvement.

Research on improving the treatment of spent fuel takes on increasing importance in view of the likely rapid growth in the number of power reactors to be installed in the Community in the coming years. Here also the aim is to reduce production costs of what may be regarded an an industrial process. The research, for which $14 million has been allotted, will be performed under contract.

## Treatment of radioactive waste

The problem of disposing of radioactive waste from reactors must be solved. This is all the more important in an area like the Community where the population density is high and where vast areas of desert, such as those found in the USA, are not available for the stocking of waste materials. Apart from the demands of public safety, it is also essential to put these operations on the best possible economic footing.

During the first five-year period, the Commission participated in research for the design and construction of a furnace in which liquids impregnated with the residues from decontaminated waste could be burnt. This research has not yet yielded the results hoped for and, for the second five-year program, the task remains of finding out how this can be done most effectively.

Euratom plan to have this work undertaken by research teams already in existence in the Community, though industrial concerns will also participate when possible. It has allotted $5 million to these studies.

## Nuclear ship propulsion

Although nuclear ship propulsion is not yet an economic proposition, this field of research cannot be neglected and several studies for using reactors as power plant in ships have been started in Europe. Euratom's rôle is to coordinate this work so as to avoid wasteful duplication and to give backing to the more promising of the research projects.

Euratom's participation in ship-propulsion research is taking place under association contracts, of which four have been concluded during the first five-year period. They cover three marine-reactor projects:

- a German project for an organic-moderated and organic liquid-cooled reactor suitable for a specially designed experimental vessel;
- a Dutch pressurized-water marine reactor;
- an Italian project for a draft design for a nuclear-powered tanker, using the most promising available reactor.

The sum of $7·5 million has been allocated for continuation of these studies during the second research period.

## Controlled thermonuclear fusion

While fission energy is produced from the splitting of atomic nuclei, nuclear fusion involves a combination of two light nuclei (hydrogen, deuterium or tritium) to form a heavy nucleus, thus releasing vast amounts of energy. There is probably still a great distance to go before thermonuclear power stations can be built, and the research is consequently of a long-term character. Euratom's work is being done under association contracts with the French atomic authorities at their Fontenay-aux-Roses laboratories, at the German *Institüt für Physik und Astrophysik* at Munich, with the Italian atomic energy authority at the Frascati centre and with the Dutch Institute for Plasma Physics. A fifth association contract is planned with a second centre in Germany. Euratom is not only directly involved in the research, but is also coordinating the projects. It has allocated $31 million for the fusion program.

## Radioisotopes

Radioisotopes are elements (gold, cobalt, phosphorous, iodine, etc.) which have been made radioactive through insertion in an atomic reactor. They can be of great value in biological research, medicine, agriculture and industry, in which their use has already brought about substantial financial economies. Euratom has already set up a Radioisotope Information Bureau which distributes information on the ways isotopes can be used in various industries. It has also begun to set up a collection of marked molecules to enable users to have access to certain variants not yet obtainable on the commercial market.

During the second program, this work will be expanded and research will be undertaken on the preparation of new radioisotopes.

Euratom has set aside $5 million for this work, which will be done mainly under contract.

## Health protection and biology

The main priority in Euratom's biological research program, which will be carried out principally under association contracts with national institutions, will be research into the effect of radiation on living bodies. The most important research fields under this heading are:

- problems of diagnosis – for example through hematological examination – and the treatment of radiation effects by bone-marrow transfusion;
- the genetic risks of radiation for human beings;
- statistical studies of the after-effects of radiation on human beings;
- the absorption, retention and elimination of certain radioisotopes by animals, with the aim of defining precise tolerance levels;
- the movements of the most important radioisotopes in the atmosphere, sea, surface waters and plants in order to obtain a better understanding of contamination risks;
- the improvement of protection equipment and the perfection of instruments and apparatus to measure the degree of radiation absorbed by individuals.

Research into the application of nuclear techniques to agricultural problems will be directed towards improving vegetable specimens by radiogenetic methods and, subsequently, towards the preservation of foodstuffs by irradiation. In the medical field, the program will concentrate on the development of new therapies.

Health protection and biological research will together receive $17·5 million.

# THE WAY AHEAD

Euratom's extended research and training program is closely related to Europe's future nuclear energy needs as first defined by the Commission in 1959.

Euratom's third Annual Report forecast that Community power requirements would increase fourfold in 20 years and would thus total 950,000 million kWh in 1980. Of this, 461,000 million would be provided by the most economic means, whatever these might be.

Experts are convinced, however, that in the long term, atomic energy will have to satisfy a large part of the ever-growing demand for electricity and that by 1970 at the latest nuclear electricity will be available at prices competitive with those of the cheapest alternative sources. Once this stage has been reached, investment in nuclear power plants will rise rapidly, and Euratom estimates that a total nuclear capacity of 40,000 MW will be at the Community's disposal by 1980.

These are the considerations which determine the choice of reactor types to be developed in the short and long term. Euratom considers it inadvisable to concentrate all its research efforts on long-term projects (*i.e.* projects of the most advanced type). A solution of this nature would jeopardize the development of the Community's nuclear industry which is at present based on the development of "conventional" reactor types. Further work on the latter is consequently essential to the development of a large-scale nuclear power industry. Euratom has therefore tried to maintain a proper balance in its 1963-67 program between short- and long-term research. It aims at putting nuclear energy on an economic footing as soon as possible through conventional reactors, while at the same time laying plans extending well beyond the stage of mere ability to compete with conventional sources of power.

## The first stage

Euratom's main short-term objective is to put nuclear power on an economic footing. This necessarily involves the development of the known reactor types which, in the present state of knowledge, hold out the best hope of industrial application.

The outstanding examples are the gas-graphite reactors of which experience has been gained primarily in France and Great Britain (where up to 4,000 MW of capacity is in operation or being installed) and light-water reactors developed in the United States (over 1,800 MW in operation or being installed).

Euratom has attempted to stimulate technical and industrial developments on these reactors in several ways. Firstly, during the first five-year period, the Community actively participated in research on these reactor types, especially those of American design. A major contribution was made to this project by the US-Euratom Joint Research and Development Program, which started in 1959. This program covers a 10-year period and will thus remain in force during the whole of the second five-year period. The fundamental aim of research under the US-Euratom program is to achieve lower nuclear power costs, mainly by improving structural materials and fuels.

Euratom also endeavours to promote the industrial use of the reactor types concerned. The US-Euratom agreement, for example, covers a $350-million joint power program, aimed at building a series of American-designed nuclear plants with a total capacity of 1,000 MW, by the end of 1965. This program is backed by US assistance with fuel supplies and a substantial financial loan. Three power projects have so far been included in the program.

In addition, Euratom is providing $32 million from research budget funds towards the construction and initial running costs of a number of power plants, and is contributing to the cost of the initial fuel charges if the plants are manufactured in the Community. In return, the Commission has access to all technical information relating to design, construction and initial operational problems. Participation contracts have already been drawn up with two Italian enterprises, SIMEA (gas-graphite reactor), and SENA (pressurized-water reactor), and with a Franco-Belgian enterprise SENN (boiling water reactor); other contracts are to be negotiated in the near future.

## The second stage

For longer-term development, Euratom is concentrating its main effort on three types of reactors which appear to be particularly promising over the longer term: the Orgel program, fast-neutron reactors, and high-temperature gas reactors.

The Orgel program is based on a method which seems particularly appropriate for medium-term projects in Europe as it uses natural uranium fuel, and the fuel cycle is relatively simple. Fuel costs should be no higher than those for current reactor types, and investment costs should be even lower. This program should therefore dovetail well with national medium-term programs – for example, research on organic liquids and the development of fuel elements for use in all-organic reactor technology. Moreover, certain Orgel research work is of general interest for all kinds of reactors. The studies on carbides, for example, will be of equal benefit to fast and to advanced gas reactors.

The advantages of high-temperature gas reactors are numerous (better neutron economy, for example), but there is still much work to be done in investigating the large number of unknown quantities. Studies are now under way in the U.K. (the Dragon project, in which Euratom has been participating since 1959), in Germany by the firm of BBC-Krupp, and in the United States by General Atomics. Euratom's main function is to ensure that the Community's work in this field is coordinated.

Fast and "breeder" reactor techniques are extremely closely linked. Apart from producing additional quantities of fissile material as part of the operating cycle, fast breeder reactors have the further potential advantage of compactness. This should help to reduce both investment and fuel costs.

The ideal fuel for these plants would be plutonium, which will be produced cheaply and on a large scale by the first-generation reactors operating on natural uranium. Over the much longer term, fusion offers the prospect of an inexhaustible source of power – sea water. Here, too, Euratom is playing its part in seeking solutions to the mammoth technological problems involved.

# APPENDIX

## A simplified explanation of nuclear reactors

The basic principle of producing electricity in nuclear power stations is simple enough. An atomic reactor provides heat obtained from the controlled disintegration of its fuel (uranium), and the heat thus produced merely needs to be harnessed to feed a turbogenerator. (Similarly, it can be made to turn the screw of a ship).

There are many difficulties in actual practice, however, and in addition many different combinations are possible in the design of an atomic reactor. These possibilities must be explored to determine those best suited to the requirements and capacity of European industry. The main variables are the fuel, the coolant, the moderator and the heat exchange system, as well as the shape of the nuclear charge on the one hand and the layout of the moderator, coolant, monitoring equipment, etc., on the other.

The fuel used in almost all nuclear reactors at present is based on natural uranium (only 1/140 of which is fissile U235) or "enriched" uranium (in which the U235 element has been artificially raised).

While the use of enriched uranium permits important reductions in the dimensions and equipment of the reactor, extremely expensive plant is required for its preparation. At the present time there is no isotope-separation plant in Europe in which nuclear fuels based on enriched uranium can be manufactured (although a factory for this purpose is being built at Pierrelatte in France).

Natural uranium, on the other hand, while having the disadvantage of requiring large reactors, is readily available in Europe. The Euratom Commission therefore considers research into the development of natural uranium-fuelled reactors to be of major importance.

The shortage of supplies of enriched uranium is also an additional reason for developing the use of plutonium, now produced as a by-product by existing reactor types, as well as for developing the thorium-U235 cycle for use in fast breeder reactors.

The type of fuel is not the only factor affecting the type of reactor chosen, however. The moderator and the coolant are also important factors.

The moderator is a substance which reduces the speed of the neutrons and so increases their chance of causing fission in the nuclei of fissile uranium. It should not be confused with the control rods, which slow down the reaction when necessary and constitute the basic safety element of the reactor. Without the moderator (ordinary or heavy water, for example) too many of the neutrons – which are emitted at a velocity of about 12,500 miles per second – would be captured by the non-fissile nuclei (U238) before having time to cause the fission of the U235 nuclei. A moderator is therefore essential to a natural uranium reactor.

The coolant is used to transfer the heat produced by the reaction process. Reactors developed in the United States (operating on enriched uranium) usually employ boiling or pressurized water as a coolant. (The temperatures reached in reactors of this type are in the order of several hundred degrees centigrade). In the natural-uranium reactors developed in Great Britain and France, a gas (usually carbon dioxide) is used to transfer the heat. The use of organic liquids obtained on an industrial scale from coal and petroleum offers a number of advantages, including low cost and a relatively high boiling point.

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Printed for the Information Service of the European Communities by Edwin Snell & Sons Limited of Yeovil, England