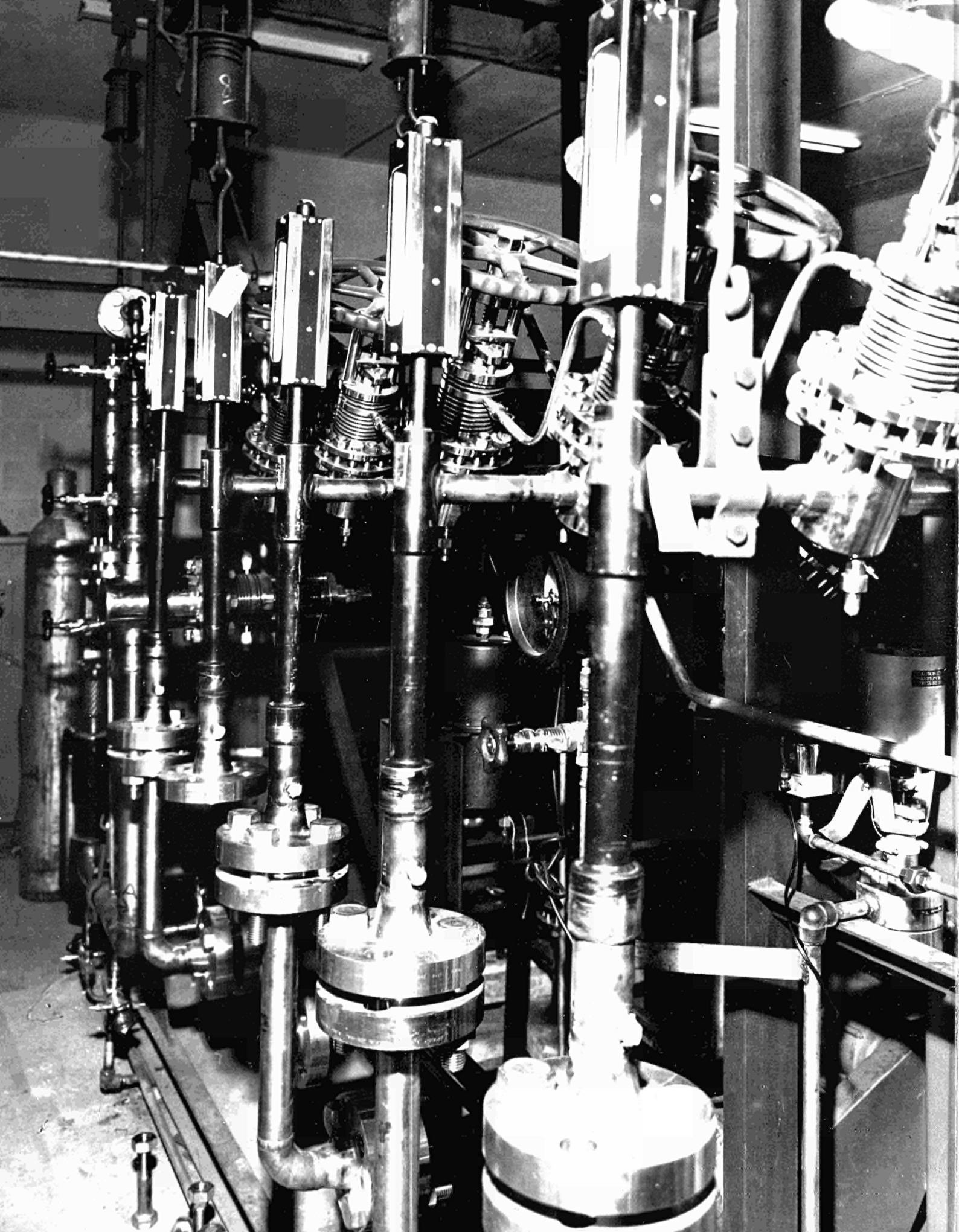
euratom

BULLETIN
OF THE EUROPEAN ATOMIC
ENERGY COMMUNITY

March 1964 **1**



Quarterly Information Bulletin of the European Atomic Energy Community (Euratom)

1964-1

Contents:

Edited by:

Euratom, Dissemination of Information Directorate,
51-53 rue Belliard, Brussels.
Telephone: 13 40 90

Published by:

A. W. Sythoff, Leiden, Netherlands

For subscription rates please see overleaf.

◀ *Test sections of a pressurised water loop (SERAI Company, Belgium)*

Cover: ... the landscape of corrosion ... *(see page 22)*

Picture credits: Inside front cover: SERAI (Belgium); page 13: CEN, Grenoble (France); pages 15-17: Euratom, Joint Research Centre Ispra/Ulrich Zimmermann; pag 31: Mazo, Paris; page 32: Information Service, Ministry of Agriculture (Netherlands); page 3 of cover: Spirale, Paris; Euratom, Joint Research Centre Ispra/Ulrich Zimmermann.

Quarterly

Five editions:

English, German, French, Italian and Dutch

Yearly subscription:

United Kingdom 18/—

United States $ 3.50

Western Germany DM 10.—

France F 12.—

Belgium B.fr. 125.—

Italy Lit. 1500

Netherlands *f* 9.—

Single copies:

United Kingdom 6/—

United States $ 1.—

Western Germany DM 3.—

France F 4.—

Belgium B.fr. 40.—

Italy Lit. 500

Netherlands *f* 2.75

Printed in the Netherlands

Quarterly Information Bulletin of the European Atomic Energy Community (Euratom)

1964-1

The Community's mission is to create the conditions necessary for the speedy establishment and growth of nuclear industries in the member States and thereby contribute to the raising of living standards and the development of exchanges with other countries (Article 1 of the Treaty instituting the European Atomic Energy Community).

It is the fate of all those who live from hand to mouth to be faced periodically with the realisation that their resources will simply not meet their needs. This has given a certain lustre to the art of making ends meet, which consists in arriving at a sober appreciation of both needs and resources, and by dint of compression of the former, or expansion of the latter, or both, to reach a state of equilibrium.

The world's growing need for energy has dictated the development of nuclear power on a large scale. It is consequently not irrelevant to try and assess the world's resources in uranium, the essential raw material of nuclear power at the present stage of our technical development, and to examine their ability in the long term to cope with the requirements of power plants.

Such an assessment has, in fact, been made recently by the Consultative Committee of Euratom's Supply Agency, and the report on their findings was published in October 1963. It will be apparent to the readers of this report (of which a summary is given in this issue), that it was inspired by realism and that its authors were determined to avoid being guilty of complacency.

There is however no question, in the report's conclusions, of any threat to the development of nuclear energy for lack of fuel. On the other hand it brings out the necessity of solving certain problems, some of them peculiar to Europe, if cheap uranium supplies are to be ensured on the long term.

The economic outlook for proven-type power reactors

HANS MICHAELIS, *Director, Euratom Economy Division*

The memorandum on energy policy submitted to the Council of Ministers by the European Executives on 25 June stated that: *Nuclear energy has now passed beyond the experimental stage and will continue to advance. The next few years will see a constant increase in its importance as a solution to the problem of ensuring energy supplies and reducing costs.*

The Report published in December 1962 by the three European Executives as a result of the survey carried out on the Community's long-term energy prospects came to the following conclusion:
In the light of the available data, there is every reason to assume that as from 1970 large nuclear power plants will be economic for base load duty.

In connection with the efforts of the Council of Ministers to define a common energy policy, this report, and in particular the above-quoted conclusion, was thoroughly vetted by a team of national experts, which in May 1963 issued the following statement:
There is complete agreement within the team with regard to the views expressed in the report concerning the outlook for nuclear energy, some members feeling them to be even somewhat cautious.

On what grounds are these optimistic estimates founded?

Documentary information

Under the terms of the Treaty, it is Euratom's responsibility to keep interested parties periodically informed about the current situation and likely future trends with regard to the cost and profitability of nuclear energy, thus fostering initiative in this field and facilitating a harmonious investment policy.
In the pursuit of this task, the Euratom Commission keeps a constant surveillance over all the factors affecting the present and future situation with regard to nuclear power costs. It is aided in this work by an extensive body of material and data:
(1) The Community has a 32 million EMA u.a.[1] share in the construction of five power reactors having a total net power of 900 MWe. In this way it hopes to promote the construction of nuclear power plants on an industrial scale and to give a boost to the nuclear industry in Europe. Under these contracts of participation, provision is made for the supply and dissemination of the information stemming from their execution, this provision likewise applying to all data relating to costs.
(2) Cost information is also submitted to Euratom by those energy producers in the Community which are building and operating nuclear power plants not covered by the programme of participation, in particular *Electricité de France*.
(3) Under the terms of the agreements for co-operation drawn up with the *United Kingdom Atomic Energy Authority (UKAEA)*, the *United States Atomic Energy Commission (USAEC)* and *Atomic Energy of Canada Ltd. (AECL)*, the Euratom Commission obtains data on the costs relating to power plants which are in operation or are in the construction or planning stage in those countries.
In collaboration with the two other executives in the Interexecutive Working Group on Energy Policy, the Euratom Commission was able to incorporate this information concerning the present and estimated future nuclear power costs in an assessment of the Community's energy economy as a whole, thusdetermining the place to be occupied by nuclear power in the overall gamut of energy sources.

Problems of comparability

Only a few nuclear power plants are in operation as yet, so our views on the present position and future cost trend are based chiefly on electricity-generating cost forecasts for nuclear power plants now in the construction or planning stage. These findings are, however, not unchallenged, since the estimated electricity-generating cost depends on the calculation method employed as well as on certain technical

1. 1 EMA unit of account (u.a.) = 1 US-Dollar

and economic factors which, having a decisive influence on the future development of nuclear energy, must be established beforehand in spite of the fact that it is as yet impossible to assign any hard-and-fast values to them.
They include:
— the final direct and indirect total capital costs;
— the annual capital cost, i.e. depreciation, interest, capital yield taxes and insurance;
— the estimated life of the power plant;
— the estimated annual utilisation time;
— the average burn-up of the fuel elements in the first and subsequent cores.
The profitability of nuclear power plants will be contingent on the price trend followed by conventional electricity. These prices are in turn dependent on the cost of constructing conventional power plants, the cost pattern of the fossil fuels used in them, in particular coal and oil, and their thermal efficiency.

Table I

Annual capital cost as % of invested capital	Annual utilisation	
	6,000 h	7,000 h
8.1%	5.4 mills/kWh	4.9 mills/kWh
10 %	6.0 ,,	5.4 ,,
13 %	7.0 ,,	6.3 ,,

Proven-type reactors

In its quest for an answer to these queries, the Euratom Commission keeps up a constant exchange of ideas and information with experts in this field, and has repeatedly discussed the matter with the government representatives dealing with energy affairs, building contractors and electricity producers, at the same time bringing up for examination the methods used in its own investigations and the results obtained from them.
The most recent and far-reaching example of such a meeting was the symposium arranged by the Euratom Commission in Venice from 29 to 31 October 1963 on the technical and economic aspects of reactor development. This symposium, which was most successful, was attended by experts representing the nuclear energy authorities, reactor construction industries and electricity industries of the Community Member States. The purpose of the meeting was to create the atmosphere for a cross-fertilisation of ideas on the present position and estimated future trend with regard to the cost and profitability of proven-type nuclear power plants.
Under the terms of the appropriate convention, these include:
— the graphite-moderated and carbon-dioxide-cooled natural uranium reactors developed in Britain and France;
— the light-water-moderated and -cooled reactors developed in the US, which run on slightly-enriched uranium, i.e. pressurised-water reactors (PWR) and boiling-water reactors (BWR).
Both these groups can be regarded as proven, since adequate technical experience has now been gained from their construction and operation. At the present time power plants of these two types already account for an output of 2,200 MWe in the western world, while another 5,600 MWe is in the process of being installed; plants for the generation of a further 4,100 MWe are projected and construction is in some cases already under way. Of the present total nuclear energy capacity of the Community (2,585 MWe), 1,505 MWe, or 58%, are obtained from the graphite-gas type and 935 MWe, or 36%, from the light-water type; the remaining 145 MWe, or 6 %, are mainly generated by the heavy-water-moderated reactors.
These reactor types can also be regarded as proven for the reason that at the present time construction firms are to a great extent able and willing to make binding estimates for the erection, on a turn-key basis, of the ready-to-operate nuclear power plant, and also—but to a more limited degree—to offer guarantees concerning the output, life and other factors determining their profitability.

Basis of calculation

The first main subject dealt with at the symposium was the method to be adopted for calculating the cost of generating electricity in nuclear power plants. The following findings are worthy of note:
(1) The gross capital costs taken as the basis of the calculations include both direct and indirect costs. The former are made up of the cost of the site, the site-preparation and construction work, the auxiliary plant, the turbogenerator set and the energy offtake, together with the reactor construction costs (incl. primary circuit and heat exchangers) plus moderator and coolant, but without the cost of the initial fuel charge and the spare fuel. The indirect costs include the engineers' fees, general and administrative charges, construction interest up to commissioning, possible price increases up to this point, customs duties,

Table II

High-output nuclear power plants which will be ready for commissioning by the end of this decade will produce electricity at the same cost as coal- or oil-burning plants, coming into service at the same time, which are supplied with fuel at the following prices per ton of coal equivalent (7000 kcal/kg) free at plant:

at an annual capital cost, as a % of invested capital, of	annual utilisation time	
	6,000 h	7,000 h
8.6%	10.1 u.a./t	9.6 u.a./t
10 %	10.8 u.a./t	10.2 u.a./t
13 %	12.1 u.a./t	11.3 u.a./t

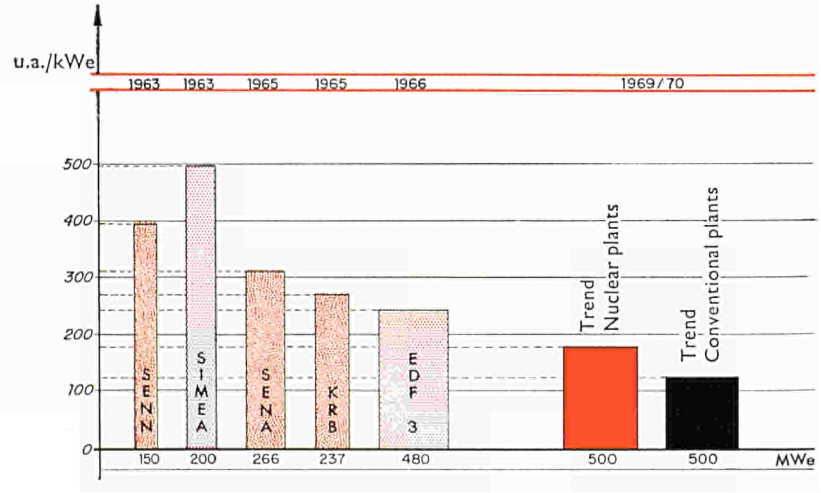
Fig. 1
— Power reactors in the Six (surface areas marked proportional to power):
— black: reactors in operation
— red: reactors either projected or already under construction (to be completed before 1967)

indirect taxes and contingencies. The capital costs should be taken to refer to the net output.
Gross capital costs of 125 u.a./kWe were regarded as representative of new high-output power plants running on coal and oil.
(2) The capital costs should be spread over the entire operating life of the plant in equal yearly sums, which should include the interest on outside and own capital resources, linear depreciation, expenditure for property and capital yield tax and insurance premiums or amounts set aside for self-insurance.
Power generation in France is exempt from capital yield tax, so that EDF reckons on a yearly rate of 8.1%. For the German Federal Republic and Belgium, this must be set at about 13%, about 4% of which represents capital yield taxes. No definite conclusions can at present be reached in the case of Italy on account of the nationalisation of the power-producing industry, but a hypothetical figure of 10% is adopted. The same rate is applied for the Netherlands.
(3) The fuel cycling costs should be based on steady-state operation and should include both the capital charges for the fuel, which are independent of the amount of energy produced, and also the costs for consumed fuel, which are proportional to the energy produced. Allowances being made for estimated technical and economic developments, reasonable values should be fixed for the carriage of fuel elements and for their insurance in transit, the chemical reprocessing and the reconversion of uranium and the conversion of plutonium.
(4) The running and maintenance costs should include salaries, spare parts, materials used for routine servicing, moderator and coolant losses and administrative overheads.
(5) Owing to the low fuel costs, the estimated annual utilisation times for nuclear power plants in the Community will be between 6,000 and 7,000 hours.
Taken as a whole, the Venice Symposium revealed that there is a considerable degree of unanimity with regard to methods of calculating the cost of producing electricity in nuclear power plants.

Electricity-generating costs

An analysis of these cost data for proven-type nuclear power plants now in operation or in the construction or design stage reveals a downward trend which, only a few years ago, would have seemed improbable. At the same time it is as yet impossible to determine which of the two reactor groups is, generally speaking, more economic.
The capital costs for high-output graphite-gas power plants are moving toward a figure of 200 EMA u.a./kWe, which is quite feasible in the case of a plant scheduled for startup in 1970. On the basis of the prices obtaining in July 1960, the direct capital costs for the EDF 3 480 MWe nuclear plant, including added value tax, total 204 EMA u.a./kWe. If all the other indirect costs are included, a cost of 267 EMA u.a./kWe is obtained.
In the case of light-water plants, capital costs of under 200 EMA u.a./kWe can even be expected, as can be seen from the tenders

Fig. 2 - Overall nuclear power plant costs



submitted in the Community by American reactor construction companies. On a firm price basis, including all indirect costs, in particular construction interest, the 237 MWe KRB nuclear power plant now under construction in Gundremmingen (Southern Germany) costs 302 EMA u.a./kWe. The technical advances since, coupled with a stepping-up of the rated output to at least double the present figure, will bring about a cut in capital costs to below 200 EMA u.a./kWe, as indicated above.

The graphite-gas plants have lower fuel costs. By taking as a basis a uranium price of $8/lb ($17.50 /kg) and a perfectly feasible burn-up of 3,500 MWd/t of uranium, a fuel cost of 1.75 mill/kWh is obtained for the EDF 3 reactor.[2]

In the case of light-water reactors, fuel costs of about 2.4 mills/kWh are expected for the KRB reactor, the cost estimate being based upon the present AEC pricelist with a plutonium buy-back price of $ 9.5/g.

For nuclear power plants which can start producing electricity by the end of this decade, the estimated power-generating costs which are shown in Table I and which roughly coincide for both reactor strings, are thus obtained (see Fig. 4).

It would appear that the light-water reactors, which are somewhat cheaper to build and more expensive to run, are favoured by the capital yield tax in the German Federal Republic and Belgium, while the fact that electricity generation is not subject to this tax in France and the Netherlands is a slight advantage in those countries on the side of the graphite-gas type reactors, which are more expensive to construct and cheaper to operate.

These cost forecasts were first mentioned in the Survey Report published in December 1962 by the Interexecutive Working Group on Energy Policy concerning the Community's long-term energy prospects. The Venice Symposium, which was in possession of the latest cost data, confirmed these estimates in view of the generally accepted assumption that there would be an appropriate reduction in operating and maintenance costs and insurance premiums.

Guarantees

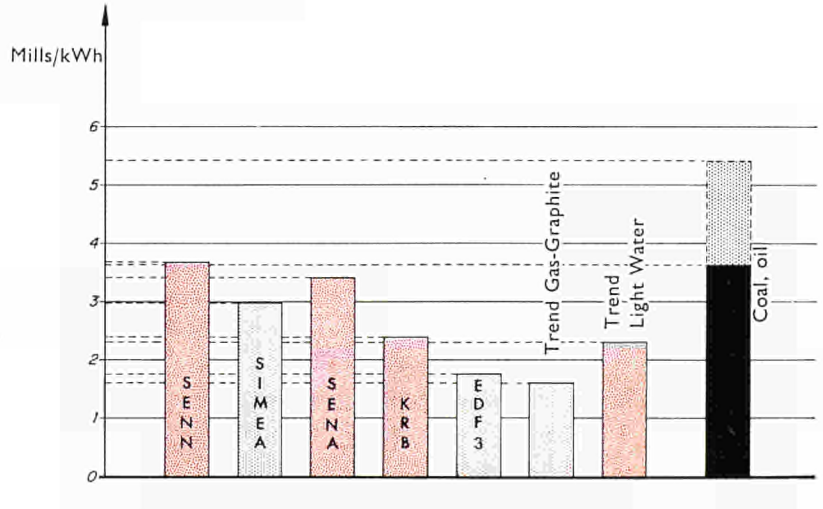
One of the thorniest problems encountered in comparisons of nuclear electricity-generating costs is bound up with the guarantees and warranties provided by the constructor and fuel element manufacturers with regard to plant operation. The situation is complicated by the fact that in certain countries, such as Germany, contracts are normally concluded for the construction of nuclear power plants on a firm-cost, turn-key basis, whereas in other countries, especially France, the electricity producer the *Electricité de France*, carries out its own design work and only farms out those items which would normally be covered by sub-contracts.

The first thorough analysis, which was based on the contracts notified to the Euratom Commission concerning the five power plants in which it is participating, revealed a surprising variety on the part of the guarantees, which broke down as follows:

— for general operational characteristics, such as low-power conditions, control, stability, flexibility etc.;
— the net output of the power plant;
— the thermal efficiency or heat consumption;
— the fuel or fuel cycle;
— the delivery time;
— the power availability;
— the total operating and maintenance costs.

The Venice Symposium demonstrated clearly that the electricity producers ask for as many guarantees as possible, while the reactor constructors and in particular the fuel element manufacturers are, for financial reasons, restricted in their ability to meet these demands. The general picture obtained was that the whole system of guarantees is much too intricate for suitable allowance to be made for them in comparisons of costs and prices.

Fig. 3 - Nuclear plant fuel costs



Nuclear power — its chances of becoming competitive

In the forthcoming phase of the struggle to become competitive with conventional power, nuclear energy must continue to forge ahead. Such aspects as dependability of power supplies and optimum exploitation of the limited sources of primary energy available will not assume major importance until later.

Both in the relevant section of the third General Report of April 1960 and in the above-mentioned Survey Report of December 1962 on the Community's future energy prospects, the Euratom Commission compared the estimated costs of producing nuclear electricity with the future cost of power obtained from coal and oil.

Coal and oil are the only primary energy sources production of which can be stepped up in a proportion sufficient to meet the

2. 1 mill = $ 1/1000

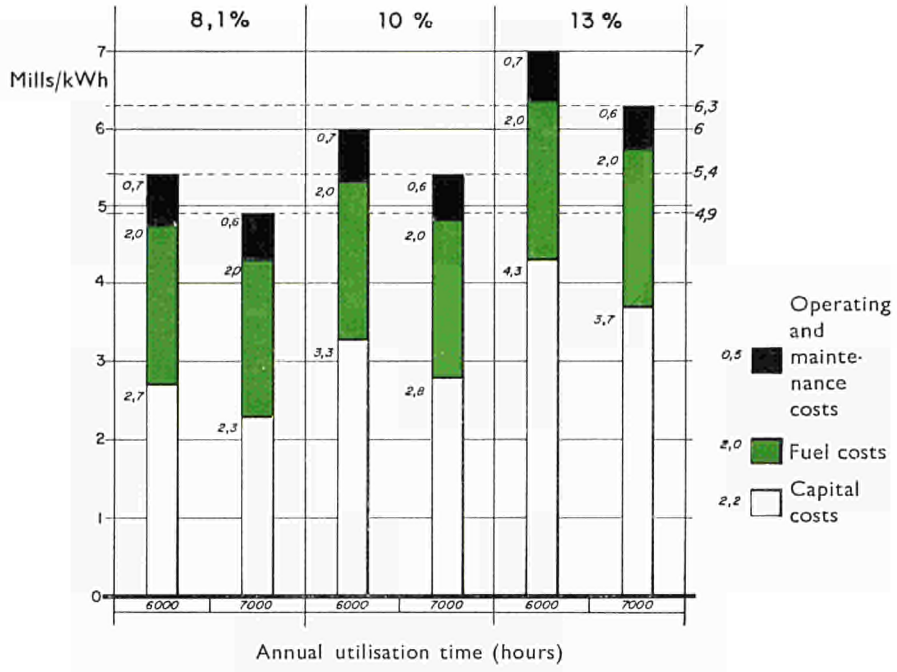


Fig. 4 - Prospective electricity-generating costs of large-scale nuclear power plants which will be ready for commissioning by the end of this decade

rapidly increasing demand for electricity, which is estimated to double every ten years.

These investigations show the competitive position (Table II) of those nuclear power plants which will be ready for commissioning by the end of this decade.

The Community's coal is now costing 14-15 EMA u.a./t at the pithead, while imported coal from the US costs an average of 12-13 EMA u.a./t c.i.f. in European ports, and fuel oil is delivered from the refineries at an average price of 10.50-12 EMA u.a./t coal equivalent, not including the substantial taxes, which at present amount to over 4 EMA u.a./t. As the Interexecutive Working Group on Energy Policy observed in its memorandum of 25 june 1962, these prices are hardly likely to fall much in the future and may even go up.

It can thus be assumed, as stated in Euratom's Sixth General Report, that large nuclear power plants in the Community countries will be on a more or less competitive footing by 1970, given an annual utilisation time of over 6000 hours. Since a further drop in production costs is likely in the years following that date, nuclear power plants will probably prove competitive even at a lower annual utilisation time, so that they can be used to a correspondingly greater extent. This finding was confirmed by the Venice Symposium.

At the same time it is unlikely that nuclear energy will make a revolutionary breakthrough into the ground now held by conventional electricity generation. Mr. de Groote, Member of the Euratom Commission, told the European Parliament in Strasbourg on 27 June 1963 that even assuming the most favourable developments in the production of nuclear energy, the amount of fossil fuels needed for the generation of electricity, such as coal, oil and natural gas, will increase fourfold between 1960 and 1975, so that nuclear energy poses no threat to the coal industry.

The Reactors of tomorrow

So far only the cost and profitability prospects of the two proven reactor strings — gas-graphite and light-water reactors — have been dealt with. Reactors of these two types will certainly predominate up to 1980. Two features distinguish the efforts made to develop advanced-type reactors, i.e. heavy-water-moderated reactors, gas-cooled high-temperature reactors, organic-moderated reactors and spectral shift reactors. These features are:

— the endeavour to bring about a further reduction in electricity-generating costs, particularly by stepping up the burnup and raising the steam temperature; this cuts the fuel cycle costs and also leads, owing to a more compact geometry, to a reduction in the specific plant costs;

— the attempt to use a greater proportion of uranium's fission energy. The proven-type reactors utilise only about 1% of this energy.

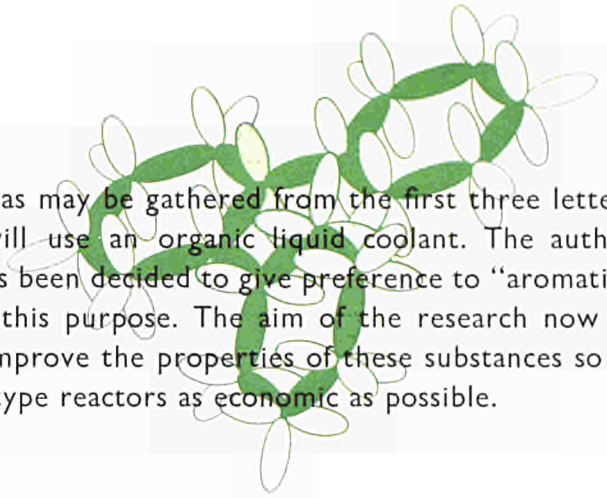
The prospective cost trend of the above-mentioned advanced-type reactors is generally more favourable than that of the proven type, but considerable efforts will still be required to make up the leeway left by the technical progress achieved in the development of the proven type. On the other hand, the attempt to achieve a more rational utilisation of the limited uranium supplies which can be obtained at low cost militates in favour of the development of advanced reactors having an advantageous neutron economy. The specific uranium requirement of heavy-water-moderated reactors, for instance, is only half that of proven-type reactors.

Breeder reactors

As far as can be seen at the moment, the ultimate objective pursued in power reactor development is the fast breeder, a reactor type which uses the fission energy of uranium at a rate many times higher than the present level and which, as stated by the Chairman of the *United States Atomic Energy Commission* in his "Civilian Nuclear Power — a Report to the President", published in 1962, is capable of solving the world power supply problem once and for all. For this reason breeder development is one of the focal points of the Euratom Commission's research and development programme.

For many years to come, thermal reactors — first of all proven-type and later advanced-design plants — will be the main suppliers of the plutonium required to start up breeder reactors. The breeder reactor system is now gradually developing and will probably predominate one day, but it will be a very long time indeed before this type of reactor can supply its own plutonium. Advanced reactors, and particularly heavy-water-moderated reactors, are also very useful in this connection, i.e. the provision of plutonium, so that this reactor type occupies a key position in Euratom's research and development programme.

The price that can be paid for the plutonium needed to start up breeder reactors is a salient factor in determining the profitability of the proven-type reactors which are being built and operated and of the projected advanced-type reactors, so that the prospective cost and profitability trend of proven-type power reactors is also contingent on the long-term development outlook for nuclear energy.



Orgel reactors, as may be gathered from the first three letters of the word, will use an organic liquid coolant. The author shows why it has been decided to give preference to "aromatic" compounds for this purpose. The aim of the research now in progress is to improve the properties of these substances so as to make Orgel-type reactors as economic as possible.

Organic coolants on trial

by MARCEL VAN DER VENNE, *Directorate-General for Research and Training, Euratom*

The Orgel Programme aims at the construction of a heavy-water-moderated "organic-liquid"-cooled power reactor. Some of the problems involved in this project are mainly chemical in character and derive from the use of this type of coolant.

The choice of organic coolants was motivated by the fact that they have a number of very useful properties, notably low vapour pressure, good chemical compatibility with standard structural materials, very slight tendency to activation by irradiation, and usability at temperatures far above 300°C. On the other hand, they are decomposed by heat and irradiation, so that an attempt must be made to obtain an accurate idea of the various facets of this phenomenon as it arises in the conditions obtaining in power reactors.

Organic liquids compared with other liquid coolants

At the present time, water is the liquid most commonly used as a coolant for nuclear reactors. The pressures used range from 60-70 atmospheres in a boiling-water reactor to approximately 140 atmospheres for a pressurised-water reactor. In either case the temperature remains below 300°C. It is thus seen that with organic fluids much higher working temperatures can be attained than with water (in the Orgel string reference design, an outlet temperature of 400°C was adopted) which brings about a corresponding gain in the plant's thermal efficiency. Furthermore, because of the organic liquids' low vapour pressure at these temperatures, working pressures of the order of 20 atmospheres are adequate. In consequence, less material is needed to contain them. Finally, the good compatibility of organic liquids with, for example, ordinary steel means that there is no need to use "nobler" materials such as stainless alloys.

Even more caution is required in the choice of materials when liquid metals are considered. Metals can admittedly be used at far higher temperatures still than organic coolants, but they give rise to extremely complex problems, stemming in particular from their high degree of reactivity with a variety of elements.

Organic coolants, then, occupy a midway position as regards the possibilities which they offer, and the problems which they raise are, in the final analysis, confined to their decomposition.

"Aromatic" hydrocarbons

As soon as it was established that organic fluids could be used in a reactor (and this dates back to the time of the basic nuclear energy patents), a great many compounds were subjected to a programme of tests aimed at singling out the most suitable substances.

It was not long before the aromatic hydrocarbons proved themselves to be ahead of all other substances by virtue of their range o properties.

They consist solely of carbon and hydrogen atoms, chemically linked to form cyclic molecules, the most representative of which is benzene C_6H_6 (see Fig. 3).

Their characteristics

It follows that the induced activity is very low, since the hydrogen atom, by absorbing a neutron, becomes a stable deuterium nucleus:

$$ {}_1H^1 + {}_0n^1 \rightarrow {}_1D^2 $$

which then turns into tritium on absorbing a further neutron. The tritium emits very soft β radiation which is arrested by a wall—albeit a very thin one—so that it in no way hampers access to the circuit (this does not, however, hold good as regards possible *contamination* by the tritium, e.g. in the event of a leak). Moreover, the small absorption cross-sections of hydrogen and deuterium, coupled with the fairly long half-life of tritium, mean that the specific activity in tritium is relatively low.

In the case of carbon there is a similar situation, since we have the reactions:

$$ {}_6C^{12} + {}_0n^1 \rightarrow {}_6C^{13} $$
$$ {}_6C^{13} + {}_0n^1 \rightarrow {}_6C^{14} $$

Carbon is likewise a very slight beta emitter, and the only problem that arises is again that of contamination.

Now the radioactivity of a coolant may also

be traceable to the presence, in suspension or in solution, of certain corrosion products. It so happens that the aromatic hydrocarbons are remarkably inert to the leading structural materials, and in particular steels and aluminium alloys. This is a great asset, as these are the materials mainly used in industry.

An examination of the conditions in which organic substances decompose under the influence of heat and irradiation shows that these conditions differ in some measure from those prevailing in an inorganic system, e.g. water.

Whereas the decomposition of water by heat, in which the molecule splits up into its constituent atoms, only takes place at extremely high temperatures ($>$ 1,000°C), hydrocarbons decompose at only a few hundred degrees; these reactions are, indeed, widely used in petroleum chemistry where the process is referred to as "cracking".

Water is also decomposed by radiations, but in this respect organic substances would show up to advantage in any comparison (apart from chain reactions such as polymerisations). However, there is one fundamental difference in that water is a *reversible* system, whereas the decomposition of the hydrocarbons is in most cases an irreversible process. In other words, water can be radiolysed and the hydrogen and oxygen produced can then be recombined either by an electrical discharge or by catalysis; on the other hand, if benzene is radiolysed there is no way of reconstituting it from its decomposition products (hydrogen, methane, polyphenyls).

Pyrolytic or radiolytic decomposition of hydrocarbons has, as its final stage, the formation of carbon and hydrogen, after a host of intermediate products; it will accordingly be necessary to reprocess the coolant in order to eliminate the substances, either too heavy or too light, which would have an unduly marked detrimental effect on the system's physical characteristics.

What happens is that the light substances increase the vapour pressure and, by volatilising at the hottest points (in the Orgel reactor these are the fuel elements) bring about a profound change in the normal heat transfer conditions. The heavy products, on the other hand, increase the viscosity of the mixture and, beyond a certain concentration, may become insoluble and be deposited on the walls.

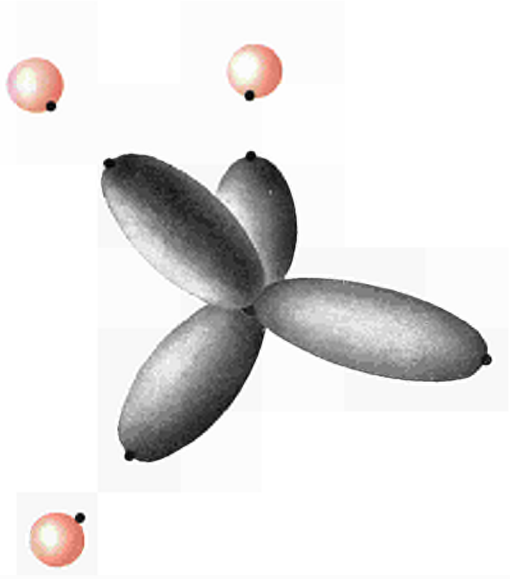


Figure 1a

The tetragonal carbon atom, which exists in aliphatic (or saturated) hydrocarbons, has four identical valencies, which tend to combine with those of other atoms, such as hydrogen, or simply with another carbon atom. . . .

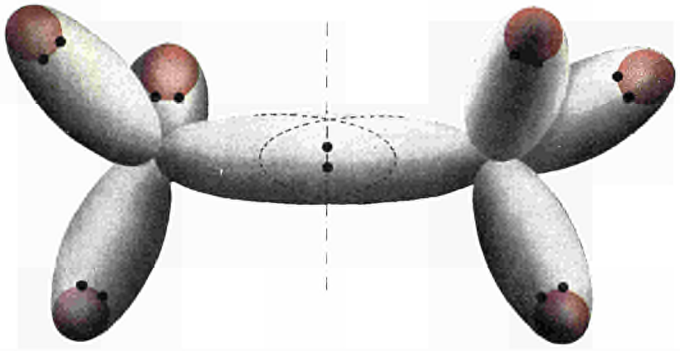


Figure 1b

. . . . so as to form, for example, an ethane molecule C_2H_6. (The figures show in diagrammatic form the surfaces on which the valency electrons will most probably occur).

t is thus seen that only a certain content of decomposition products can be tolerated and that once this value has been reached it is necessary to eliminate these products as they form and replace them by fresh liquid. The choice must therefore be directed to substances having the lowest decomposition rate, always with due regard to the unsuitability of any liquid, even a slowly decomposing one, in which the heavy products do not possess a certain degree of solubility.

Polyphenyls

Experience shows that the aromatic hydrocarbons are, comparatively speaking, very stable in the conditions with which we are concerned here. There is good reason to believe that this resistance to heat and radiation is related to their "aromaticity", more particularly to the special electronic structure inherent in this property (see Figs. 2 and 3).

However, benzene, the simplest of the aromatics, has too low a boiling temperature (80°C at atmospheric pressure). Preference therefore goes to either diphenyl or terphenyl, which, in addition to very good stability, have boiling points of 250°C and 350°C respectively (in the case of Orgel the coolant must have a very high boiling point so that the vapour pressure should be as low as possible, to permit the use in the core of pressure tubes which are relatively thin and thus absorb few neutrons).

The polyphenyls are obtained simply by the "addition" of benzene rings (they are actually obtained by heating, i.e. pyrolysing benzene) of which they have the major characteristics.

We are therefore prompted to choose the terphenyls which, furthermore, have the useful property of being able to retain their breakdown products in solution even when they contain more than 50% of such products.

Some disadvantages of terphenyls

Nevertheless, the terphenyls which are thus seen to be very efficient organic coolants, have certain drawbacks, among which are their relative dearness and the fact that they have a fairly high melting point; the mixtures of the three isomers

Figure 2a

The trigonal carbon atom, which is found in ethylene (unsaturated) hydrocarbons, has three identical valencies (formed by "σ" electrons), the fourth being weaker and of a very different nature (formed by a "π" electron, which may exist with equal likelihood on either side of the plane in which the σ electrons are found). By combining with a second trigonal carbon atom and four hydrogen atoms, it forms . . .

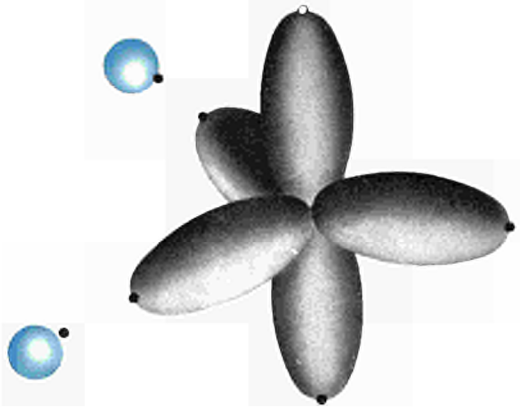
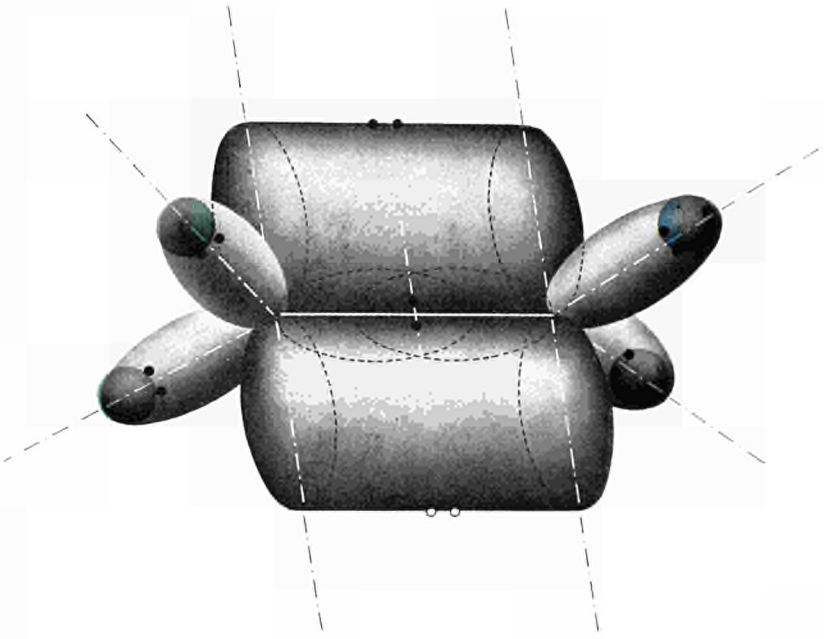


Figure 2b

. . . ethylene C_2H_4. Between the two carbon atoms will be observed the first bond, which is in the same plane as the four C-H bonds, and also the second C-C bond, formed by the combination of the two π electrons.



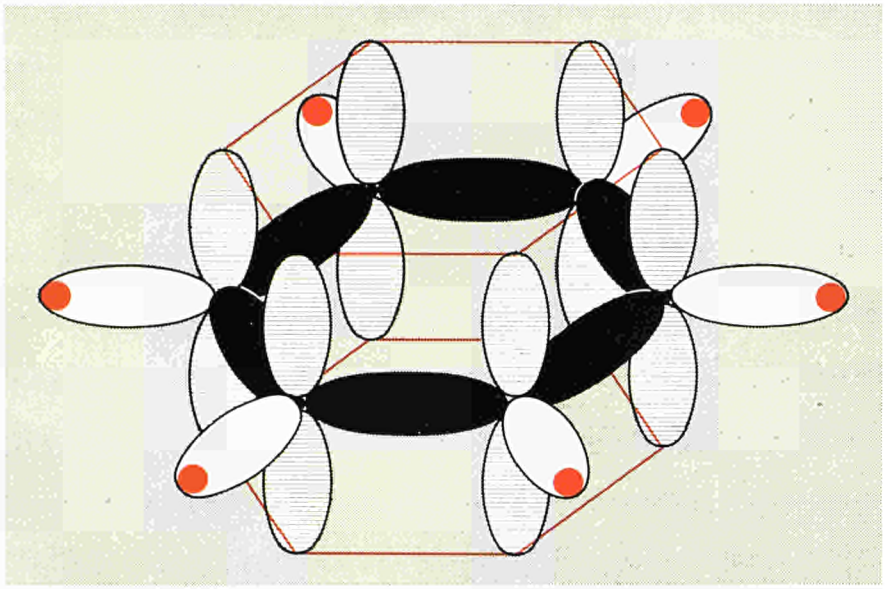


Figure 3
The benzene molecule is formed by six trigonal carbon atoms and six hydrogen atoms. It will be seen that this is a far cry from the simple juxtaposition of three "ethylene" units, since the π electron of a given carbon atom may equally well form a bond with the one on its right or with the one on its left.
The result is a veritable "crown" of π electrons, which may exist with equal probability on either side of the cycle plane. The uncertainty involved in the location of the electrons is a typical feature of "aromaticity". The ease with which the crown can become deformed without destroying the cycle, rather in the manner of a rubber shock-absorber, may account for the stability of the "aromatic" molecules.

(see Fig. 4) are generally solid at room temperature, which means that the overall equipment must be preheated. It should be pointed out that the mixture obtained during fabrication contains nearly 30% of the "para"-isomer and that its melting point is in the region of 150°C. This value may be reduced, to 80°C for example, by decreasing the para-terphenyl content to approximately 4%, but this "enrichment" in "ortho"- and "meta"-isomers adds more than 50% to the price of the mixture! A compromise must therefore be found.

Other possible choices

Consideration has accordingly been given to the rejection of polyphenyls in favour of aromatic hydrocarbon mixtures such as are encountered at certain stages in the oil industry and which are available at low cost. In this case it is felt that a higher decomposition rate can be tolerated (from an economic standpoint, the factor that counts is the *price* of the substance expended), but it is vital that the decomposed mixture should remain homogeneous, and in particular that there should be no coke formation.

To sum up the studies carried out in this field, it may be stated that mixtures are available whose irradiation behaviour is comparable to, or sometimes better than, that of the phenyls but which deteriorate rapidly as soon as the temperature rises appreciably above 350°C. It should be added that these mixtures have been subjected to a number of processes which have improved their properties but at the same time have increased their cost . . .
At the moment there are no experimental data enabling us to settle this question once and for all, but certain oil fractions have a decomposition rate, measured in-pile at 380°C, involving a lower liquid consumption cost than that entailed by terphenyls in identical conditions.
Studies have also been made of other organic materials, containing other atoms alongside carbon and hydrogen (oxygen, nitrogen, sulphur, phosphorus, etc.); in some cases, the induced activity is no higher than that of hydrocarbons, but generally speaking, their stability at high temperature and under irradiation is definitely inferior; moreover, decomposition of some of the systems studied gives rise to corrosive substances.
Other organic derivatives have been suggested, which it is claimed would be more stable than the polyphenyls. Unfortunately, there are virtually no really well-founded data on the physical properties, chemical resistance and the price of these substances, and an enormous amount of work would have to be carried out in order to arrive at a reliable assessment of them.
It must also be borne in mind that it is vitally necessary to be thoroughly acquainted with the characteristics of a coolant before using it in a reactor—and this means that a great many experiments have to be carried out in a great many fields before the reactor coolant system can be confidently stated to be safe.

An original solution: deuterated polyphenyls

Yet another solution, and quite an original one, has been devised for improving the polyphenyls; this idea consists in replacing the hydrogen atoms in the molecules by deuterium. In this way, substances are obtained whose radiolytic stability is distinctly improved and which also absorb far fewer neutrons. This latter property, apart from its influence on the stability of the

molecule, is of capital importance for an Orgel-type reactor, in which it really is necessary to reduce the absorbent materials to a minimum.
The hydrogen contained in the terphenyl surrounding the fuel element and serving to cool it actually represents an appreciable fraction of the neutron-absorbing material of the entire channel. It is accordingly necessary to arrange the fuel-cluster rodlets in such a way that they are as close together as possible and to minimise the quantity of coolant around them.
The substitution of deuterium for hydrogen would make it possible, by improving the neutron balance, to utilise less compact clusters, for which a larger quantity of coolant would be required. This would obviate a number of mechanical and hydrodynamic problems while at the same time increasing the burn-up.
Unfortunately, the use of deuterated coolants is inhibited by their cost. It is furthermore essential, in view of the price of deuterium, to ensure a very low rate of leakage, comparable to that permitted in a heavy-water circuit, and this entails an increase in investments and operating costs. At the present time, the fabrication and utilisation prices of deuterated terphenyls would appear to rule this concept out as a competitive proposition.

Current solution

For the most part, the chemical studies carried out under the Orgel Programme have involved the use of a mixture of terphenyls abundant in "meta"-isomer. This choice is the result of a compromise struck between the prices and melting points of various commercial mixtures, leading to the adoption of one of these mixtures, Progil's OM-2 fluid, some of whose characteristics are shown in the following table:

ortho-terphenyl	80%
meta-terphenyl	15%
para-terphenyl	5%
overall melting point	80°C
boiling point (760 mmHg)	350°C

Special attention is being paid to the definition of the behaviour of this mixture in Orgel-type power-reactor conditions.

RESEARCH IN PROGRESS

Methods of analysis

One of the first tasks of the research workers engaged on organic liquids has been the development of satisfactory methods of analysis. This is because it is necessary to determine the composition of the fluids used and the variation which they undergo in testing. It may now be said to be possible to analyse a mixture for its terphenyl and lighter and heavier products content as well as for the major part of the inorganic impurities present.
Another important job is to improve detection sensitivity for the few mineral substances for which it appears to be inadequate. This is the case, for instance, with oxygen, which may be one of the main factors responsible for fouling. By way of illustration, the impurities content is usually expressed in parts per million, which testifies to the extreme accuracy required in such analyses.
As regards the organic constituents, analysis is carried out for benzene and for polyphenyls having up to six aromatic rings. Strictly speaking, the problem is not solved completely, since although it is possible, beyond the tetraphenyls, to isolate the substances contained in the mixture, it is not possible to identify them all. In addition to determinations of individual substances, methods have been devised which give the overall content in substances with molecular masses higher than that of the terphenyls. One of the major problems of organic analysis is the identification of very heavy substances, such as those which are formed by radiolysis, and here attempts to find a solution are still in progress.

Compatibility tests

At temperatures up to 450°C, the terphenyls have no noteworthy corrosive action on alloy or non-alloy steels, or on aluminium compounds, as long as their water content remains below 500 ppm (parts per million) and no oxygen is present. With graphite, too, no reaction is observed. On the other hand, magnesium, which is sensitive to traces of oxygenated substances (such as water), cannot be used. In the case of zirconium alloys, the position is still more complex as it would certainly seem that, by contrast, the surface film of oxide must not be destroyed and that it should be reconstituted if damaged, a fact which might well make it necessary to specify a minimum water content.
All these studies have still to be amplified so as to take account of the erosion that may be caused by the organic fluid when circulating at high speed.

Stability tests

An accurate idea of the coolant's rate of decomposition is an essential datum for the Orgel string. As is known, this rate varies depending on several factors, e.g. the temperature, and perhaps the composition of the coolant, which also influence the kWh price of power supplied by the plant. Thus, for instance, the gain in efficiency achieved by stepping up the coolant outlet temperature must be set against the higher decomposition rate which will result.
A study is being made of the part played by various parameters in the decomposition rate of the terphenyls. In particular, efforts are being made to distinguish between the heat and irradiation effects as well as to differentiate the action of the γ rays from that of the neutrons, which are the main constituents of the mixed radiations occurring in reactors.
To sum up, everything takes place as though the irradiation of polyphenyls produced relatively long-lived active centres which promoted pyrolytic decomposition. This effect persists, even after irradiation has been completed. The quantitative aspects of the process have still to be clearly defined to allow of an accurate coolant consumption calculation for the various Orgel solutions envisaged.
One of the chief problems still outstanding relates to the determination of the destructive potential of the various radiations. If it is desired to forecast the decomposition which will occur in a given radiation field, it must be possible to assign a certain level of effectiveness to each type of radiation. The temptation exists, for the purpose of these studies, to use several sources each emitting only one type of radiation. The fact is, however, that in the case of γ rays the choice is restricted by the very stability of polyphenyls, the strongest fields available having merely one-tenth of the intensity of those obtaining in in-pile loops, which means not only that the experiments must be lengthy but also that the

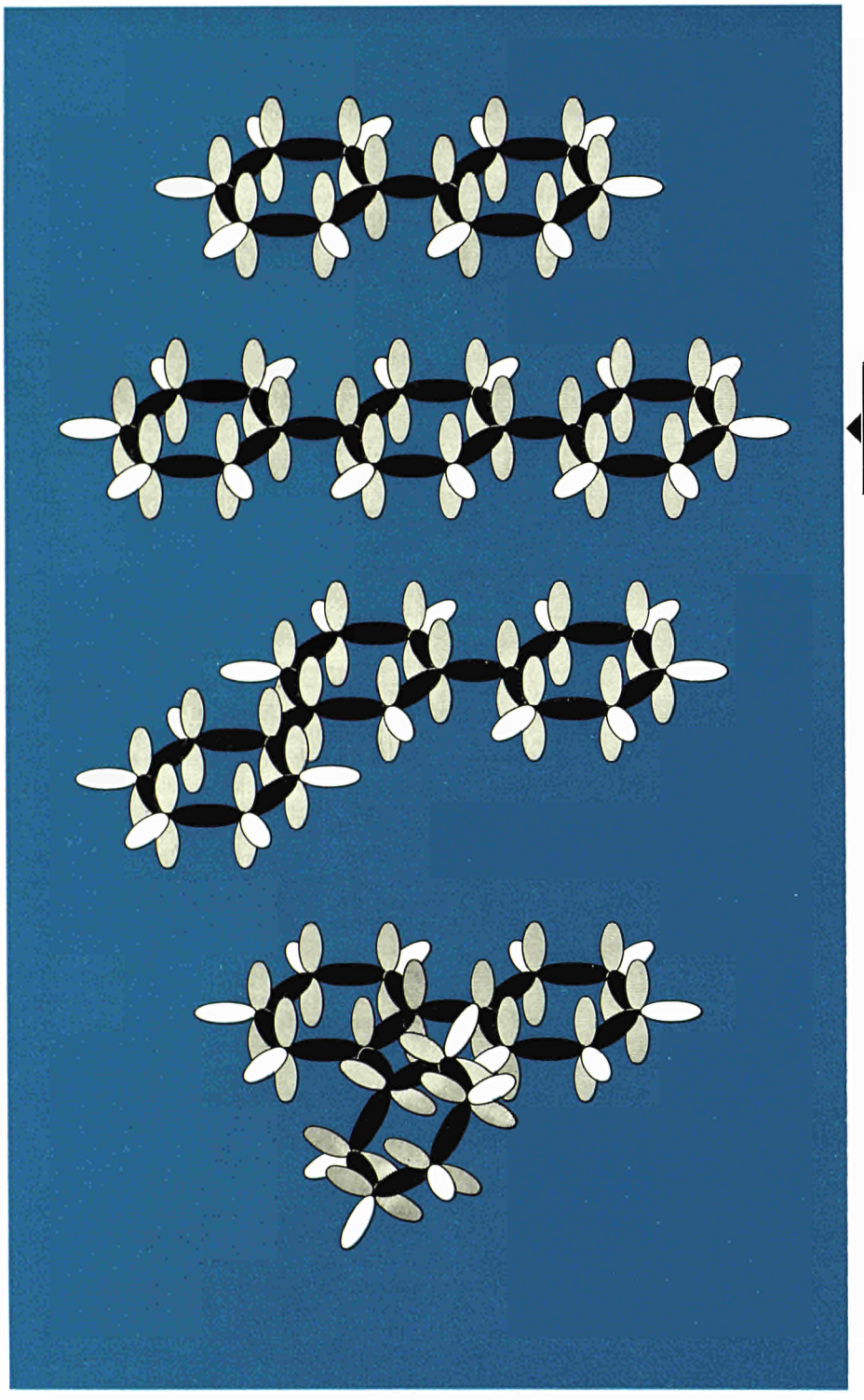


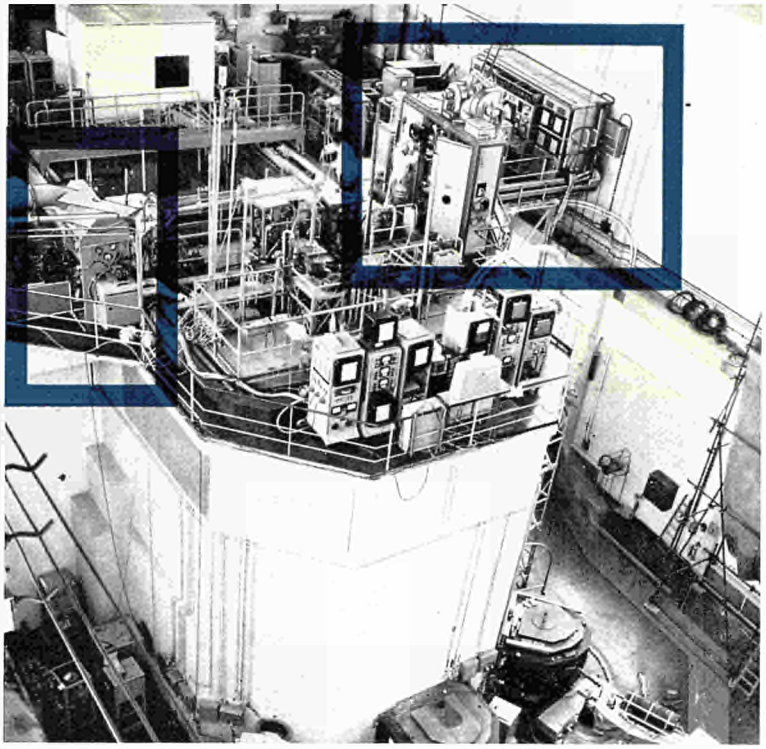
Figure 4
The diphenyl and the three terphenyl isomers are obtained by juxtaposition of benzene rings and display the major characteristics of such rings. The crowded character of the ortho-terphenyl molecule will be observed.

maximum working temperature must be limited so as to prevent observation of the, radiolysis phenomenon from being distorted by the interference of pyrolysis effects.

As regards fast neutrons, only accelerators can produce these without at the same time setting up considerable γ fields. Even so the fluxes thus available are far too weak to be of any use.

The most promising method appears to be that involving the use of in-pile devices which are shifted about to vary the relative proportions of the two types of radiation under study. A great deal of skill is called for in the performance of such tests. In particular, they require improvements in the dosimetry of the incident radiations so as to discriminate between their effects with a sufficient degree of accuracy.

If the decomposition of terphenyls are examined more closely, they are seen to consist of a wide variety of substances, from hydrogen to multi-ringed polyphenyls, including some alkylated molecules (possessing side-chains). A complete analysis of such a complex mixture would be a most laborious undertaking and one out of all proportion to its practical worth. For this reason, we must confine ourselves to de-



The Mélusine *reactor at the Grenoble (France) Nuclear Study Centre. On the right and on the left of the picture may be seen the two loops with the help of which the in-pile behaviour of organic coolants will be studied at temperatures ranging from 200 to 450° C.*

fining the mixture according to the size of the main groups which it contains.
The position may be summed up by saying that pyrolysis produces lighter substances than radiolysis.
Study of the mechanism of these reactions and the rate at which they take place is, of course, not easy, in view of the complexity of the substances formed and the wide variety of possible reactions. Nevertheless, in the case of both heavy and volatile substances, some overall data are available on their formation. From the weight standpoint, the light fractions can be ignored, as they account for only a small part of the decomposed terphenyls; it is, however, essential to provide for coolant degassing if we wish to avoid the interference arising from bubble formation at hot surfaces and liable to cause fuel element melting by burn-out.

Fouling and clean-up

All nuclear technology experience shows that it is imperative to ensure conditions of absolute cleanliness in every primary reactor circuit. It is also well known that the oil industry, in which an enormous amount of know-how has been acquired, likewise applies very strict criteria to its installations, particularly with regard to the permissible oxygen contents. It is therefore in no way surprising that an organic coolant to be used in a reactor must also be maintained in a state of high purity. If it is not, fouling is seen to occur on the hottest walls, i.e. those of the fuel elements, which, through the temperature surge thus produced, may have catastrophic consequences. It is therefore essential to prevent any impurity from entering the fluid.

However, the danger of accidental deterioration of the coolant cannot altogether be ruled out, and accordingly a purification plant must be available. This plant is being developed under a research programme, but there are already processes in existence which give satisfaction in that, even when a fluid is employed for which no precaution as to cleanliness has been taken, it is possible to cool an experimental fuel element by keeping its fouling rate at a very low level, which permits proper functioning throughout the life of the element concerned. These purification processes involve filtration and adsorption.
But a purification device must answer yet another purpose: apart from the materials which are harmful from the fouling standpoint, it is necessary to eliminate the decomposition products formed by the combined effect of heat and radiations.
We have already seen that, by degassing, the light substances can be disposed of, but this still leaves the heavy residues, for which it is usual to apply low-pressure (in order not to overheat the fluid) distillation.
Another method employed is that of solvent extraction, which can eliminate selectively those substances which, through their low solubility and high viscosity, constitute the greatest potential hazard. Encouraging results have been obtained by this method.
Finally, the idea has been conceived of reprocessing the decomposition products in the hope of obtaining substances similar to the original terphenyls. It is a tempting plan, as in the ultimate we should have a virtually reversible system, in which the heavy substances formed by radiolysis would be decomposed outside the reactor and the new mixture thus obtained fed back into the circuit. By the use of catalytic hydrogenolysis, it has thus been possible to effect the partial regeneration of coolants; however, there are no long-term test techniques for assessing the quality of the fluids thus obtained.
In conclusion, it may be said that terphenyls constitute a coolant which can be used in a power reactor in comparatively rigorous conditions and that at present it is not the behaviour of this coolant that imposes limitations on a reactor string such as Orgel. Furthermore, we are nearing the time when it will be possible to assess the part played by the organic coolant's behaviour in the costs of a power plant under various sets of operating conditions.
With the suitability of terphenyls to act as coolants thus established, efforts must now be focussed mainly on the achievement of improvements. As we have seen, there are several angles from which this task may be tackled—utilisation of oil cuts in a mixture with terphenyls, use of solvents to extract the most troublesome decomposition products, coolant regeneration, etc. By working on these various approaches, it should be possible to bring about some improvement in the economics of an organic-cooled reactor.

ECO
Expérience Critique Orgel

PIERRE BONNAURE, *Head of the Regulation and Automation Service, Reactor Physics Department, Ispra Research Establishment, Euratom*

Euratom's Joint Research Establishment at Ispra is actively engaged in the construction of the ECO reactor, a name which derives from the designation "Expérience Critique Orgel" (Orgel Critical Experiment). The work has now virtually been completed and the checking and start-up operations are in progress, so that over the coming year the physicists and neutronics experts will be able to embark upon the first experimental investigations on the physics of the Orgel reactor.

The assembly of this device, the first reactor to be actually designed by Euratom staff and built entirely under the aegis of Euratom, calls for a few observations:

The Orgel programme, which is the mainspring of the Ispra Establishment's activities under the second five-year plan, raises a wide range of problems which were from the outset tackled in the laboratories. In the various technological fields concerned, these studies gave rise to an accumulation of practical data culminating in a fuel element/channel assembly concept which could be applied in a power reactor. These results cannot be said to be firm until the materials and geometries involved have undergone searching irradiation tests, in conditions as close as possible to those which will obtain in the projected power reactor. These were the considerations which underlay the design and construction of the ESSOR reactor, which was the subject of an article by Mr. Chassignet in the June 1963 issue of this Bulletin.

In the field of reactor physics, more or less the same thing is happening and calculations made with the most up-to-date codes and the most powerful computers will continue to involve a subtantial margin of uncertainty until a degree of practical experience has been acquired for the purpose of revising the results and adjusting the codes. In the case of the Orgel string, as with natural-uranium fuelled reactors in general, the reactivity balance is a delicate matter. A slight error in estimating the reactivity reserve gives rise automatically to a considerable increase or drop in the reactor's burn-up potential.

It is quite understandable, therefore, that the originators of the project should aim at the greatest possible accuracy when estimating the neutron balance at the various stages of the reactor's career. Furthermore, the organic liquid used as coolant in an Orgel reactor serves, by virtue of its composition, as a subsidiary moderator alongside the main heavy water moderator. This sets us a difficult problem when we come to calculate the neutron spectrum in a lattice having two moderators at different temperatures—on the one hand the hot organic liquid circulating in the fuel clusters, and on the other the relatively cold heavy water which surrounds them.

A number of experiments have therefore been planned in order to arrive at a sufficiently thorough understanding of the physical phenomena which occur in an Orgel reactor—thermalisation experiment, exponential experiment EXPO, critical experiment ECO.

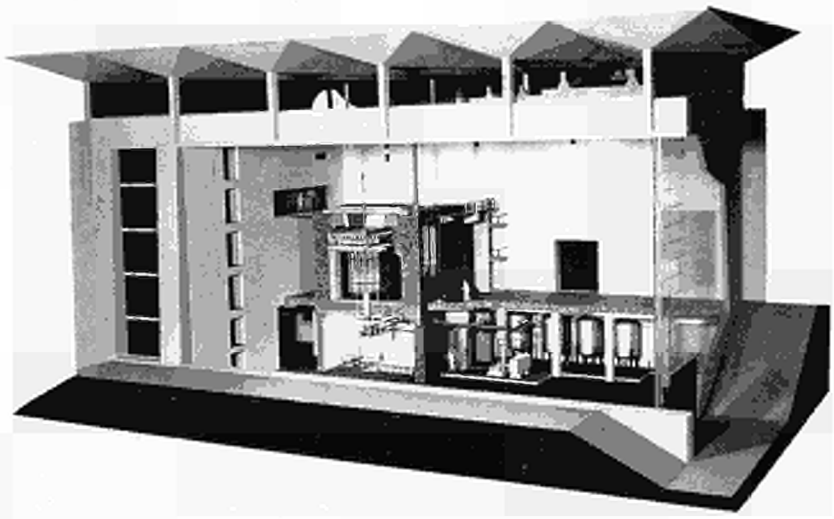
Reactor design

The ECO reactor is basically a simple critical experiment, that is to say, a heavy-water vessel big enough to house a critical-size lattice.

As the critical size for a natural-uranium-fuelled Orgel reactor is fairly large, use must be made of a sizeable vessel and thus of considerable tonnages of heavy water and uranium.

In order to cut down on these particular items, a graphite neutron reflector was fitted at the sides and bottom of the reactor vessel. This feature unfortunately induces flux distortions limiting the non-perturbed zone which can actually be used within the vessel for flux measurements, and makes it difficult to interpret the results in the "substitution method".

After careful examination of the advantages and drawbacks of various geometries, it was decided to adopt an aluminium vessel 3 m in diameter and 4.21 m high capable of holding 221 fuel elements 2.90 m high. The 100-ton graphite reflector is an octagonal prism about 4.9 m wide and 4 m high, with a central well 3.12 m in diameter and 3.12 m high, in which the reactor is housed. A mobile boral blanket located between the



vessel and the graphite can be used to neutralise the effect of the radial reflector whenever it is necessary to operate in non-reflected conditions.
The heavy water level in the vessel must be readily controllable so that "criticality approaches" can be effected in absolute safety. For this purpose, ECO has a fairly complicated system of heavy-water pumps with varying deliveries, as well as feed governor tanks, the contents of which, calibrated to extreme precision, may be discharged pneumatically into the vessel so as to bring about gradations in the heavy water, and thus the reactivity, level.
One of the parameters to be optimised in a power reactor is the lattice pitch. ECO is accordingly fitted with an automatic pitch modification system which can be used to set up any rectangular mesh configuration in the 170-300 mm range.

Furthermore, in the hope of improving the accuracy of the buckling versus lattice pitch measurements, ECO has been constructed so as to accommodate mechanisms capable of producing oscillating lattice pitch variations in the neighbourhood of the design value. This design feature constitutes a new development; it is thus an experiment in itself and the system will not be tested out until a certain amount of experience has been acquired with the reactor.
The principle of the substitution method, to which reference has been made above, consists in carrying out buckling measurements using only a small number of fuel elements in the lattice to be studied (e.g. 25) instead of substituting *all* the fuel elements in the reference lattice (150 to 200).
This method, itself an economic one, would soon be discarded if it were possible merely to substitute a single fuel element. However, the reactivity variation resulting from such a substitution would be difficult to measure by a static method. On the other hand, if it is intended to carry out this substitution at periodic intervals, the resultant reactivity modulation would probably be measurable. With this in view, ECO has been fitted with a demountable axial channel which passes right through the reactor from one side to the other and enables two fuel elements (the element under examination and the reference element) to be oscillated vertically. The oscillating device is a shielded 8-ton apparatus capable of assembling automatically two fuel elements and their rack, of raising and lowering a weight of 500 kg at a speed of 1 m/s and of stopping the assembly at the same point in each cycle after 4 m travel to an accuracy of a few millimetres. The oscillator will be used first of all with a synthetic fuel element simulating a used element.
The value of this method of oscillation is highlighted in cases where we need to measure the progressive behaviour of the fuel after irradiation in a test reactor such as ESSOR; i.e. as only one active element is involved, the reactor shielding problem is much less acute. The dimensions of ECO were in fact selected to enable it to operate at 1 kW while containing a fuel element with an irradiated central zone.
The shielding designed on the basis of these factors takes the form of a 1.70 m thick concrete shell.
As ECO is first and foremost an experimental physics reactor the core must be readily accessible. The upper shielding is provided with a motor-driven swivel lid with a radial port. The lateral shielding has a sliding door which gives access to a leaktight chamber

containing the reactor vessel and the reflector, which is penetrated by 43 horizontal experimental channels. The leaktight chamber is ventilated, being kept at under pressure, and the air is vented via a small stack located outside the building. In the event of an accident, any pressure surge occurring in the vessel is taken up by this leaktight chamber and the air discharged through the stack.

This chamber also houses the drive mechanisms for the four control plates which enable the power to be stabilised automatically at the required value, as well as the mechanism of the boral blanket which is positioned as a function of the water level in the vessel and which neutralises the influence of the graphite reflector located above this level.

A matter of some delicacy which arises in the evaluation of a reactor's neutron balance, especially when a coolant is employed which at the same time acts as a moderator, is connected with the measurement of the temperature coefficients.

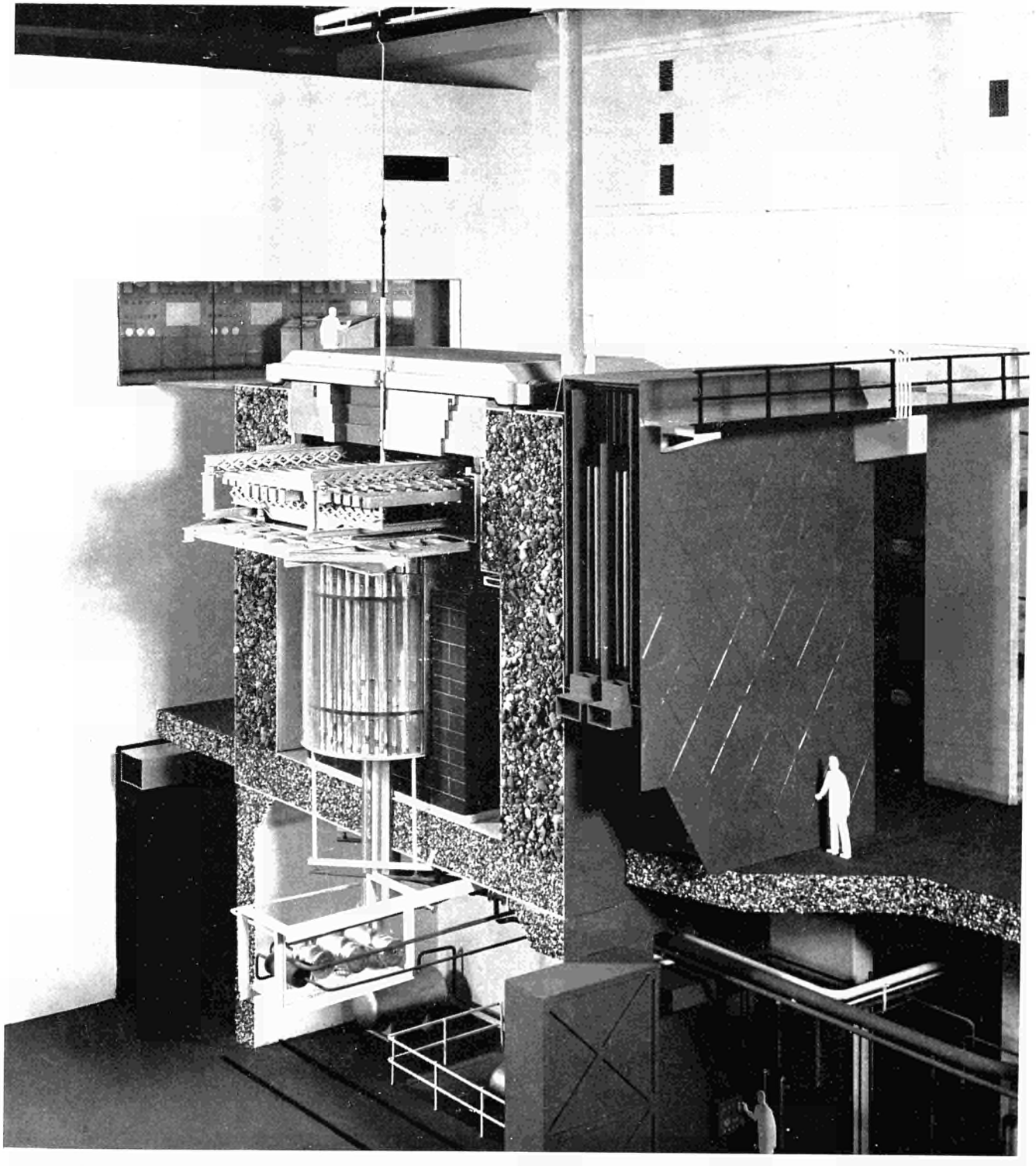
In ECO it is possible to ring the changes on the water temperature in a continuous and controlled manner between 10° and 80°C and that of the organic coolant in the 80° to 300°C range. For this purpose, the vessel and the core tank are heat-insulated and a pump circulates 60 tons of water an hour across an assembly of double-walled exchangers and heating elements. The heavy water is injected into the vessel through four perforated columns (the geometry of which was carefully selected on the basis of the results of tests carried out in a hydraulic mock-up of identical size) in such a way as to obtain a highly satisfactory homogeneity of the temperatures involved without affecting the stability of either the free surface or the fuel elements (the latter are in fact only suspended in the vessel). The heavy water emerges from the vessel through a specially-designed annular central manifold.

The organic liquid with which the fuel elements are filled may be heated up to 300°C by fitting each of the clusters with a heating unit consisting of a motor-pump group connected to a heating element and a regulator. The pump, which is immersed in the organic liquid and driven by a leaktight magnetic coupler, circulates the coolant inside the fuel cluster in a "hairpin" circuit. Here too, the aim has been to devise a solution affording the highest degree of homogeneity in the internal temperature distribution.

For temperature coefficient measurements, it is sufficient to equip in a similar way the 25 fuel elements in the central zone, described as the "replacement" or "substitution" zone.

Shielded rotary plug, showing the radial loading slit together with pivoted closure

ECO mockup



To complete this account, it may be added that the critical experiment ECO is provided with a set of auxiliary devices which can be used for carrying out a wide variety of reactor physics experiments—mobile beam-extraction channel for time-of-flight spectrum analysis, axial beam-injection channel for a hook-up with a 1 MeV van de Graaff accelerator, mobile source, sundry probes, etc.

At the present time, ECO has an initial fuel load, made up of 189 clusters of 19 uranium metal rodlets. A substitution set consisting of 25 clusters of 7 uranium carbide rodlets is in course of fabrication. Uranium carbide is, in fact, intended as the fuel for an Orgel power reactor.

ECO "Complex"

The reactor is housed in a hall 40 m long, 25 m wide and 20 m high, with two overhead cranes, one of 50 tons—powerful but unwieldy—which is necessary for removing the swivel lids and mobile slabs, and the other of 5 tons, which is more suitable for the routine minor operations.

The reactor block is located near one of the ends of the building, so as to leave a maximum of free space for other reactor physics experiments such as the exponential experiment EXPO, which is due to start up shortly. A trap in the floor and a reinforced basement designed for an additional load of 800 tons have been installed on the assumption that a second critical experiment or a swimming-pool reactor, for example, will be set up later.

The reactor end of the building consists of a habitable six storey building which contains the following rooms and equipment:

— two floors of basement: auxiliaries (compressors, end of technical galleries, low-voltage and air-conditioning control panels, emergency generating group, etc.);
— ground floor: main entrance, caretaker's lodge and radiological protection point, toilets and decontamination points;
— first floor: relay and electronic control room, fuel-element assembly room;
— second floor: control room (level with top of reactor) and standby control room;
— third floor: drawing office and store for reactor spares.

The habitable block, which is traditionally known as the "airlock", is connected by an overhead gallery with the operating personnel laboratory building. This building contains, in addition to the normal office space, a mechanics workshop and two electronics laboratories for the setting-up of experiments. Here the experimental physicists have four offices at their disposal, together with a fully equipped counting room and an experiment-assembly room.

ECO, a European experiment

The construction of this assembly has provided the Euratom Commission with its first opportunity to co-ordinate the activities of enterprises representing most of the Member States.

Contracts for the construction of the building and the reactor have been awarded to an Italian firm and a Dutch consortium respectively. The Supply Agency has provided the uranium, France the graphite for the reflector. The hydraulic tests have been carried out in Belgium, while the United States is supplying the heavy water on a lease basis.

For Ispra too, operation ECO has been—and still is—a singularly instructive experiment which has afforded an opportunity of putting to a severe test a number of departments which have only recently been set up and are thus unaccustomed to combined-operations work within a tight time-schedule. It would be an overstatement to say that everything has gone without a hitch or without raising any problems. The tentative time-limits have certainly been exceeded by a long way; nevertheless, in spite of the difficulties caused by the geographical distances involved, the diversity of tongues and the fact that the whole set-up is of fairly recent creation, a complex unit has emerged in a very brief period of time. A year after the laying of the first stone of the building, the contractor responsible for the construction of the reactor took possession of a practically completed reactor hall. Six months later the reactor itself was near completion. In another few months, with its control system installed and with all its circuits checked and tested, the ECO reactor will be all set to go critical.

After two years' work, and well in advance of the fourth anniversary of its transfer to Euratom, the Ispra Establishment will embark upon the operation of its first critical experiment.

Almost all of us are only too well aware, on the basis of our everyday experience, of the insidious effects of corrosion and the efforts necessary to combat it. In water-cooled and -moderated nuclear reactors corrosion becomes a particularly vicious opponent—we may go so far as to say that it constitutes the major stumbling-block to the full development of this type of reactor. The basic and applied research under way both in Europe and the United States is expected to provide the means of parrying corrosion attack.

The battle against corrosion

by PHILIPPE BERGE, *Directorate-General for Research and Training, Euratom*

The problems created by the deterioration of metals owing to corrosion arise in all branches of industry. Colossal efforts are made to protect metal components and develop more resistant alloys, and also to obtain a more thorough grasp of the mechanisms governing corrosion, which can appear in so many different forms. Back in 1949, Professor Uhlig placed the annual loss due to corrosion in the US at 5,500 million dollars and came to the conclusion that metal corrosion should rank as a national calamity and that an all-out struggle should be waged against it.

The development of nuclear energy raises new and particularly tricky problems in this context, for the materials selected for the construction of a nuclear reactor must comply with unprecedented specifications owing mainly to the fact that these materials will be subjected to an intense radiation flux.

The materials used, and in particular those employed in the fuel cladding, must above all possess a low neutron capture cross-section. This requirement alone limits the range of materials which could possibly be selected for use in the reactor.

Secondly, none of the materials used must yield corrosion products which can become active in the reactor and have a long half-life, for the circulation of these corrosion products and their accumulation in certain parts of the reactor give rise to tricky decontamination problems.

Thirdly, the action of the radiations can have an effect on the corrosion rate itself. In the homogeneous reactor based on the use of uranyl sulphate as fuel, for instance, almost insurmountable problems have been raised by the corrosion of various materials which come into contact with the irradiated fissile liquid. This increase in the corrosion rate may be due either to the action of the neutrons on the metal or the oxide, or the ionising action of the radiations, which modifies the liquid by radiolysis.

Furthermore, it is virtually impossible to add inhibitors (organic substances which, if added in small amounts, reduce the corrosive effects of the medium appreciably) since they are decomposed by irradiation. Finally, the safety factor must be high, since any accident hazard in a nuclear reactor is a potential source of disaster.

As a result of all these conditions, there are only a few metals which can be used as

Fig.1
Pitting corrosion on a sample of 18-8 stainless steel (SERAI, Belgium)
Enlarged 12 times

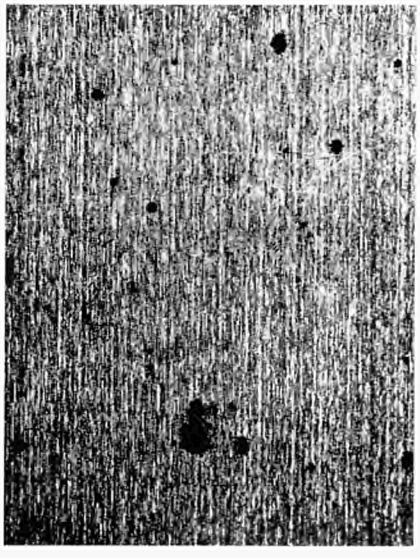


Fig. 2
Crack propagating inwards in an 18-8 stainless steel by transgranular stress corrosion (Metallurgical Chemistry Laboratory, Vitry-sur-Seine, France)
Enlarged 800 times

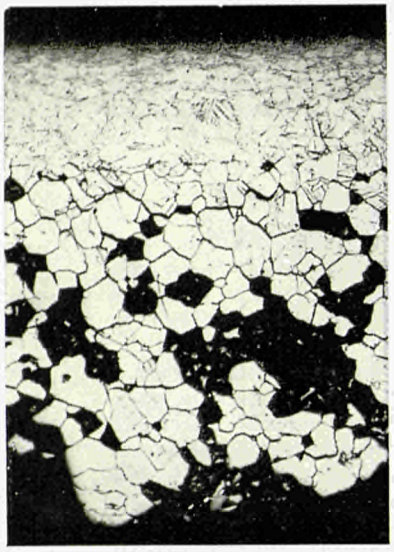


Fig. 3
Intergranular corrosion of a stainless steel. It should be noted that the cold-worked edge of the sample is not subject to this corrosion (SERAI, Belgium)
Enlarged 150 times

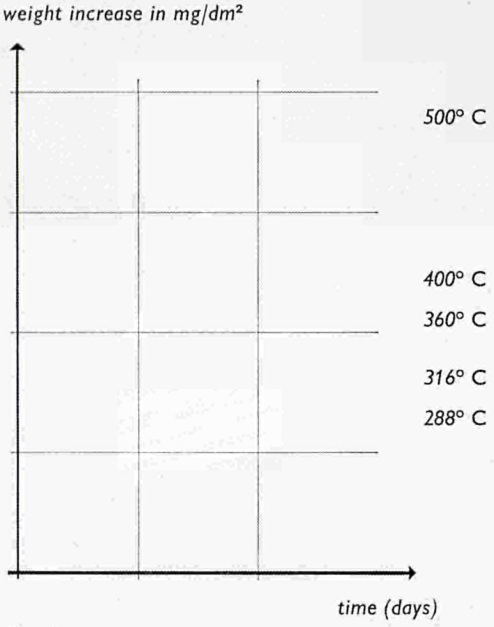


Fig. 4
Corrosion of Zircaloy-2 in high-temperature steam

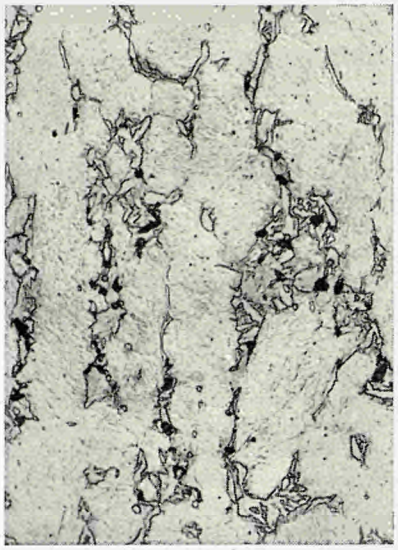


Fig. 5
Precipitation of hydride in zirconium—1087 ppm H_2 (Metallgesellschaft, Germany)
Enlarged 600 times

structural materials and especially as cladding in reactors.

Corrosion problems in water-cooled reactors

In the case of water-cooled reactors, only two types of materials are worth considering—steels and zirconium alloys.
Stainless steels were used in the first water-cooled reactors. At the water temperatures employed, i.e. around 300°C, these iron-chrome-nickel alloys offer a remarkable corrosion resistance (several mg/dm². month, which corresponds to a penetration of about one-thousandth of a millimetre a year), on the proviso that the water is of very high purity. Their neutron cross-section is acceptable if enriched uranium is used.

The great advantage of the zirconium alloys lies in their much lower neutron cross-section. In addition, Zircaloy-2, which was developed some ten years ago, possesses an excellent corrosion resistance in water at 300°C.

Since stainless steel is expensive, a considerable saving could be made if ordinary steels were used. A study published in "Nucleonics" in 1961, for instance, points out that by using ordinary instead of stainless steel in the Hanford NPR plutonium-producing reactor, a saving of 10 million dollars could be made on the total bill of 145 million. However, the ordinary steels used in conventional power plants behave satisfactorily only if the free oxygen content of the water can be kept very low. This condition is, however, not feasible in a reactor since oxygen and hydrogen are constantly released as a result of radiolysis of the water and there is a risk that this radiolytic oxygen might cause localised corrosion phenomena such as pitting, a particularly insidious form of corrosion (Fig. 1).
It should nonetheless be noted that at temperatures around 300°C the presence of oxygen in the water is *less* dangerous than during reactor shutdown. It is even probable that a high oxygen content increases the hot corrosion resistance while being disastrous in the cold state, since the oxides formed in the hot and cold states in the presence of oxygen are of different types. A major effort is being made in an attempt to throw light on these problems, in order to obtain cheaper energy by lowering the cost of the materials used in construction.

Fig. 6a-d - A few examples of the growth of oxides from nuclei (Metal Oxidation Laboratory, Free University, Brussels)

Another case of localised corrosion, this time affecting stainless steels, is encountered in high-temperature steam in the presence of oxygen and is known as "stress corrosion". This type of corrosion is only found in components subjected to mechanical stresses, the most vulnerable being perhaps the fuel cladding, the walls of which are relatively thin (Figs. 2 and 3). The corrosion then takes the form of cracks, frequently invisible to the naked eye, which can cause the component to break. The generation of steam heated up to high temperature in so-called nuclear superheat reactors would enable the electricity output to be stepped up. Unfortunately, stainless steels are subject to very severe stress corrosion when exposed to superheated steam in the presence of oxygen, for which reason they cannot at present be used as cladding materials under these conditions.

Furthermore, recent results have shown that even in conventional boiling-water reactors the cladding cracked in a similar fashion after a fairly long period of time, thus throwing doubt on the possibility of using stainless steels as cladding materials in reactors of this type.

The use of zirconium alloys as cladding materials in boiling-water reactors also led to severe corrosion phenomena, but they can now apparently be used without any risk if the temperature is not too high (between about 300 and 350°C). The cracks in zirconium alloys were due to an excessively high fluoride content in the uranium oxide inside the clads. However, the materials were subjected to appropriate procedures to eliminate this risk.

On the other hand, if higher temperatures are involved, Zircaloy-2 cannot be used (Fig. 4), since its corrosion rate increases and its mechanical properties deteriorate rapidly when the hydrogen formed by the oxidation reaction penetrates into the metal and is precipitated in the form of zirconium hydride (Fig. 5).

This problem arises not only in superheat reactors but also in conventional boiling-water reactors where high heat flux conditions are required, for when the fuel cladding is already oxidised the oxide layer formed acts as an insulator and thus raises the temperature at the metal-oxide interface to a value much higher than that of the water.

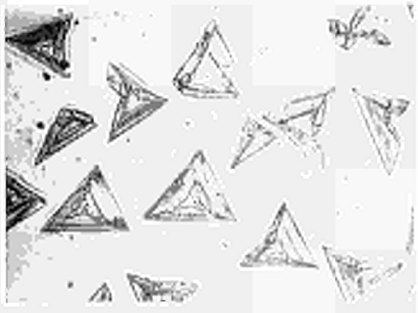
If, therefore, neither stainless steel nor Zircaloy-2 can be used in superheated steam at high temperature, other materials must be found which can withstand these conditions. Superheat reactor construction projects now under way are: Beloyarsk (USSR), Bonus (Puerto Rico), Borax-5 (Idaho), VESR (California) and Sioux Falls (South Dakota). In all of these it was originally intended to use stainless steels. In the face of the risk of stress corrosion, unless a solution is not found soon, the designers will have to consider replacing them by Inconel alloys, which have a very high nickel content and seem, partially at least, immune to this type of corrosion, but which also have numerous drawbacks in the form of a high neutron capture cross-section, high cost, rapid deterioration of the mechanical properties under irradiation. Nonetheless, there are grounds for thinking that the mechanism of this intergranular stress corrosion could be clarified in the not-too-distant future if the necessary steps were taken. It is probable that a means would then be found of enabling stainless steels to be used under superheat conditions. Research work on corrosion in water-cooled reactors has thus two main aims—the utilisation of less expensive materials and the use of cladding materials compatible with more stringent temperature and heat flux conditions.

Certain other results of corrosion are also important and are being covered by appropriate research work, mainly into the behaviour of the corrosion products carried away in the liquid, and dealing with such problems as how they circulate in the reactor, where they become deposited, and to what extent they are activated. It has been observed that these substances become deposited throughout the circuit, but particularly on the fuel elements, in the heat exchangers and at any point, e.g. near a valve, where there is a bottle-neck. This can result in numerous difficulties such as a deterioration in the heat exchange, an accumulation of radioactivity at certain points and malfunctioning of the valves. In order to alleviate these difficulties, the reactor water must be filtered, but in the long run this does not prevent the formation of deposits. The circuits must therefore be decontaminated at regular intervals by chemical scouring. Certain acid mixtures are used which are well suited for scouring various materials, but, when different

Enlarged 500 times

Enlarged 1000 times

Enlarged 1000 times



Enlarged 1000 times

Fig. 6a - Oxide nuclei on samples of copper or copper-nickel alloy (low nickel content) oxidised at different temperatures (620-705° C) and different oxygen pressures (10^{-4}-10^{-3} mm Hg)

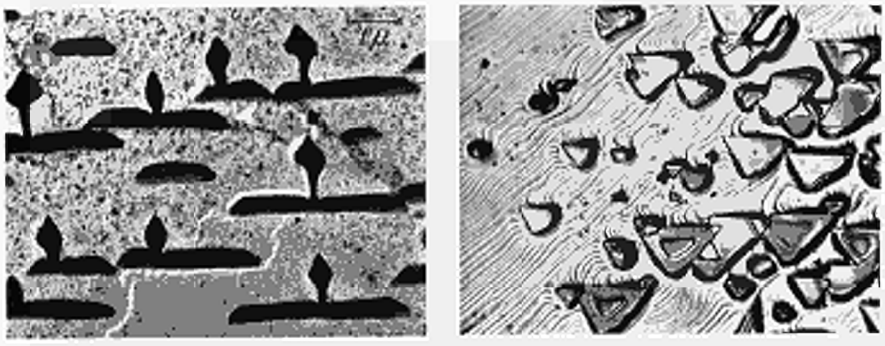


Fig. 6b Enlarged 1000 times Enlarged 10,000 times
Nickel oxide on copper-nickel sample (1% nickel)

metals are in contact with each other, an electrochemical cell is created in acid solutions resulting in severe corrosion of the baser metal.
One could go on enumerating the special problems bound up with corrosion, but the list is likely to be long since even the remedies resorted to seem to raise other difficulties in their turn!

Research under the Euratom/US Agreement

On both the European and American side, quite a large part of the Euratom/US Joint Research and Development Programme is being devoted to corrosion studies (see article by Mr. Kruys, Euratom Bulletin No. 1, 1963, p. 8). All these studies are being carried out under contract.

Corrosion under irradiation

As far as conventional power plants are concerned, the use of normal carbon steels and, in the case of the very high superheated steam temperatures, the application of stainless steels, do not present any serious problem, and it is only under irradiation that corrosion becomes a major drawback. Furthermore, the effect of irradiation on the corrosion rate in the case of zirconium alloys has been covered by a number of projects, but the results of such studies often turn out to be contradictory. Whereas, according to the technicians at Harwell (United Kingdom), the corrosion rate is stepped up in the presence of irradiation by a factor of as much as eight in steam around 340°C, other researchers contend that the effect of irradiation on the corrosion of zirconium is zero in water at high temperatures.
In-pile tests now in progress under the Euratom/US Programme are being carried out both in a corrosion loop with a water-steam mixture circuit (in the Saluggia reactor, Italy) and in autoclaves (in the Geesthacht reactor, Germany) in an attempt to throw light on the problem.
These tests are, however, extremely difficult to carry out and have the disadvantage of giving an overall effect without providing an insight into the irradiation mechanism or indicating which radiations are responsible for the differences observed.

Basic studies

A programme of basic research has therefore been launched enabling separate studies to be carried out on the effects of radiation on water or steam and on metals or their oxides.
For this reason, the stontium-90/yttrium-90 source used (at the Battelle Institute, Frankfurt, Germany) is one in which the ß-emissions were of a high ionising power capable of modifying the oxidising gaseous atmosphere without having any effect on the lattice of the metal or the oxide. An extremely sensitive balance, enabling variations in weight of less than one-millionth of a gram to be detected, is used to see if radiations can alter the oxidation rate of steels or zirconium in different media.
Furthermore, the use of optical and electronic microscopes to observe the first stages of the oxidation of different metals (at the University of Brussels and the Physics Laboratory of the CEN, Mol, Belgium) should be able to show whether preliminary irradiation affects the shape or number of oxide nuclei which precede the formation of more homogeneous layers. It is quite probable that the first oxidation stages studied in this way are not unrelated to the subsequent oxidation rate (Fig. 6). It is with the aid of the electronic microscope, but by transmission through metal sheets machined down to a few hundred thousandths of a millimetre, that the shape and distribution of internal precipitates such as zirconium hydride can be studied as a function of the lattice flows, especially those induced by neutron irradiation (Fig. 7).
In another part of the basic research programme, electrochemical methods are used for studying the degree of protection which oxide films afford the metal. By measuring the electrical capacity of the films, for instance, valuable data are obtained on their homogeneity. By conducting identical tests alternately out-of-pile and in-pile (BR1, Mol, Belgium), a better insight is gained into the influence of irradiation on the formation of protective oxide films and on the properties of these oxides.
In company with many other metals, iron,

Fig. 6c - Copper oxide nuclei (electron microscopy)

Fig. 7
Germination of niobium oxide—electron microscopy by transmission (Physics Laboratory, CEN, Mol, Belgium)
Enlarged 32,000 times

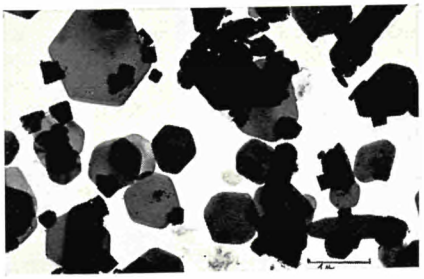
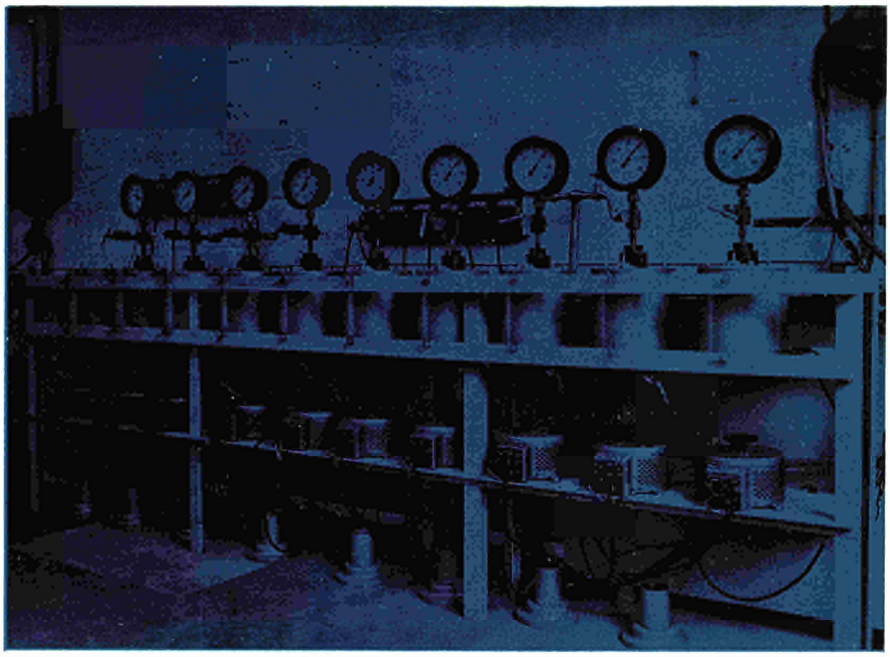


Fig. 6d
Nickel oxide nuclei at 920°C (electron microscopy) on copper-nickel sample (1% nickel)

Fig. 8
Autoclave battery for corrosion tests in high-temperature water and steam (SERAI, Belgium)



stainless steel and zirconium are inevitably subject to oxidation in the presence of water; after rapid formation for several hours the oxide then shields these metals against severe corrosion. The extent to which corrosion then occurs in permanent operating conditions will be in proportion to the porosity of the oxide formed. It is on these oxide layers, therefore, known as passivation films when they are very thin, that the corrosion strength of a metal in a given medium is dependent.
These tests likewise make it possible to predict the conditions under which galvanic corrosion occurs, i.e. speeded-up corrosion of a metal in contact with a nobler metal.

Development of new alloys

Zircaloy-2, which contains small amounts of tin, iron, chromium and nickel, is by far the most widely used zirconium alloy in boiling- and pressurised-water reactors. As a result of the addition of these elements, which make up less than 2% of the total, its corrosion strength is considerably better than that of pure zirconium.
There is reason to hope, therefore, that zirconium alloys containing other elements could be developed which would enable zirconium to be used at extremely high temperatures, and a considerable amount of work has been done in this direction. Certain alloys developed under the Euratom/US Agreement seem to be substantial improvements. The mechanical properties of one of them, for instance, containing niobium and tin, are appreciably better than those of Zircaloy-2. Its irradiation behaviour is now being studied by the Metallgesellschaft AG, Frankfurt, Germany. Other alloys (a zirconium-chromium binary alloy and a zirconium-copper-iron ternary alloy) appear to offer a better corrosion resistance at 450°C and especially less marked hydrogen-embrittlement (General Electric, Vallecitos, US).
Basic studies are also being carried out on this embrittlement and the hydride particles which cause it (University of Bologna, Italy; Siemens, Erlangen, Germany).
These alloys were developed after a large number of tests had been carried out on various additives. At this juncture, the favourable or unfavourable effect of the addition agents can only be observed and not elucidated. Systematic tests for developing a ternary or quaternary alloy are extremely lengthy and costly, for the requirements with regard to price and neutron capture cross-section, which are so important in the base metal, are much less stringent in the case of small additive contents. There are therefore a very large number of metals which could be studied and all the possible combinations would entail an enormous number of experiments. It is for this reason that basic studies have to be carried out parallel to these tests in order to shed some light on the oxidation mechanism of these alloys as well as on the part played by the various components. In this way the possibility should be provided of guiding research work dealing with alloys not only for zirconium but also on a more general plane. With the same aim of investigating the influence of addition agents and impurities,

Fig. 9 - Oxide formed on a milled boiler steel exposed for 2000 Hours to 400°C steam (SERAI, Belgium) Enlarged 1200 times

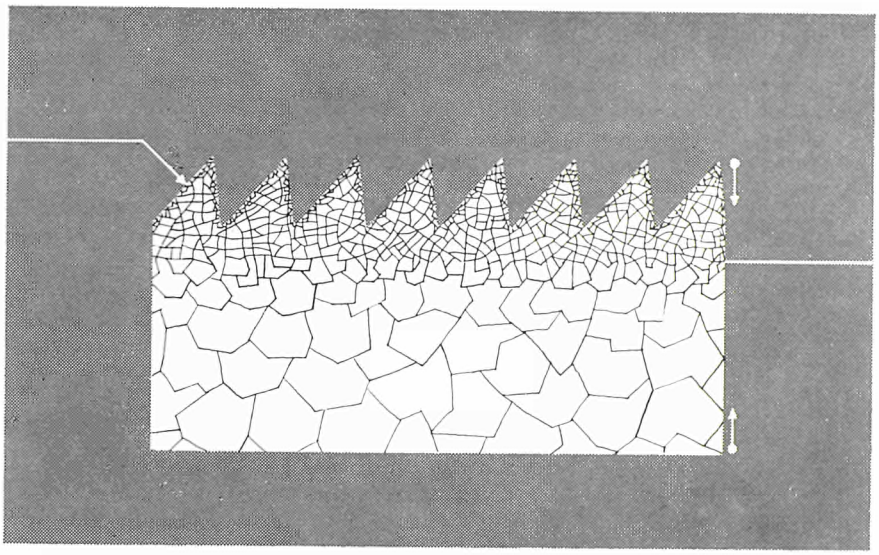


Fig. 10
Mechanically treated metallic surface

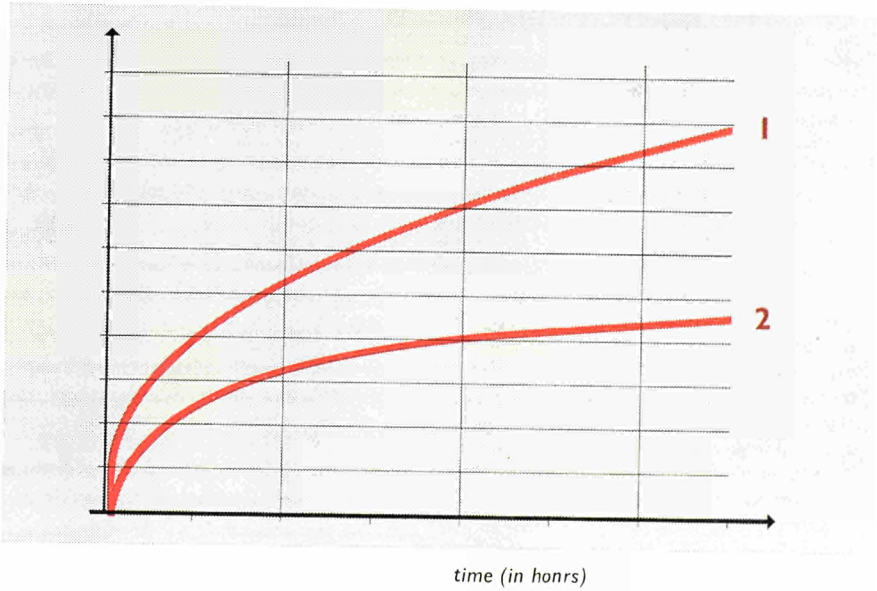


Fig. 11
Oxidation curve of an ordinary carbon steel in water at 300°C
1 mechanically polished (carborundum paper 600)
2 electrolytically polished

a study has been undertaken (at the Metallurgical Chemistry Laboratory, Vitry-sur-Seine, France) on the properties of stainless steels made from the purest iron, chromium and nickel obtainable. The properties of stainless steels prepared in this way are very different from those of industrial stainless steels. By the controlled addition of small amounts of addition elements it should be possible to gain an insight into the part played by these elements and thus to prepare improved steels, either by starting with purer materials or by purifying to eliminate impurities known to be harmful.

Furthermore, alloy studies are being carried out using other base metals such as beryllium (Nuclear Metals, Inc., US) or niobium (Battelle, Columbus, US), which have a very low neutron capture cross-section but a corrosion sensitivity which has hitherto rendered them unacceptable for use in high-temperature steam.

These tests are being carried out in the hope that it might be possible to manufacture alloys having a corrosion resistance superior to that of the pure metal, in the way that Zircaloy-2 is preferable to pure zirconium.

Improving conditions under which tested materials are used

Among the studies coming under this heading mention might be made of a research project aimed at recombining the oxygen and hydrogen formed by radiolysis in superheated steam. If the bulk of the oxygen formed could be recombined in the form of water by means of a catalyst, such as finely-divided platinum, stress corrosion in stainless steels, one of the causes of which is the presence of oxygen in the steam, could be avoided (General Nuclear Engineering Corporation US).

Another study (SERAI, Belgium) can also be listed under this heading. It is aimed at evaluating the influence of the surface treatment on corrosion in high-temperature water and steam (Fig. 8). Results of major practical importance have already been obtained. In the case of an ordinary carbon steel, it was shown that with suitable surface treatment corrosion was three times less severe in water at 300°C and steam at 400°C. The surface of the machined parts, by mechanical treatment, does in fact acquire not only a roughness depending on the degree of finish but also a crystalline structure different from that of the base metal (Figs. 9 and 10). The thickness of this cold-worked layer varies depending on the treatment used and can be as high as several tenths of a millimetre. On the other hand, this superficial cold-working is rendered unnecessary if chemical or electrochemical polishing is carried out. The purpose of this study is to determine which of these two factors, cold-working and roughness, is decisive when the aim is to bring about an improvement by means of treatment such as electrolytic polishing (Fig. 11).

In the case of stainless steels, mechanical treatment involving surface cold-working is likewise very harmful at 300°C, while at higher temperatures (400°C) it becomes very favourable!

Major practical conclusions can be drawn from this study, especially with regard to the use of ordinary steels in water reactors in place of stainless steels. The results are now being checked under extreme dynamic conditions. In particular a corrosion loop is being used for investigating the behaviour of these steels when the pressurised water circulates at a rate of over 10 m/sec (see nside front cover).

It will be seen from this brief outline of the corrosion research programmes covered by the Euratom/US Agreement that a by no means negligible part of the work is of a basic character, for it is with the aid of basic research that we are likely to arrive at a better insight into the corrosion mechanism and the means of inhibiting corrosion phenomena. Furthermore, in addition to acting as a considerable aid in our efforts to devise better alloys and better conditions for their use in water reactors, studies of this type enable us to derive laws of general application.

It is perhaps no exaggeration to say that corrosion is the arch-enemy of the water reactor. One particular consequence, as we have seen, is that it rules out the use of high temperatures and heat fluxes. If there were no special corrosion problem, these reactors could have taken advantage of almost all the conventional steam-generating techniques, which involve the use of temperatures of over 600°C and thus make possible high outputs. It is not surprising, therefore, that the problems raised by corrosion are being tackled with such vigour since their solution would inevitably lead to an improvement in the economics of the water reactor.

On 24 October 1963, the Euratom Commission published a report on "The Problem of Uranium Resources and the Long-Term Supply Question" drawn up by the Consultative Committee of the Community's Supply Agency. The Commission has signified its approval of the conclusions reached in the report, which are sketched out in broad outline below.

The problem of uranium supply in Europe

What are the free world's uranium reserves at the present time?
How are these reserves going to develop between now and 1970?
What is the possible demand for uranium in the free world after 1970?
What are the supply possibilities after 1970?
What supply problems are peculiar to the European Community?
These are questions which are answered by the Consultative Committee of the Euratom Supply Agency in a report recently submitted to the Commission.
The fact is that the development of nuclear energy, geared as it is at the present time to the fission of heavy elements, and in particular uranium, is conditioned in large measure by the quantities in which this element is available in the free world. Furthermore, the uranium deposits must be sufficiently rich and sufficiently extensive, as otherwise the price of uranium might rise to a level at which it would be liable to slow down the momentum of nuclear energy's economic progress.
It was primarily with the object of setting out as accurately as possible the facts and figures of this crucial problem of uranium resources and the long-term supply position that the Consultative Committee produced its report. From the surveys carried out, three main ideas emerge clearly:
— a comparison of requirements and resources shows that the free world will not run short of low-cost uranium in either the present decade or the next one.
— nevertheless, in order to ensure that uranium reserves are available at the right time and the right price, it would be advisable to take appropriate measures in the near future, and in particular to start prospecting for uranium deposits and then to set about exploiting them.
— these supply prospects demonstrate the importance of developing breeder reactors, as with this string not only is the fissile part of natural uranium (U-235) able to be used as before but also the fertile part (U-238) can be converted into plutonium, which is itself fissile. Thus the breeders will extract the maximum energy that it is technically possible to obtain from uranium, and thereby directly bring about a considerable reduction of the proportion accounted for by uranium in the cost of nuclear power. In consequence, it will be possible to tap substantial uranium-bearing deposits which are already known but are at present unfit to be worked on economically acceptable terms owing to the low uranium content of the ore.
It is a fact that the world's uranium industry is at present over-producing and that prices have slumped and will remain very low during the years immediately ahead. It would, however, be blithely optimistic to interpret this as meaning that there is no

TABLE I
URANIUM RESERVES AS AT 1.1.1962
(exploitable at below $ 10/lb U_3O_8)

	Ore in millions of tons	Average content	Uranium metal in metric tons
USA	64	0.2 %	130,000
Canada	143	0.1 %	145,000 *
South Africa	680	0.017%	115,000 **
Other countries	—	—	60,000
Free world total:			450,000

* Other estimates take into account a further 60,000 tons which are also apparently recoverable.
** Estimate by the Chamber of Mines of the Republic of South Africa; in respect of reserves exploitable at a price of $ 8 per lb of U_3O_8.

TABLE II DEVELOPMENT OF RESERVES IN THE 1962-70 PERIOD

(in metric tons)

	Reserves as at 1.1.62	Extraction in the period 1962-70	Reserves as at 1.1.71
USA	130,000	71,000	59,000
Canada	143,000	25,000	120,000
South Africa	115,000	18,000	97,000
Other countries	60,000	16,000	44,000
Free-world total	450.000	130,000	320,000

supply problem. Any raw material supply policy must be drawn up on a long-term basis and the question arises whether the present slack state of the uranium market can continue for long in view of the increased demand which will result from atomic energy production after 1970.

Present reserves of the free world

The Consultative Committee has summarised in a table (Table I) the data available at the time of the survey on the present reserves of the free world. This table only gives those reserves the exploitation of which would make it possible to market uranium at a price not in excess of a certain ceiling. The ceiling adopted is $8-10 per lb of oxide U_3O_8 present in chemical concentrates, but it should be stressed that this is only a reference price acceptable in the present circumstances. It is, for instance, quite permissible, when examining all possible ways of meeting future requirements, to take account of the vast resources of low-content ores which today are regarded as too costly to exploit.

Development of reserves in the 1962-1970 period

It is possible, on the basis of the purchase contracts running over the next eight years, to assess the inroads which will have been made into reserves by the beginning of the next decade. As can be seen from Table II, these inroads will be quite considerable, since by the end of 1970 there will be only 320,000 tons left of the 450,000 tons available in 1962—in spite of the fact that the estimated rate of production will temporarily show a very marked decline in comparison with the levels attained in the years 1959-61 (an average of 22,000 t/a for 1962-66 as against 30,000 t in 1960).

There is, of course, a chance that in the meantime new high-grade deposits will have come to light. Even so, the downward trend just referred to is scarcely calculated to induce private companies in the United States and Canada to embark on costly prospecting operations—unless special government policy is involved. This is, in fact, a point to which the Consultative Committee reverts later in its report.

The fact remains that the mining industry will be in a state of depression in 1970—i.e. at the very time when there is likely to be an upswing in nuclear power production.

Possible demand for uranium in the free world after 1970

Before judgement can be passed as to the possible inadequacy of the 320,000 tons of reserves remaining at the beginning of 1971, it is necessary to calculate the scale consumption is likely to assume after that date.

Any forecast cannot but be of a speculative character. However, taking account of the estimates of nuclear capacity to be installed as published by the various countries, we arrive at the figures set out in Table III, which shows uranium needs for the period from 1970 to 1980.

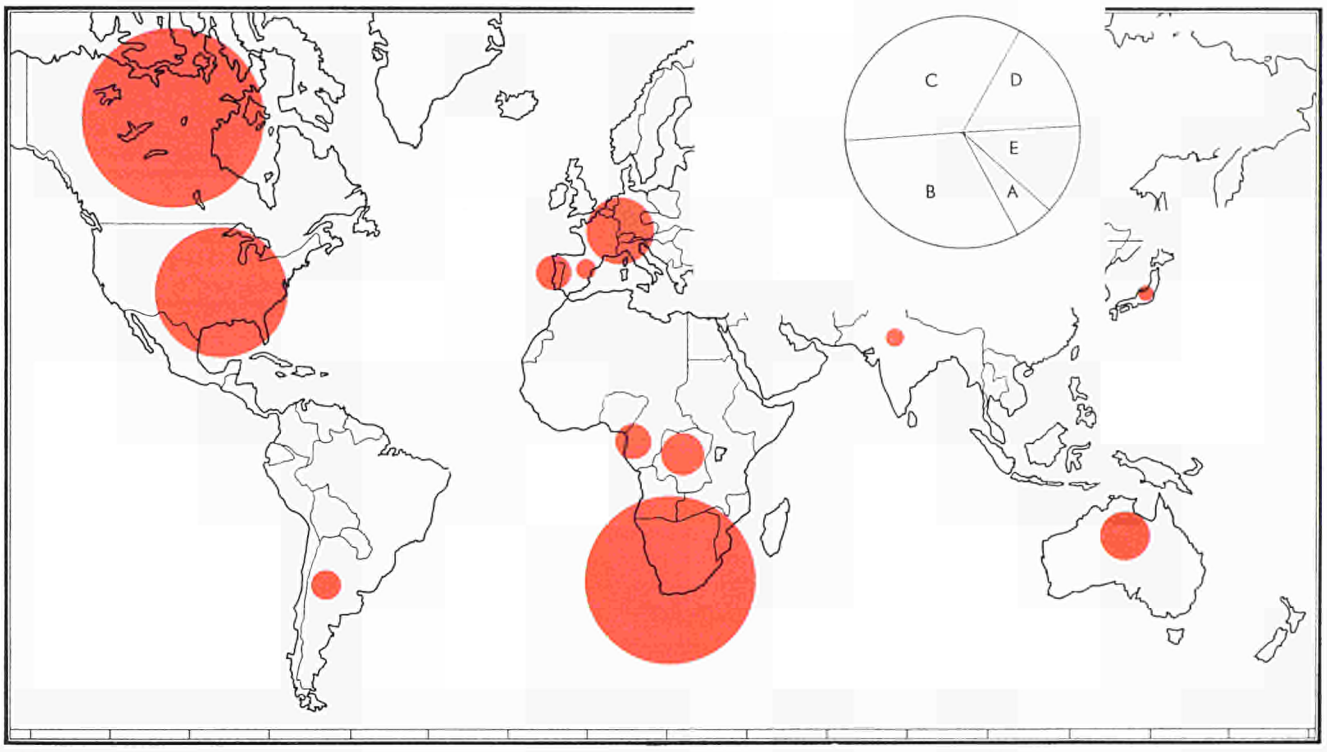
These figures are only approximate, but they would not appear to be in the least exaggerated. Total reserves, then, are likely to shrink to about 100,000 tons. On the other hand, it must not be forgotten that the ten years in question will be marked by a steady expansion of nuclear energy. Requirements shown in the table as 190,000 tons thus represent the integral of a curve of consumption, which will shoot up from 8,000-10,000 t/a in 1970 to 35,000-50,000 t/a in 1980.

By extrapolating beyond 1980, then, we see that known reserves able to be worked at a price of not more than $10 may well have been entirely used up by 1985.

Supply possibilities after 1970

This last observation may appear alarming. But it must be borne in mind that the reserves in question are those *known at the present time*; moreover, these forecasts have so far excluded all deposits, whether known or not, currently deemed unexploitable because of their low metal content. And these untapped deposits are today evaluated in terms of millions of tons.

It should be pointed out that the cost of the various operations involved in the production of uranium is directly proportional to the amount of ore to be processed. Clearly, therefore, the cost of the uranium extracted will, broadly speaking, be in inverse propor-



Known reserves, exploitable at a rate of 8-10 $ per pound of U_3O_8, as at 1 January 1971

N.B. The uranium supply available does not depend solely on these resources but is contingent mainly on production capacity (in South Africa, for example, uranium is a by-product of the gold extraction industry, so that its production rate bears no relation to the extent of available reserves).

Cumulative requirements for the period 1970-80 (estimated)

A Canada
B United States
C European Community
D United Kingdom
E other countries

tion to the ore content. Thus if the ore has a uranium content of 0.05%, the cost of the uranium extracted will be twice as high as if the content had been 0.1%.

The current estimate is that if the ore has a 0.1% content the cost per lb of U_3O_8 will be between $5.5 and $8. To this price should be added the amortisation of the prospecting and exploration costs, which come to $1-2 per lb of U_3O_8.

It is thus seen to be worth while continuing exploration as long as the cost of prospecting for fresh deposits is lower than the extra cost which the exploitation of known low-content deposits would involve. In view, therefore, of the exploration prices we have just quoted, there would seem to be no point in exploiting low-content deposits, since the cost rises steeply per lb of U_3O_8 (for instance, the $5,5-8 per lb for a content of 0.1% becomes doubled for a content of 0.05%).

In the coming years, the uranium market may be expected to develop along the following lines:

During the years immediately ahead, the

TABLE III URANIUM REQUIREMENTS BETWEEN 1970 and 1980

(in metric tons)

	Annual requirements in 1970	Annual requirements in 1980	Cumulative requirements 1970-1980
Europe	4,000	20,000	100,000
North America	3,000	14,000	70,000
Other countries	1,000	4,000	20,000
Free-world total	8,000	38,000	190,000

scantiness of demand will compel producers to supply uranium at near rock-bottom prices, which will no longer include the margins necessary for replenishment of their resources—even though their plant may already have been amortised.

After 1970, the expected rise in demand will make it necessary to instal new plants, and prices will consequently tend to take an upward turn. However, in view of the sharp rise in annual requirements from 1970 onwards, this stage will soon bepassed. Indeed, any analysis of the situation at that time must allow for another factor, which is the maximum production capacity of the various deposits. (The most striking example of the operation of this factor is to be found in South Africa, where uranium is a mere by-product the output of which is directly linked with the rate of gold production. On the basis of current market forecasts for gold, it can therefore be estimated that uranium output will not rise above the level of 5 to 8000 t/a, which bears no relation to the size of the reserves.) Output on currently known deposits will actually be insufficient to meet demand and *fresh deposits*, which have yet to be discovered, will have to be tapped. Extra costs will therefore have to be borne which will have a substantial effect on prices.

The overall conclusion of the Consultative Committee is as follows:

(1) The 320,000 tons of reserves outstanding on 1 January 1971 will at most equal only 15 years' consumption.

(2) An analysis of the production set-up suggests that these deposits will not even be sufficient to ensure adequate production capacity after 1975.

(3) New deposits will therefore have to be prospected over the next ten years, since the known low-content deposits appear in any event to be far more costly to work than those which may be revealed by new explorations in the light of present know-how.

(4) Numerous parts of the globe which have yet to be explored doubtless contain uranium deposits which it would be economic to mine. In view, however, of the fact that no spectacular discovery has been made in the world since about 1956, it would seem that a sustained effort will have to be made and that, whatever happens, the development of nuclear energy means that immediate priority will have to be given to the perfecting of breeding techniques.

Supply problems peculiar to the European Community

One point that emerges straight away from an examination of the supply problems peculiar to the Community is the marked imbalance between the various continents, through which Europe may find itself in an adverse position from a commercial, if not a political, standpoint. The fact is that the Community's needs for the 1970-80 period total about 65,000 tons, whereas its annual production capacity is no more than 1,500 tons and its present known resources are of the order of 25,000 to 30,000 tons. Imports from sources outside the Community are therefore indispensable.

A partial solution to this problem would be to acquire interests in currently dormant mines or to build up stocks while the price of uranium remains at a low level.

However, there is a radical solution which must be applied without delay—namely, the exploration of new deposits either in Europe itself or in other parts of the world so as to achieve an optimum spreading of sources of supply.

In this context, Europe naturally has a major stake in the rapid development of breeder reactors.

All this must not be construed as meaning that the progress of nuclear energy in Europe is in any way jeopardised.

Such an interpretation would overlook the fact that Europe's conventional energy is dear and that its resources of such energy are being severely taxed by the growing pressure of demand, as a consequence of which it is being thrown more and more on external sources of supply.

It would, however, be regrettable—and this is the conclusion of the Consultative Committee on the subject—for "Europe to be condemned, through lack of foresight, to acquire all its uranium in conditions which are economically unfavourable and subject to political risks".

Nor must it be imagined that breeders constitute a panacea. Such reactors can, in fact, only be commissioned gradually, depending as they do on the quantities of plutonium produced by the primary reactors. The improvement of breeder techniques and the exploration of new deposits must accordingly be viewed as two dovetailing methods of ensuring a sound basis for the development of nuclear energy in Europe.

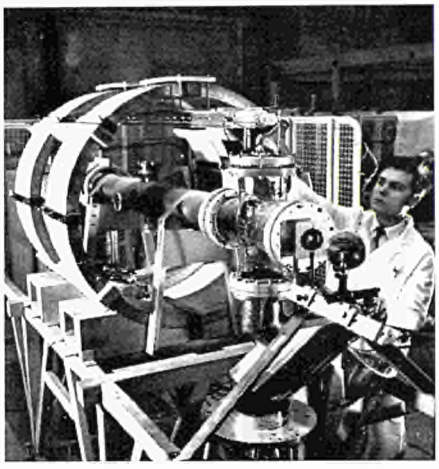
MICHEL GIBB, *Editor*

Major results in Europe in the field of nuclear fusion

The annual meeting of the *Division of Plasma Physics* of the *American Physical Society* was held at San Diego, US, from 6 to 9 November 1963, and significant reports were given by representatives of the European Community's laboratories specialising in nuclear fusion and plasma physics.

Great interest was aroused, in particular, by the paper read by a member of the Euratom/CEA team at Fontenay-aux-Roses, France, dealing with the discovery of a whole group of magnetic fields possessing a number of interesting properties.
As is known, magnetic fields are used in the majority of nuclear fusion experiments for confining the plasma, but researchers have usually come up against a problem here, for the first category of available configurations of magnetic fields provides a stable confinement, i.e., of relatively long duration, but has the drawback that the intensity of the field is zero at certain points in the configuration. In the second category, this situation is reversed, for the intensity of the field is never zero, but the configuration is basically unstable and causes rapid displacement of the plasma.
The interesting feature of the new type of configuration is that it can be stable without the intensity of the field dropping to zero. A specific example of these fields was proposed by Soviet physicists and tested successfully in several laboratories. Now a vast range of configurations is available to scientists.

The results obtained at Garching, Germany, and Frascati, Italy, with regard to plasma diagnosis were also received with interest. These involve, in particular, laser methods for studying the density and confinement of the plasma.



A research device at the Nuclear Fusion Research Laboratory at Fontenay-aux-Roses (France)

The Eurisotop Bureau organises a meeting of activation-analysis experts

On 21 and 22 November 1963, the Eurisotop Bureau held a working session on the applications of activation analysis, which was attended by more than fifty representatives of institutes and industrial enterprises in Community countries.
The meeting was concerned primarily with the practical measures—very often of an organisational nature—which are essential to the introduction of activation analysis in industry. It has in fact been established that very few analyses are carried out by this method in the Community.
Nevertheless, activation analysis is undoubtedly advantageous in many cases. The technique consists in irradiating the sample to be analysed and then, by counting the induced radioactivity, obtaining an accurate indication of the elements present in it. One of the major advantages of this method is its great sensitivity; it will, for example, detect elements which are present only in trace quantities. Moreover, it is less laborious than most conventional methods of chemical separation and does not require destruction of the specimen.

The participants were unanimous in their desire that the Eurisotop Bureau should be entrusted with a number of important tasks for the purpose of ensuring the expansion of activation analysis techniques. In addition, it was decided to set up as advisory and executive bodies ten working groups which will be presided over by leading experts in the Community.

Euratom liaison meeting on nuclear ship propulsion

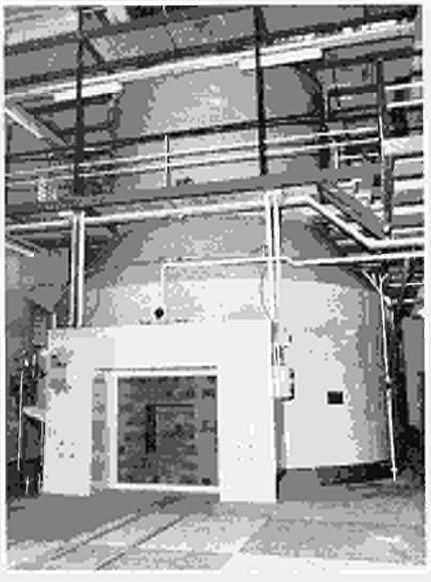
On 17 January the Euratom nuclear ship propulsion committee met, bringing together experts from Euratom and its association contract partners as well as representatives from the member governments. The meeting provided the opportunity to survey the work being done in the Community.
During the meeting recent experiments and research plans for the immediate future were described. The report of the German delegation gave rise to particular interest by providing full details of the technical aspects of the type of pressurised water reactor which will power the 16,000 dwt experimental bulk carrier whose keel was laid in October 1963 and which is now under construction. This project is being undertaken by *GKSS (Gesellschaft für Kernenergieverwertung in Schiffbau und Schiffahrt)*.

The Italian and German delegations also gave explanations of the collision experiments involving the study of the structure to be incorporated in the hull construction for the protection of the containment vessel of an atomic reactor in case of collision.
The participants were unanimous in their approval of the projects, all of which they held to be scientifically profitable. They indicated their satisfaction with the rôle of co-ordination and stimulation played by the Euratom Commission.
Euratom is participating in nuclear ship propulsion research through three association contracts:
— with *GKSS* for research into special sea reactor design and operation problems. The main subjects of experiment are shielding and the effects of the movement of a ship on reactor operation;
— with the Dutch *Reactor Centrum Nederland (RCN)* for research connected with the design of an advanced PWR reactor;
— with the Italian *Fiat* and *Ansaldo* concerns with the support of the *Comitato Nazionale per l'Energia Nucleare (CNEN)*; the first phase of the research work, which involved making a comparison between several types of PWR and BWR reactor led to the selection of the forced circulation PWR as the most promising type.

Negotiations are pending concerning a possible Euratom participation in the construction of the reactor to be installed in the *GKSS* ship.

First experiments in the Wageningen reactor

The first irradiation tests in the controlled-chamber of the reactor at the *Institute for the Application of Atomic Energy in Agriculture (ITAL)* at Wageningen (Holland) were carried out at the end of last year.
The reactor, which is specially designed for the Institute's needs, is of the "swimming-pool" type, is fuelled by 90%-enriched uranium, and has an output of 100 kW. It is equipped with an irradiation device which enables samples to be exposed simultaneously to fast neutrons (10^{12} fast neutrons/cm².sec) and to thermal neutrons (10^{11} thermal neutrons/cm².sec), and with a "thermal column" across which a flux of 10^{8} thermal neutrons/cm².sec can be maintained.
Furthermore—and this is the most original feature of the *ITAL* reactor—there is a chamber under the reactor core in which luminosity, temperature and humidity can be exactly fixed. In this way it is possible to irradiate entire plants (or animals) in well-defined conditions over a useful surface of several square metres.
This controlled chamber has just been used for the first time; for the moment, only a thermal neutron flux is available, but a device for supplying fast neutrons is being developed.
It will be remembered that the *ITAL* Institute is connected with Euratom by a contract of association.



Concrete protection shield and thermal column containing the graphite of the ITAL reactor

Training in Euratom research establishments

The issue of the Official Gazette of the European Communities published on 21 January 1964 contained the details of a new scheme which is to be introduced for bursaries and for the participation of visiting scientists in nuclear research carried out by Euratom.

Bursaries

These bursaries are intended for graduate scientists, who are to be provided in this way with the opportunity of continuing their education in research establishments belonging to Euratom as well as in institutes or laboratories working under contracts of research or association with Euratom. There are three categories of such awards:
— for scientists who are writing *theses* in the natural sciences on subjects which fall within a field covered by the Euratom research programme and who intend to carry out the work involved in Euratom research establishments;
— for scientists who, after graduation, wish to *specialise* in a particular branch of nuclear science;
— for young lecturers at *institutes of technology* who are carrying on with their teaching career but who wish to carry out experimental work dealing with their subject in a research centre and to keep in touch with applied research.
The bursaries will be awarded for a period depending on the time required to complete the research involved, but not exceeding 24 months. They will be worth sums ranging from about $ 200 to $ 400 per month, depending on qualifications, age, personal circumstances, etc.

Visiting scientists

Euratom also has a scheme under which visiting scientists can spend up to a year working on Euratom research projects. They are sent and continue to be paid a salary by their own research establishment, while Euratom grants them in addition a foreign living allowance and pays their travelling expenses.

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Student trainees

The student trainee scheme, which has been running since 1960, enables some 300 students a year to familiarise themselves with the various fields of nuclear science and technology (see also Euratom Bulletin No. 3/1963). The trainees receive about $ 150 per month.

These training programmes are designed to provide scientists and students with the opportunity of transcending their own national horizons and assimilating the new European style of research and collaboration. The trainee scholarships and bursaries are also available to nationals of non-member States and particularly to applicants from the newly-developing countries.
Those interested can apply either direct to Euratom or through the establishment to which they belong. Application forms may be obtained from:
Euratom, Directorate-General for Research and Training, 51-53, rue Belliard, Brussels.

New publication: "Nuclear Medicine"

Euratom has drawn up a contract with the *Excerpta Medica* Foundation of Amsterdam concerning the organisation of scientific documentation of literature on nuclear medicine. Under this contract, *Excerpta Medica* will scan the world's medical literature and select articles relating to nuclear medicine. Specialists in this field will then make abstracts of the articles, which will appear in a new monthly publication entitled "Nuclear Medicine". At the same time, copies of all the bibliographical data and abstracts will be forwarded to Euratom's Information and Documentation Centre, which will then make them available to experts throughout the Community through the use of its new electronic machines, thus adding to and rounding off the programme of the Euratom Commission for dissemination of information.

Ispra Research Establishment (Italy)—Expansion measurement apparatus for solids in the Metallurgy Department.

Development of Graphite-Gas Reactors
Conclusion a of Series of Research Contracts

A series of research contracts were recently concluded by Euratom for the development of graphite-gas reactors, in particular with:
— the French *Commissariat à l'énergie atomique (CEA)*, for studies on so-called integrated loading and unloading systems for fuel elements. The loading and unloading device would in future be located not *above* but *inside* and at the top of the reactor pressure vessel;
— the German company *AEG* and the French company *Alsthom*, for studies of the economic advantages of increasing the characteristics of the primary circuit (in particular the gas pressure);

— the French company *Bertin* for studies of the phenomenon of heat exchange by the natural convection of high-pressure gas;

— the German company *Deutsche Babcock & Wilcox* and the French company *Indatom* for the development of a system for thermally insulating a concrete vessel with water shields;

— the German company *Deutsche Babcock & Wilcox*, for studying, with the aid of in-pile gas loops, graphite oxidation and carbon migration;

— the French company *Fonderies de précision* and the German company *Karl Schmidt G.m.b.H.* for the manufacture of magnesium-zirconium alloy fuel cladding by die-casting.

These research projects come under Euratom's second five-year programme under the heading of "research into proven-type reactors."

Electricité de France EDF 2 power reactor, under construction at Chinon.

Canada/Euratom Agreement—joint work on fuel elements

The primary aim of the Euratom/Canada cooperation agreement is to exchange information on heavy-water and natural-uranium reactors; a further object is the joint pursuit of certain research projects in this field.
Thus large-diameter (28 mm) uranium-carbide rods with SAP (sintered aluminium powder) cladding were fabricated at the Ispra establishment of the Euratom Joint Research Centre from materials supplied by Community industries, and then sent to the Canadian national nuclear research centre at Chalk River for irradiation.
A considerable technical effort had been expended on developing these large-diameter rods in order to cut the cost of the ORGEL fuel element. It now remained to check their properties by irradiation-testing.
They were irradiated in the X 7 organic-liquid loop of the NRX reactor towards the end of 1963, and successfully underwent 2 months' irradiation at temperatures fully representative of an ORGEL reactor. The elements are now undergoing thorough inspection in hot cells.

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