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The Future Utilization of Nuclear Energy in Europe

K. Wirtz

GESELLSCHAFT FUR KERNFORSCHUNG M. B. H.

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For the 2nd FORATOM Congress, Frankfurt, September 29 to October 1, 1965 two reports have been prepared for Section IV of this Congress on "The Future Utilization of Nuclear Energy in Europe". One report deals with the international situation, the second one with the Federal Republic of Germany only.

The basis for the national and the international reports was a questionnaire to Section IV of the Congress that had been sent to the member countries of FORATOM beforehand. The questions were the following:

1. Will there be in the future a market and a requirement for small stations of 30 to 50 MWe?

2. What importance should be attached to direct conversion during the next 10 to 20 years? Direct conversion is intended to include all those systems in which there is no conventional change of energy between the core of the reactor and the production of electric current. This will therefore include MHD generators.

3. What will be the problem of the efficient use of nuclear fuel in the decades to come (see the article by J.R. Dietrich on "Efficient utilization of nuclear fuel", Power Reactor Technology, Vol.6, No.4, 1963)?

4. What arguments are there at a given moment for or against the utilization of breeder reactors based either on the cycle thorium - uranium-233 or uranium-238 - plutonium-239? To which process should preference be given? What work is required in this field?

5. What are the prospects for the reactor types of the future (molten salt reactors, high-temperature gas-cooled reactors with gas turbines, suspension reactors, etc.)?

A short summary of the replies to these questions will be found in section 1.8 of the international report. More detailed evaluations may be found in the other sections of the national and international reports.

Conclusions Concerning the Future Utilization of Nuclear Energy in Europe

International Report

Section IV

of the 2nd FORATOM Congress
Frankfurt, September 29 - October 1, 1965

Report by: Professor Dr. K. Wirtz
Karlsruhe Nuclear Research Center
and Technical College, Karlsruhe

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1. Survey of the National Reports to the Questions of Section IV

Seven countries submitted reports on the questions raised in Section IV. This is a survey of these reports arranged by countries.

1.1 Belgium

Belgium does not yet have a long-term atomic energy program. Therefore, there is no basis for the evaluation of the future fuel requirements. Yet, various studies were conducted with the aim of gaining an overall picture of the requirements up to 1985. Up to that year an annual increment in the demand for electric energy of 6.5 percent, gradually decreasing to 5.5 percent, is estimated. The percentage of nuclear energy in this increment is estimated to be about 20 percent in the beginning and gradually increasing to 80 percent later on. On this basis one arrives at a demand for natural uranium oxide of about 10 tonnes of uranium per annum in 1970 increasing to some 90 tonnes of uranium per annum in 1984, this increase not being smooth but showing peaks for every installation of new power stations. Also the demand for enriched uranium has been estimated. A more detailed consideration of the future need for nuclear fuel is thought to be useful.

A market is envisaged for small power stations on a nuclear basis. The VULCAIN reactor is hoped to generate 25 MWe on the basis of some DM 1,000/kW of installation cost and at a fuel cost of 2.6 mills/kWh.

With respect to direct conversion Belgium neither has had any experience nor conducted investigations.

In the introduction of fast breeder reactors where a short doubling time is thought to be particularly important, one sees a way to the more effective utilization of nuclear fuels. Belgium tries within the framework of EURATOM to participate in the development of fast breeders. This type of reactor is believed also to offer possibilities of economic development. For various reasons less good chances are given the thorium-uranium-233 cycle at the moment: The characteristics of the plutonium-uranium-238 cycle are regarded to be better known than those of the thorium-uranium-233 cycle. The useful reserves of uranium-238 are believed to be larger than those of thorium. Finally, the nuclear characteristics of plutonium are regarded as being better than those of uranium-233 (better breeding potential).

The Belgian report, finally, shows a sceptical attitude towards all other advanced types of converters. However, Belgium has conducted studies about a fast superheat reactor with steam cooling (HERMES). An advanced development offering good prospects is investigated in a study of the reactor SATURNE (1,000 MWe).

1.2 United Kingdom

The British report starts from the assumption that nuclear energy now has reached the stage where the original intentions have been fulfilled, i.e. to make available economic reactors for the utilization in large electric grid systems. In Britain there are five large nuclear power stations and

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four more are being built. Tenders have been invited for a tenth one. The energy costs of the latest nuclear power station in Wylfa, which contains a gas-cooled reactor with graphite moderator and natural uranium like the rest, will be cheaper than those of coal-fired power stations.

For the future development these are the main aims: Further reduction of the cost of present stations as well as introduction of reactors of the advanced gas-cooled type which is believed to permit a strong cost reduction. The Atomic Energy Authority has found this type of reactor, once it has amortized over 25 years and is operating at a load factor of 85 percent, to be able to generate electric power at some 1.7 DPf/kWh.

According to the British report another main goal is the generation of cheap nuclear power in small units. A market is envisaged for small power reactors, if they are economically attractive. Data showing how toachieve this economy are not indicated.

Another goal is seen in the economic utilization of nuclear fuel, mainly by fast breeder reactors which will use for the fuel the plutonium generated in the first series of British nuclear power stations as well as the uranium-238 left over there from the reprocessing of the fuel. The use of thorium either in thermal or in fast breeder reactors is not envisaged for the near future. However, if atomic energy would play the part by the year 2000 to the extent that can be foreseen today, the inclusion of thorium as a fertile material would have to be regarded as an important part of future reactor development.

The British development regards other reactor variations. Thus, the Atomic Energy Authority builds a pressure tube reactor cooled by water vapor as well as a heavy-water moderated and cooled reactor. For the breeder reactors it is hoped that an order for a prototype of some 250 MWe can be placed still in 1965 which would make energy out of fast reactors available in Britain by 1970, i.e. just about the time when the prices of natural uranium will increase, as far as we are able to foresee today.

For the near future the British report does not envisage any utilization of thermoelectric or thermionic conversion for the process of energy generation.

1.3 France

The main argument in favor of the introduction and development of nuclear energy in France is seen in the fact that nuclear energy promisses very good economy even compared with the generation of energy on the basis of fossile fuels for which France has to spend a very high amount of foreign exchange now. It is believed in France that atomic energy development will come about as a matter of course if it is competitive under these aspects: Investments, proportional costs, availability. All aspects are judged to be favorable. Some work on the future utilization and needs of nuclear fuel has been done; we present it in chapter 3. From the considerations the following aspects emerge:

a) In the attempt not to scatter the efforts over too many projects indiscriminately France will continue to concentrate upon the development of these types: gas-graphite-natural uranium; heavy water-natural uranium (corresponding to the British Magnox-reactors); fast breeder on the basis of plutonium-uranium-238.

b) The development of the light water concept is followed with interest just as the development of the types showing remarkable efforts of development, e.g. the ORGEL project at Ispra or the graphite-helium-cooled high-temperature reactor (DRAGON or BBC/Krupp reactor).

c) In adjusting the short-term and intermediate programs the price per kilowatt-hour taking into account the fluctuations of currency - which are hard to calculate in advance - as well as the security of supply, is given more emphasis than the conservation of natural resources. Yet, the long-term problem ist not overlooked.

d) France is convinced that at the present time the risks of a failure in the development of nuclear energy are negligible.

e) The technical prospects of specialized concepts, e.g. the molten salt reactor, are regarded sceptically. In the long run the best chances are attributed to the fast breeder reactors not only because of the better utilization of fuel but mainly because of the hope of their offering exceptional economic potentialities.

1.4 Italy

The Italian report does not see any future for small power stations based on nuclear energy, mainly for cost reasons.

With regard to direct conversion it is believed that thermionic converters as well as thermocouples are not sufficiently developed to attain practical importance for any foreseeable period of time. Thermionic as well as thermoelectric converters are experimentally investigated in Italy. Magnetohydrodynamic generators are given closer study in Italy, but no predictions are possible about their usefulness.

Also with respect to the fusion of light elements for power generation a prediction is deemed to be impossible at the present date.

The importance of an economic utilization of nuclear fuels is recognized. A solution of the problem is believed to be the development of the breeder reactor. However, no arguments are given to show the course of development. Therefore, the report is positiv with regard to the development of breeder reactors, in particular with respect to the fast breeder based on the cycle uranium-238 - plutonium-239. In Italy the technical problems connected with this development are discussed. In the Atomic Energy Program of the Comitato Nazionale per l'Energia Nucleare (CNEN) for 1965/69 attention is devoted to the development of breeder reactors, especially under the aspect of cooperation with EURATOM. Some chances for the thorium-232 - uranium-233 cycle are foreseen in the high-temperature reactors with gas-cooling as well as in the heavy water reactors, but the development is believed to be less advanced.

Among the more exotic variations some are credited with good potentialities, e.g. the concepts using liquid fuel or the molten salt reactor, but the difficulties of technical development of these types are emphasized.

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1.5 Switzerland

Switzerland sees prospects for small nuclear power stations of 30 to 50 MWe as long as they are economic.

With regard to direct conversion little chances are given the technical application of the thermionic or the thermo-electric principle for some time to come. The magneto-hydrodynamic generator is judged more favorably, but a long period of development is envisaged before technical application will be possible economically.

The problem of effective utilization of nuclear fuel is not an urgent one at the present state of Swiss development.

Among the more exotic reactor variants the gas-cooled high-temperature reactor is judged as favorably in the report as the fast breeder reactors. However, concepts using fuel suspensions, metallic or ceramic melts etc. are treated with some scepticism.

1.6 Spain

The report sees chances for small nuclear power stations ranging from 30 to 50 MWe in the case that they supply sufficiently cheap electric energy in certain parts of Europe as well as in other regions of the world where the supply of conventional fuel is expensive. The size of the market is treated with some reserve.

In the coming ten to twenty years no technical application is seen for the direct conversion in the field of electricity generation on a nuclear basis.

It is the view of the Spanish authors that no fuel problem will impede the development of atomic energy if the uranium-238 - plutonium breeding cycle can be carried through successfully. In case an improvement in the utilization of fuel should become necessary prior to the introduction of fast breeders, the heavy water reactor based on the pressure tube design would be a suitable choice among the thermal reactors.

The development of breeder reactors is regarded as a necessity. It is thought likely that the fast breeder on the basis of uranium-238 - plutonium will be in the market earlier than the thermal breeder based on thorium and uranium-233. Spain herself is interested in a fast reactor of the Argonne Fast Source Reactor type for study purposes. This will be a pure research tool without any possibility for generating energy.

For the future the further development of now proven power reactors of the light-water type (pressurized and boiling water reactors) as well as the gas-graphite type is envisaged. The chance for heavy water reactors to play a major part before the development of the fast breeder has been completed is judged positively. It is also deemed possible that in the case of gas cooling the more advanced types (Advanced Gas-cooled Reactor (AGR), High-temperature Gas-cooled Reactor(HTGR)) will enter into the picture. Reactors using natural uranium as fuel might always have a chance again for reasons connected with national economies. This is said to be as true of the gas-graphite types as of the heavy water reactors. The Spanish report contains no speculations about the prospects of "exotic" types of reactors.

1.7 Federal Republic of Germany

Because of cost reasons the report does not see a market for small nuclear power stations for the immediate future. Judged from the demand, such a market would be present in the Federal Republic. This is emphasized especially by some large German industrial firms. In the Federal Republic smaller types of nuclear power stations are developed. In case it should become evident, contrary to all expectations, that they are able to supply electric energy at competitive prices, they might expect a demand of several hundred MWe per annum.

In the opinion of German industry methods of direct energy conversion will have no economic significance within the supply of energy on a nuclear basis for the next 10 to 20 years.

The efficient utilization of nuclear fuels for the coming decades is the subject of investigations carried out by a joint study group of scientists and representatives of industry at Karlsruhe Nuclear Research Center. These results are reported in chapter 3.

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In the Federal Republic prospects are envisaged for the thermal breeders operating on the basis of the thorium - uranium-233 cycle as well as for the fast breeder reactors run on the basis of the uranium-238 - plutonium cycle. The introduction of breeder reactors is believed to be necessary in the long run. On the whole, it seems as if slightly better prospects were envisaged at present for the fast breeders based upon the uranium-238 - plutonium cycle. Both types of breeders are studied by German industry. It is hoped that not later than by 1968 data will have been worked out for prototypes of fast breeder reactors of 200 to 300 MWe with sodium cooling or steam cooling which are intended for construction either on a national basis or in cooperation with other European nations in the years from 1968 to 1971.

Another problem pursued with interest in the Federal Republic is the question whether there is going to be a generation of advanced converters in addition to the present proved types of power reactors (boiling water and pressurized water reactors, Magnox reactors) and the breeder proper; among these mainly the heavy water reactors would have to be counted.

Considerable efforts are taken in this field in the Federal Republic, but it is recognized that these advanced converters will have a chance mainly if they offer considerable economic advantages. In view of the decreasing costs of electric energy of the types mentioned above this might turn out to be a difficult job (e.f. also chapter 3).

Exotic variants (molten salt reactors etc.) are judged with reserve, but some studies are conducted.

1.8 Summary

Here only a brief conclusion shall be drawn from the reports of the European countries for Section IV of the Congress. In the following chapters several points are dealt with in more detail. On the whole, the comments on the individual questions of Section IV agree remarkably well. No FORATOM country envisages the fusion of light elements into the nuclear power generation or the use of direct conversion for improving the efficiency of nuclear stations. Several reports do envisage a market for small power stations, but do not indicate much hope for an economic development. Unanimously a very good chance is envisaged for the fast breeder. The reports also agree on a continued development of the presently successful power reactors of the boiling water or pressurized water concepts, respectively, or of the gas-graphite type. The reports recognize the necessity of studies on the economic utilization of fuel, but a systematic investigation was carried out only in a few cases. These will be dealt with in chapter 3. The advanced converters, such as heavy water reactors, are regarded with interest, yet, no report attempts to state whether they will find a place in the market for nuclear power stations before the development of fast breeder reactors has been concluded. In one aspect all the reports agree: solely problems of cost will determine the future situation. In this connection the development of a promising new type may depend upon a country's willingness to spend the considerable funds necessary for the development of a reactor line. If this is not the case, a concept which may be promising on principle can be doomed for failure because the funds for its development, which may be between DM 500 and 1,000 million, are not available.

2. More Detailed Treatment of Some Problems

2.1 The Market for Small Nuclear Power Stations

In the British report one future aim of the development is stated to be the creation of inexpensive nuclear energy in small units. The main reason is said not to be their use in European power grids. This would be impossible for cost reasons. However, there might be a market for smaller power reactors for demonstration purposes in Europe. One example is given in the offer of a 50 MWe demonstration reactor of the AGR type for a German group of utilities. Water reactors might also become important in this respect. Let me quote: "There have been interesting developments in the search to reduce capital costs and to achieve low fuelling costs through long fuel life. Among these are the developments of pressurized water reactors, such as the concept of the integral reactor with heat exchangers, pumps, and other equipment included in the reactor vessel; the use of burnable poisons in the fuel to even out the effects of fuel burnup; and the use of spectral shift - varying of the moderator composition through changing the ratio of light and heavy water." Unfortunately, these more general remarks are not supplemented by design features or cost figures.

The German report also points out that some German industries have positive views of the market and the demand for small power stations. In the industrial power stations of the Federal Republic which contributed about 37 percent of the standby capacity installed in the Federal Republic in 1963, about 20 percent were in the power range from 10 to 15 MWe; about the same number was due to powers ranging from 50 to 100 MWe. The average rate of growth of the capacity installed in industrial power stations is stated to have been about 7 percent in the years 1960 to 1963. In addition, there are the power stations of the Bundesbahn (Federal Railways) the power of which amounts to almost 12 percent of the overall standby power of the Federal Republic and which are exclusively within the power range regarded here. Without the railway power stations, which have a kind of special position in the energy supply of the Federal Republic, and at a growth rate of 7 percent the increase in capacity in 1964 would have been about 600 MWe in plants between 10 and 100 MWe. However, no statistical information exists yet for 1964. From the 1963 statistics it can be taken that out of the new public power stations started upon with a total capacity of 1,980 MWe more than 26 percent, i.e. 526 MWe, were contributed by powers between 10 and 100 MWe. The share of the market in the range of small and medium powers is stated to have increased accordingly in the public power system compared with large plants in 1963.

Beside this statistical analysis of the market there are a series of technical aspects which, in the opinion of some German industries, indicate that at least medium-sized installations between 50 and 100 MWe are going to maintain their share in the domestic market also in the future. Among these aspects there is the fact that industrial power stations only in exceptional cases will require larger units. Due to the structure of our average big cities the same fact applies to municipal heating power stations, if an intensive utilization of the available waste heat is the aim in these plants. In addition, the competitiveness of these heating power stations is said to be safeguarded by the very utilization of waste heat. In any case, the cost share due to the interconnected system may be reduced by energy production controlled by demand. For this type of plants an important export market is also envisaged.

It has been pointed out also that at the 3rd Geneva Conference a French study (A/Conf.28/P/46) was submitted which showed that combined electricity and heat generating stations might compete economically with conventional installations up to relatively small units of some 100 thermal megawatt also on a nuclear basis. There was also work from the Soviet Union (A/Conf.28/P/319) which for the coming ten to twenty years envisaged some 20,000 MWe being installed in the power range from 20 to 50 MWe.

These data and considerations of a market analytical nature are one of the factors determining some German industries to regard the development of gas turbines combined with power stations and heating systems equipped with gas-cooled high-temperature reactors as a promising variation of the development of high-temperature reactors also in the medium power range. The arguments relating to gas turbine development will be treated in the following section. Unfortunately, there is also a complete lack of statements about the problem of costs in these presentations. In the author's opinion it appears to be not very likely, therefore - until the contrary has been proved - that small nuclear power stations will be competitive with small power stations operating on a coal or oil base.

2.2 Gas Turbines

The gas turbine process would offer the possibility of utilizing the thermodynamical advantages of gas-cooled high-temperature reactors in a good way, because the direct coupling of reactor and turbine would result in a particularly simple process. Moreover, the temperature level of the coolant of a gas-cooled high-temperature reactor meets the requirements of a hot-gas turbine.

There seems to be sufficient experience with smaller gas turbines in a closed cycle so that the application of this machine in connection with a reactor should not introduce any additional uncertainty. Thus, in the past few years the Gutehoffnungshütte AG, Federal Republic of Germany, has built several hot-air turbines in the power range between 2 and 14 MWe which proved to operate successfully. One plant of 14 MWe in Oberhausen reached an operating period of some 30,000 hours by the end of 1964. These plants use turbine inlet temperature above 700°C. It is believed that in such a power station of 25 MWe with a gas turbine a plant efficiency of some 37 percent can be achieved. In addition, it would be possible without any loss of efficiency in power generation to use more than one third of the thermal power introduced into the gas for heating purposes in a range of temperature between 60 and 120°C. Also the temperature of waste heat would offer a possibility of operating an expansion evaporator for desalting sea water in combination with a gas turbine in a closed cycle. In this type of multi-purpose plant on principle 70 percent of the heat introduced could be utilized. The series connection of a closed gas turbine plant ahead of a steam generator, which in turn operates on a steam turbine, would be a principal possibility of increasing overall plant efficiency. German industry thinks that by going to helium gas instead of the air used so far in the already proven types of gas turbines up to 150 MWe per unit might be realized.

In May of this year a symposium was held in Paris on "The Use of Gas Turbines in Nuclear Power Stations". There were some important contributions, chiefly by the British delegates, which showed that Britain seems to think gas turbines could be built up to a power of 250 MWe. This is a power range which seemed to be completely closed to the gas turbine so far. It is higher by about one order of magnitude than all gas turbines really built to this day, and it is hard to estimate what costs and development work are required to actually reach this power range. Thus, the National Gas Turbine Establishment treats the efficiency and the component sizes of a nuclear-heated closed gas turbine cycle of 250 MWe power with argon or helium cooling. The reference design study with helium for the coolant which has been regarded has these technical data:

Maximum gas temperature	1,100°K
minimum gas temperature	310°K
maximum pressure	40 atm
minimum pressure	13.64 atm
thermal efficiency	40.7 percent
mass flow for 250 MWe power	678 lb/sec

In the statements of the study these data are about the extremes of temperature and efficiency which may be attained in gas turbine plants over the coming decade.

The DRAGON Project considers a gas-cooled high-temperature reactor which would be suitable for this type of plant of 250 MWe. The cooling gas is helium at an outlet temperature of 1,100°K and a pressure of 39 atm. The reactor is housed in a pressure vessel made of prestressed concrete. No details about the reactor design are given, but the development of high-temperature reactors with helium cooling should be possible in this range of powers and temperatures.

At the Paris symposium on gas turbines the Rolls Royce Company also presented a study on a gas turbine of 250 MWe. Helium is also used here for the cooling gas at 1,100°K.

If the development of reliable gas turbines of 250 MWe were possible, the use of three or four of such turbines combined with a high-temperature reactor plant for 1,000 MWe would be a potential line of development to reach high thermal efficiencies.

3. Nuclear Fuel Requirements and the Cost Structure of Nuclear Energy Development

3.1 Data from various countries about the future need for electric energy generated by nuclear processes

On the basis of the information given in the national reports under Section IV as well as of other publications assumptions have been listed in Table 1 about the generation of nuclear energy in the whole western world, the United States of America, the United Kingdom, the European Economic Community (EEC), and other European countries. References are quoted at the end of this section. The figures offer sufficient information to permit an estimate under certain conditions of the need for nuclear fuels as well as the cost structure of the whole nuclear energy development. This type of analysis has been carried out so far actually only by a few FORATOM countries. To the extent it has been done the results will be discussed briefly in the following sections. Table 1 shows that the installed nuclear electricity generating power assumes an increasing percentage of the whole generation of energy which is going to be about 50 percent in the year 2000 for the whole European Economic Community as well as for the Federal Republic of Germany.

References:

H. Michaelis	Technische Rundschau (Switzerland) 30 and 31, 1965 "Die wirtschaftlichen Aussichten der Kernenergie in Europa"
EURATOM	Symposium on the Long-Term Orientation of Nuclear Energy Development in the European Community, Venice, April 12-14, 1965 "Basic Aspects of an Industrial Policy (tentative program)"
W. Penney	3rd International Conference on the Peaceful Uses of Atomic Energy 1964, A/Conf.28/P/559 "Nuclear Power in the United Kingdom"
J. Cabanius H. Horowitz	Third International Conference on the Peaceful Uses of Atomic Energy 1964, A/Conf.28/P/31 "The French Nuclear Power Program"
G.F. Tape	Third International Conference on the Peaceful Uses of Atomic Energy 1964, A/Conf.28/P/192 "Future Needs and the Role of Nuclear Power"
R. Gibrat	Third International Conference on the Peaceful Uses of Atomic Energy 1964, A/Conf.28/P/99 "The Essential Factors in a Balanced Nuclear Economy"
Kernforschungs-zentrum Karlsruhe	KFK report published by the Karlsruhe Nuclear Research Center (in preparation) "Kernbrennstoffbedarf und Kosten verschiedener Reaktortypen in der Bundesrepublik Deutschland"

Table 1: Forecasts about the Electric Power Installed on a Nuclear Basis (in units of 1,000 MWe)

Year	Western World	USA	U.K.	EEC	France	Federal Republic of Germany		Belgium	Total electric power installed	
						optimistic	pessimistic		EEC	Fed.Rep.of Germ.
1965	6.3	1	3.7	1					90	40
1970	23	6	5.3	4	2	2	2	0.18	120	55
1975	86	32	10.3	15	8	8	7	0.64		75
1980	202	70	16	40	20	20	16	1.9	227	98
1985	372	125	26	75	39	38	28	4		118
1990				135	68	62	43		409	150
2000				370	170	132	85		730	230
2020						310	213			450
2040						760	405			760

3.2 Forecasts about the natural uranium requirements

From the data given in section 3.1 it is possible in principle to deduce some forecasts showing the natural uranium consumption, if it is known at the same time what types of reactors will be used in the nuclear power generating economy. This is possible only within specified limits - especially so for the more distant future. Therefore, the data showing the consumption of natural uranium must be regarded only as a consequence of assumptions about certain lines of power reactor development intended or planned by the individual countries. The most detailed investigations are available from EURATOM, France, and the Federal Republic of Germany. Some other countries have also attempted to elaborate data on the basis of the foreseeable development for the coming years. The data are listed in Table 2. The potential demand for enriched uranium was converted into the equivalent demand for natural uranium by multiplication of the enrichment percentage by the factor 150. The figures cannot claim accuracy in detail; they should rather demonstrate the orders of magnitude as well as the gradients of increase in demand.

In the data for the European Economic Community (EURATOM) the figures used were taken out of example IV of the tentative program of EURATOM. This example reflects the succession of light-water converters, heavy-water converters, and fast breeder reactors in the domain of EURATOM.

The figures for the Federal Republic of Germany are based upon the data taken out of the optimistic bracket in Table 1 as well as a combination of light-water reactors and fast breeders for which the additional condition must be fulfilled that all the plutonium arising from light-water converters and later from the breeders is used for the startup of new fast breeders.

The French data are based upon a combination of gas-graphite reactors, heavy-water reactors and fast breeders.

The data of the different countries are fairly consistent; this is remarkable if one considers that they were estimated independently. Data of a similar degree of accuracy are not available for the United Kingdom.

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Table 2: Forecasts about the Natural Uranium Consumption in some FORATOM Countries (cumulated data in 1,000 t)

Year	EEC (EURATOM)	France	Federal Republic of Germany	Belgium	Spain	Switzer-land
1970	6	3.7	2.5	0.36	1.5	0.3
1975	25	6	10	0.80	5.2	1.9
1980	54	20	25	1.7	12	5
1985	100	38	48	3.5		
1990	176	59	75			
2000	330	110	150			

References:

EURATOM — Documentation EUR/C/1000/2/65d, June 1965, "Situation and Perspectives of Nuclear Energy in the European Economic Community"

Kernforschungs-zentrum Karlsruhe — KFK report published by the Karlsruhe Nuclear Research Center (in preparation) "Kernbrennstoff-bedarf und Kosten verschiedener Reaktortypen in der Bundesrepublik Deutschland"

3.3 Production of plutonium

Three countries submitted rough estimates of cumulated production of plutonium in their national reports. They have been compiled in Table 3. The importance of these figures becomes evident when one considers that about 3 tonnes of plutonium are required for every 1,000 MWe of installed power in fast breeder reactors (i.e. about 4/3 core loadings).

Table 3: Production of Plutonium by Converters (cumulated data in t)

Year	United Kingdom	France	Federal Republic of Germany
1975	20	5	6
1980	35	20	20

3.4 Multi-type strategies

In the long run most FORATOM countries anticipate the concurrence of several types of reactors in the provision of nuclear energy. The United Kingdom, e.g. envisages that already by the seventies the Magnox reactors (gas-graphite) will be joined by fast breeders. For the coming decades France expects that there will be gas-graphite reactors, heavy-water reactors, and fast breeders side by side. In the Federal Republic it is also assumed that in the coming decade several lines of development will be pursued simultaneously, such as light-water, heavy-water, and fast breeder reactors. A forecast attempted today for the Federal Republic would have to take into account at least two types, i.e. light-water reactors and fast breeders. It is known that there are several reasons for supplementing or replacing the most proven present types, i.e. gas-graphite reactors and light-water reactors, which it is hoped, will be offered by the future lines of development: Lower investment costs, better utilization of nuclear fuel, and better thermal efficiency. The fast breeder, in particular, would use for the fuel the plutonium arising from converters together with part of the depleted uranium-238 arising as a waste in separation plants.

More detailed studies of the concurrence of several types of reactors within one national program are available from France and the Federal Republic.

The French national report states what the development of fast breeder reactors would be like if they would be associated exclusively with the gas-graphite reactors. If introduced in 1982 fast breeders would contribute about half of the total nuclear power generated from about 1988 on. The increment in gas-graphite reactors would decrease, and by about the year 2000 no gas-graphite reactors would be built any more. The alternative regarded in the report shows that from 1979 on only thermal heavy-water converters would be built instead of gas-graphite reactors and the produced plutonium again would be used for the startup of fast breeders. In that case the fast breeders would make up half of the program in 1990. Gas-graphite reactors and heavy-water reactors will be equally important by that time each contributing a quarter of the program. Although the heavy-water line produces less plutonium per kilowatt-hour than the gas-graphite reactors (because part of the plutonium ist burnt already in situ in the heavy-water reactor), their introduction will not considerably change the rhythm of development of fast breeders, but will result in a 20 to 30 percent increase in the total power installed in thermal reactors.

Depending upon the combination of types of reactors selected there will be a diferent consumption of natural uranium by the French program up to the year 2000:

Gas-graphite reactors only	325,000 t
Gas-graphite reactors with heavy-water reactors	195,000 t
Gas-graphite reactors and fast breeders	140,000 t
Gas-graphite reactors with heavy-water reactors and fast breeders	110,000 t

For the Federal Republic the report elaborated by the Studienkreis Kernenergiereserven Karlsruhe quotes similar variations of the demand for natural uranium, depending upon the combination of reactor types regarded. Table 4 contains an estimate of the maximum cumulated natural uranium demand for mono and dual-type combinations up to the years 2000 or 2040, respectively. The estimate was based on the combination of a series of special converters of 1,000 MWe each with two design studies of sodium-cooled breeder reactors (Na-1: Karlsruhe Nuclear Research Center; Na: study by General Electric) for 1,000 MWe at the overall demand for nuclear energy shown in Table 1 (optimistic estimate). First, it is obvious that the individual types by themselves as well as in combination with the breeders consume very different amounts of natural uranium. In every case the plutonium generated in the converters is invested exclusively in the fast breeders. Up to the year 2000 the total demand for natural uranium in all cases, also in the monotype economies, is of an order of magnitude (100,000 to 300,000 t) which seems to be acceptable under the aspect of availability of natural uranium resources. Beyond the year 2000, however, the natural uranium requirements for converters only become unbearably high; together with the breeders it would remain within tolerable limits even then. The difference in designs of the two sodium-cooled fast breeders by the Karlsruhe Nuclear Research Center with the breeding ratio 1.38 and the General Electric Company with the breeding ratio 1.25 clearly shows to what extent the whole demand for natural uranium is influenced by the breeding ratio in the course of time.

Not too much importance should be attached to the detailed figures in the table. However, the orders of magnitude and the tendencies of demand offer a revealing picture.

Table 4: Estimate of the maximum cumulated demand for natural uranium in the Federal Republic of Germany for mono- and dual-type strategies up to the years 2000 or 2040, respectively (in 1,000 t of natural uranium)

	mono-type strategy		with Na-1 breeder KFK breeding ratio 1.38		with Na-breeder GE breeding ratio 1.25	
	2000	2040	2000	2040	2000	2040
Light-water reactor ORNL design [1]	248	2200	133	220	146	640
Light-water reactor SSW design [2]	290	2500	123	210	140	470
Gas-graphite reactor CEA design [3]	327	3200	117	160	144	375
Heavy-water reactor SSW design [2]	168	1700	69	109	76	235
Advanced gas-cooled reactor, UKAEA design [6]	232	2050				
Thorium high-temperature reactor General Atomic design [1]	114	800				
Sodium-cooled fast breeder [7] General Electric design [4]	8.1	57				
Sodium-cooled fast breeder [7] Karlsruhe design [5]	13.3	87				

[1] Pressurized-water type; report ORNL 3686 "A comparative evaluation of advanced converters"

[2] Pressurized-water type; communication by Siemens-Sehuckertwerke AG

[3] Cf. French national report for the 2nd FORATOM Congress; also, personal communication by R. Gibrat

[4] General Electric Company; report GE AP 4418

[5] Karlsruhe Nuclear Research Center; KFK 299

[6] Communication by UKAEA through Nukleardienst GmbH

[7] The figures indicate the need of depleted uranium-238 in case the breeders are started with an independent plutonium supply. These are hypothetical cases mentioned for reasons of comparison.

The report by the Studienkreis uses these data for cost estimates under the assumption of increasing uranium prices (up to 1985 $ 8/lb U_3O_8, up to 2000 $ 20, up to 2040 $ 30).+ Table 5 shows some results of these cost estimates. Like the data of Table 4 the report attempts to penetrate as far as possible into the details of the individual line of reactors and their combinations. Under investment costs the direct as well as indirect capital costs were considered. For the heavy-water type the costs of D_2O have been taken into account. The rate of interest assumed for ownership capital and borrowed capital is 7 percent per annum, for the rate of taxation 2.7 percent per annum, for property damage insurance and third party liability insurance 0.5 percent per annum each; the life of the plant is assumed to be 25 years; the periods of planning, construction, and startup are assumed to be 5.5 years. The fuel costs not only include the costs of raw material, fabrication, etc. but also those of reprocessing (cf. section 3.6), transportation, etc. For details see the study.

Table 5 compares the costs for the case I that the total amount of nuclear energy in the Federal Republic is supplied only by light-water reactors of a certain type (ORNL design) and, case II, by the combination of two types (i.e. of the same light-water reactor and the fast breeder Na-1 of 1,000 MWe designed by Karlsruhe). The breeders will achieve importance by 1980 and from then on will have a definitely cost reducing effect. The investment costs are entered under the assumption that they will remain constant.

From the tables quoted as well as on the basis of further information out of the report by Studienkreis Kernenergiereserven some other conclusions may also be drawn. The overall annual energy cost according to Table 5 composed of the capital costs, the operating costs, and the fuel costs reach the amount of DM 1,000 million by 1975. Roughly the same amount of funds has to be provided for investments. About 1977 the capital costs alone will reach the DM 1,000 million level. By the second half of the eighties the difference in annual energy generating costs between mono-type strategy and dual-type strategy according to Table 5 also reaches the amount of DM 1,000 million and

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+ In the Karlsruhe report also the case is considered that the prices of uranium remain constant at $ 8/lb up to the year 2000.

Table 5: Per-annum costs of the mono-type strategy with the light-water type ORNL (I), and the dual-type strategy with the light-water ORNL and the Na-fast breeder Na-1, Karlsruhe (II) (in DM 1,000 million)

(Capital, operating, and fuel costs added up result in the total cost of power generating shown in the first column) +

Year	Total cost of power generation		Investment costs		Capital costs		Operating costs		Fuel costs	
	I	II	I	II	I	II	I	II	I	II
1970	0.24	0.24	-	-	0.13	0.13	0.014	0.014	0.095	0.095
1975	1.0	1.0	0.95	0.95	0.52	0.52	0.063	0.063	0.39	0.39
1980	2.3	2.3	1.55	1.6	1.25	1.28	0.19	0.18	0.90	0.80
1990	8.0	6.4	2.6	2.8	3.9	4.1	0.46	0.47	3.6	1.9
2000	17	15	4.6	4.9	8.3	9.0	0.97	1.0	7.7	5.0

+ DM 4 = $ 1

increases rapidly afterwards. It is useful to bear these figures in mind when taking decisions about the costs of developing a new reactor line which, as a rule, are of the order of DM 500 million to 1,000 million.

Another interesting result of the study shows that when increasing the price of uranium concentrate from $ 8/lb to $ 30/lb the specific energy costs will rise by about 3 percent for the fast breeder, by some 8 percent for the heavy-water reactor, by some 15 to 20 percent for the light-water reactor, and by about 25 percent for the advanced gas-cooled reactor (AGR).

The study furthermore attempted to estimate the cost per kilowatt-hour for various types of reactors for the years 1970 to 1985 and 1986 to 2000, taking into account the rising costs of uranium. The figures should be taken with a grain of salt; they are only intended to offer guiding points. Although they have been derived under the economic conditions existing in the Federal Republic for 1,000 MWe reactors, they might be of some value also in judging the situation in other European countries. (Table 6)

In case only a limited amount of natural uranium, say 200,000 t, should be available or consumed up to the year 2040 in the Federal Republic, this results in an interesting relation between the breeding ratio of fast breeders and the necessity of introducing an intermediate generation of advanced converters (e.g. heavy-water converters). For, if the breeding ratio of the fast breeders employed around 1980 would be considerably below 1.38 this would require the addition of a generation of heavy-water converters the maximum installation of which would be reached between 1985 and 1990. If the breeding ratio is at least 1.38 or more, no additional generation of highly converting heavy-water reactors would be necessary. In this case the maximum in the installation of converters would be in the early nineties. If light-water reactors are employed, a capacity of 45 GWe is expected whose supply with enriched uranium would have to be guaranteed. In case this supply could not be guaranteed and one would have to revert to converters using natural uranium or enriched fuel with recycled plutonium, the employment of fast breeders would be delayed, and a much higher demand for natural uranium would be the consequence.

Table 6: Kilowatt-hour Prices in DPf for 1,000 MWe Reactors +

1970 - 1985		1986 - 2000	
Na-breeder General Electric	1.62	Na-1 breeder Karlsruhe	1.65
Na-1 breeder Karlsruhe	1.62	Na-breeder General Electric	1.76
Thorium high-temperature reactor, General Atomic	1.80	Thorium high-temperature reactor, General Atomic	2.00
Light-water reactor ORNL	1.91	D_2O reactor SSW	2.08
Advanced gas-cooled reactor, UK	2.02	Light-water reactor ORNL	2.09
D_2O reactor SSW	2.09	Advanced gas-cooled reactor, UK	2.25
Gas-graphit reactor France	2.19	Gas-graphit reactor France	2.31
Light-water reactor SSW	2.12	Light-water reactor SSW	2.31

+ The accuracy of the figures is of relative importance only;
DPf 1 = 2,5 $ mills

The introduction of a heavy-water converter generation in addition to the initial light-water or gas-graphite reactors, respectively and the fast breeders results in a marked reduction in the necessary overall demand for natural uranium. Investigations of three-type strategies, which still have to be conducted, ought to show whether the advantage due to the lower overall demand for uranium offsets the cost disadvantages of a three-type economy. Some light will be cast upon this problem in section 3.5 dealing with the potential requirements for enriched uranium in the European nuclear power generating economy.

3.5 Some remarks about the future capacity of supply with enriched uranium

The present capacity of American diffusion plants for uranium-235 is estimated at a throughput of some 35,000 t of natural uranium per year. The installed electrical power necessary to process this quantity is estimated to run into some 7,000 MWe. There is no indication that the United States intend to increase this capacity.

German estimates show that a yield of enriched uranium sufficient to fuel light-water reactors of an overall power of 225 GWe would correspond to a throughput of 35,000 t of natural uranium. In the closing speech at the 1964 Geneva Conference Seaborg stated that the United States were able to supply enriched uranium for a total power of some 100 GWe on a current basis. It may be assumed that the balance in separation capacity is used for military purposes.

With regard to consumption in Europe there are these considerations: France and the United Kingdom will probably either have a low demand or a demand covered by separation capacity of their own. Under the assumption of a dual-type strategy of light-water reactors and fast breeders of the breeding factor 1.38 a maximum of 45 GWe in light-water reactors would result for the Federal Republic of Germany in 1995. When adding the United States and other potential consumers, a minimum demand for enriched fuel corresponding to an overall power of 200 to 250 GWe would have to be taken into account for 1995. However, this would be only a temporary demand for about ten to fifteen years which would vanish with the further expansion of fast breeders.

In case Europe should plan to build a separation plant, there would be two ways in principle of achieving this aim:

Either a separation plant is erected for an annual throughput of 20,000 t of natural uranium. The price of the enriched uranium coming out of this plant would be 25 percent above the corresponding U.S. price. The plant would work to capacity only for a relatively short time; working with less than full capacity would increase the prices.

The other way would be to erect a separation plant for an annual throughput of 5,000 t of natural uranium. The price of the enriched uranium would exceed the corresponding U.S. price by some 200 percent, but the plant would work to capacity over a longer period of time.

Such increase in the fuel price in addition to the rising prices of natural uranium would imply a considerable disadvantage for light water reactors. This might be a strong incentive to build an additional generation of heavy-water converters fueled by natural uranium along with the breeders. This would offer the following advantages: There would be no bottleneck with respect to separation plant capacity; the breeders would not be dependent upon a breeding ratio of at least 1.38; a delay in the appearance of the breeders could be put up with more easily, and, on the wohle, a lower demand for natural uranium would be the consequence; finally, the question of Europe requiring a separation plant of its own would be reduced to a mere political problem.

The question of the extent of this additional generation of heavy-water reactors relative to the light-water reactors would have to be examined more closely. The time of their employment would not have to be before the date now envisaged for the breeders (about 1980). This three-type strategy (light-water, heavy-water, fast breeder reactors), incidentally, corresponds qualitatively to the Model IV recently submitted for discussion by EURATOM in the first tentative program (EUR/C/1000/2/65d of June, 1965).

In retrospect this shows that on the basis of these considerations the heavy-water converters have to be preferred over the other advanced converters; they do not necessarily appear as an intermediate but as an additional generation to the breeders. (At this point, incidentally, there is a difference to the well-known study by J.R. Dietrich on "Effective Utilization of Nuclear Fuels", Power Reactor Technology 6, No.4, 1963, in which the breeders have a later start and a lower breeding performance.)

One alternative to the introduction of heavy-water converters which is still uninvestigated to serve the purpose of avoiding bottlenecks in enriched uranium consists in starting up additional fast breeders on uranium-235 from 1980 on and use them, so to speak, as optimum converters. This possibility has to be checked in more detail still.

3.6 Throughput of the reprocessing plants for the examples given in Table 4

In Table 4 of section 3.4 data have been given for the requirements of natural uranium of the Federal Republic. The requirements proved to be highly dependent on the types of reactors as well as the type of strategy employed, i.e. the combination of converters and breeders. In Table 7 an estimate is given for the Federal Republic for the same cases, again under the assumption of the optimistic forecasts of Table 1 of the fuel throughput of reprocessing plants resulting from the different strategies. These figures may be taken as the first indications of the future reprocessing capacity to be planned in Germany and, mutatis mutandis, in Europe.

It shows that with increasing enrichment of the fuel the throughput decreases strongly. The light-water reactors need only about one fourth of that of the gas-graphite types and only about one half of the heavy-water converters. In the case of light-water reactors the combination with breeders has no considerable bearing upon the throughput, whereas it has a strong influence in the case of natural uranium converters. In an overall planning of the nuclear development this relation between the type strategies of reactors and the required capacity of the reprocessing plants has to be taken into account.

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Table 7: Throughput in tonnes per annum of the reprocessing plants in the Federal Republic of Germany as a function of reactor strategies of Table 4 +

a: mono-type strategy   b: dual-type strategy with Na-1 breeder KFK

	1975		1980		1990		2000	
	a	b	a	b	a	b	a	b
Light-water reactor ORNL	252	252	656	648	2171	1945	4772	4038
Light-water reactor SSW	212	212	552	521	1828	1664	4017	3724
Gas-graphite reactor CEA	1018	1018	2652	2319	8777	5375	19300	7690
Heavy-water reactor SSW	548	548	1430	1287	4727	3321	10390	5813
Na-1 breeder KFK	176	-	457	-	1512	-	3322	-

+ Cf. Report of the Karlsruhe Nuclear Research Center KFK (in preparation)

4. Summary and Future Prospects

4.1 Present situation

The statements made in the last sections show a picture of the impending introduction of nuclear energy in the supply of electricity which is much more distinct and detailed than the impressions offered by the 3rd Geneva Conference one year ago. Geneva was under the impression of the first big nuclear power stations available on the free market, like Oyster Creek. It was recognized that some types of power reactors had experienced a breakthrough with regard to their costs and availability. The new situation necessitated a thorough analysis of the future. The efforts of achieving such analysis were in the focus of this FORATOM Congress. We can say that many important results have been found and a multitude of questions has been answered. Yet, there are some questions not less important, which remain open.

By estimating the future need for nuclear energy EURATOM as well as some nations from among the FORATOM members have laid a first foundation for an analysis of the market of nuclear fuels and nuclear power stations. However uncertain these analyses may be in some points, they still supply strong arguments in favor of moving away from the now favored light-water and gas-graphite reactors towards more advanced developments. The heavy-water reactors and fast breeders, above all, must be counted among these types. The employment of fast breeders on a broader scale may be assumed for about 1980. The exact date depends upon the time required to make the fast breeders ready for the market. This cannot be safely predicted today, because important scientific and technical questions still have to be cleared. This, incidentally, is one of the reasons why at least two coolants for fast breeders are seriously investigated in Europe at present, namely sodium and steam, and also of the fact that the use of a gas for the coolant has not yet been excluded from the investigations. To shed some light upon just one of the technical difficulties let me tell you that a 1,000 MWe fast breeder with sodium cooling requires sodium pumps of a capacity of about 10,000 m^3/h.

Sodium components of that size so far have been developed neither in Europe nor in the United States. It cannot be excluded that this development will entail unexpected technical and cost problems.

If one supposes the fast breeders to join the development at the time expected and perform economically, the considerations about the concurrence of several reactor types and their influence on the uranium consumption show that even in the most favorable case, namly the concurrence of light-water, heavy-water, and breeder reactors, the present capacity of the diffusion plants, especially those in the United States, would be utilized to capacity in the nineties. In that case the wish for a uranium-235 separation plant in Europe would be raised only under political aspects in the nineties. By far more important and requiring much attention and further thought in the coming years is the question whether or not a European separation plant might prove to be necessary also under technical aspects, i.e. when the development of the concurrence of light-water, heavy-water reactors and fast breeders would not occur in the scheduled rhythm or heavy-water reactors were not available for some reason or the other. + The question of a separation plant has been raised in this clarity for the first time at the present Congress, and important, even if preliminary, hints about size and time schedule of their operation have been given.

4.2 Next steps in development

The development in the field of power reactors ahead of us in Europe is characterized by these dominating aspects. Britain has announced that a fast breeder prototype with sodium cooling and about 250 MWe would be commissioned in the near future. Owing to its resources of plutonium Britain has assumed a leading position in the scientific research into this type of reactor. In the Federal Republic two variations of a fast breeder prototype are investigated, i.e. the sodium-cooled type already mentioned and a steam-cooled version. Among other advantages these two types offer increased

+ It is not yet possible to obtain an accurate overall impression of the technical and economic sides of heavy-water converters. Let me just mention the struggle with the tritium problem, a question which certainly is not simple from the technical point of view and is likely to make the use of heavy-water as a coolant a fundamental problem forever.

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protection against a delay in the employment of breeders because of technical aberrations. France and the Federal Republic are about to start the design of prototypes of the sodium-cooled fast breeder which are intended for commissioning in 1968. The Federal Republic would start building the KNK reactor, a reactor of 50 MWe power with sodium cooling and zirconium hydride moderation which may also be regarded as a test bed for sodium components under reactor conditions. The British, French and German intentions or steps in the heavy-water reactor field are known. The development of heavy-water reactors is important not only under the aspect of creating advanced converters; in addition, this type carries an important inherent technical potential with respect to the subsequent development of thermal breeders.

All these developments require considerable financial expense. The Federal Republic, for instance, anticipates costs of the order of DM 300 million for the prototype of a fast breeder reactor. This directly entails the question of cooperation on a European level. When judging these possibilities it is certainly good to be guided by pragmatic aspects. In the field of fast breeder reactors it is apparent that Britain has decided to develop and build the prototype all by herself. Belgium and the Netherlands have indicated their intention to participate in the German prototypes.Whether and to what extent a correlation of the French and German projects is possible, is still open. The possibility of proceeding along several courses might seem to be disconcerting under the aspect of economic and personnel resources. On the other hand, however, it should not be forgotten that it must be considered a valuable sign for the European conditions just as for the United States to maintain a certain competitive situation also in these fields. This does not have to exclude a continued lively exchange of experience in the field of reactor physics research of the type existing at present between France, the United Kingdom, and the Federal Republic of Germany.

4.3 Types of cooperation

These big projects in the nuclear field will certainly exert a strong influence upon the future types of cooperation among the parties involved, namely

> on the national level upon the cooperation between government, research centers, reactor industries, and utilities;
>
> on an international level upon the cooperation among governments and its consequences upon authorities like EURATOM.

On the national level the distribution of roles between government, research centers and industry in organizing nuclear energy will play an important part. In the Federal Republic of Germany industry more and more assumes the development proper of nuclear power stations. The prototype of the fast breeder is also intended to be designed and built under the full responsibility of industry on the basis of preliminary work carried out in the Karlsruhe Nuclear Research Center. On the side of the purchaser it is intended to engage, in addition to government authorities, the utilities which, as you all know, are private enterprises in the Federal Republic. Operation is also to be taken over by the utilities, if possible. This makes the situation in the Federal Republic similar to the conditions existing in the United States, but the detailed process of integration mentioned here, which has a tremendous impact on the economic structure and the economic success, might be different. In Britain and France the role of the atomic energy authorities and the government is likely to be more pronounced, because in these countries the utilities are also nationalized industries.

On the international level the cooperation among various nations will be determined by the problem of how the groups of industries participating in this development will achieve cooperation beyond the national frontiers. It would have to be brought about chiefly on a basis of pure private economy and in a way familiar to industry.

It is not yet quite clear in what way the governments will be able to contribute to the common projects. At least for the countries of the European Economic Community EURATOM seems to offer itself as a potential joint authority. However, this would require clarification of the question whether the present conditions under which EURATOM participates in some developments, i.e. by association, are fruitful also for the case that national industrial groups carry out the development under their own responsibility and by employing funds of their own. It seems to be doubtful at least. Economic competition and contributions from private industry are inclined to impede a common attitude, e.g. in the patent sector outside firm industrial groups. Should it prove to be impossible to clear these questions satisfactorily, it may be expected that bilateral agreements will be concluded between the governments of individual countries to promote and support joint projects. Notwithstanding its undoubted important function as an international authority the future role of EURATOM in the direct promotion of technical developments will consist less in the pursuit of programmatic intentions than in a sound pragmatic attitude. FORATOM itself is free of political and programmatic restrictions. Therefore, FORATOM could play an important role with respect to the process of integration coming up with the big projects within Europe.

Conclusions concerning the Future Utilization of Nuclear Energy in Europe

Report of the Federal Republic of Germany on questionnaire No. IV of the 2nd FORATOM Congress in Frankfurt, September 29 - October 1, 1965

Speaker: Professor Dr. K. Wirtz
Karlsruhe Nuclear Research Center and
Technische Hochschule Karlsruhe

Questionnaire No. IV was submitted to a number of industrial companies, nuclear research centers and other organizations in the Federal Republic and has been answered, at least in part, by the most. These are some of the organizations which have returned their comments: Allgemeine Elektricitäts-Gesellschaft (AEG), Badenwerk, Babcock und Wilcox, Gutehoffnungshütte AG (GHH), Maschinenfabrik Augsburg-Nürnberg (MAN), Nuklear Chemie GmbH (NUKEM), Studiengesellschaft für Kernkraftwerke Hamburg, Preussische Elektrizitäts-Gesellschaft AG, Siemens-Schuckertwerke AG (SSW), Vereinigte Elektrizitäts-werke AG (VEW), Nuclear Research Establishment Jülich, Karlsruhe Nuclear Research Center, Federal Ministry of Economic Affairs.

In evaluationg the replies to the partial questions the procedure will be to combine all comments relative to each partial question into one brief summary put at the beginning of the statements. Afterwards, detailed problems will be treated of each partial question to which more detailed comments were received.

The report is concluded by a summary of the speaker (section IV).

1. Is there any prospect of a future market or need for small nuclear power stations (30-50 MWe)?

1.1 Summary of comments:

The majority of opinions of the manufacturers of nuclear power stations as well as of the utilities is in the negative. No prospect of a real market for small nuclear power stations is seen. This doesn't take into consideration smaller reactors which may be built as prototypes or pilot plants. However, these must not be regarded as products to be sold later on.

It is conceded that for special purposes, e.g. emergency power equipment, where the price neither of the plant nor of the power generated is important, special types may be of some importance. Two manufacturers, i.e. GHH and MAN, in contrast to the others answer the query for the future of small nuclear power stations in the affirmative. These companies state that there was a market for generating plants of this size. In 1963 a large percentage of all newly installed peak load capacity was built in this energy range. The interested parties were industrial enterprises with power generating plants of their own as well as municipal utilities. With respect to municipal utilities it is pointed out in other comments, however, that they would all join the large interconnected power systems before long, because local electricity generation in municipal power stations will become increasingly unprofitable.

1.2 Arguments:

Two manufacturing companies have positive views about the future market of and the demand for small power stations. Gutehoffnungshütte e.g. points out that in the industrial power stations contributing about 37 percent of the peak load capacity installed in the Federal Republic by the end of 1963 about 20 percent were in the power range of 10 to 50 MWe and about just as much in the power range from 50 to 100 MWe. The average growth rate of the peak load capacity installed in industrial power stations was roughly 7 percent per annum in the years 1960 to 1963. In addition, there were the generating stations of the Bundesbahn (Federal Railroad System) the peak load capacity of which amounted to almost 12 percent of the overall peak load capacity of the Federal Republic and which were exclusively within the range of powers investigated here. Without the power stations of the Bundesbahn, which occupy a rather special position in the energy supply of the Federal Republic, and at a growth rate of 7 percent the increase in capacity in 1964 would have corresponded to some 600 MWe in plants of between 10 and 100 MWe; however, there were as yet no statistical data for 1964. The statistics for 1963 contained the information that out of the new public power stations started up in that year amounting to a peak load capacity of 1980 MWe more than 26 percent, i.e. 526 MWe, were due to powers between 10 and 100 MWe. The market share in the range of small and medium capacities thus had increased in the public utility grid in 1963 compared with larger-sized plants.

Apart from this statistical market analysis there are several technical aspects which, in the eyes of GHH, are in favor of at least medium-sized plants of 50 to 100 MWe maintaining their share of the domestic market also in the future. One of these aspects was the fact that industrial power stations require larger units only in rare cases. The same was true of municipal thermal power stations because of the structure of our average large cities, if a large-scale utilization of the waste heat generated in these plants is intended. In addition, the competitiveness of these thermal power stations compared with large-scale power stations was guaranteed just because of this utilization of waste heat. Generally speaking, it was possible by orientating the power production by the demand to reduce the cost percentage of the integrated power grid. An important export market seems to be also apparent for these plants. Moreover, mention is made of the fact that at the third Geneva Conference a French study had been presented (A/Conf.28/P/46) proving that combined electric power and thermal generating plants on a nuclear basis were well able to compete economically with conventional plants up to relatively small units around some 100 MW_{th}. There had also been a paper by the Soviet Union (A/Conf.28/P/319) envisaging for the coming 10 to 15 years the installation of some 20,000 MWe in the range between 20 and 50 MWe.

All these data and considerations helped to make GHH regard the development of gas turbines combined with thermal power stations with gas-cooled high-temperature reactors also in the range of medium energies as a promising variation of their development of high-temperature reactors. The argument referring to the gas turbine will be resumed under item 5. No mention is made of cost problems.

MAN also sees no fundamental reason to preclude the future utilization of nuclear power stations also of relatively low powers. A market is envisaged especially for countries not yet having a large interconnected power grid.

As was mentioned already under 1.1 the concepts of GHH and MAN are not in agreement with the majority of the reactor manufacturers and utilities maintaining that cost reasons are against small power stations and that especially the smaller municipal utilities will have to encounter drawbacks for the coming decade.

2. What importance is attributed to the so-called direct conversion for the coming ten to twenty years?

2.1 Summary of comments:

It is interesting to note that manufacturers as well as the utilities in their majority express the opinion that for the next 10 to 20 years there will be no economic importance of direct conversion. The arguments differ. In most cases, however, it is pointed out that, e.g., the magneto-hydrodynamic generator but also the other energy conversion units are only in the initial phases of development. Only after conclusion of these phases, which will not be the case until 1970 in the opinion of AEG, the possibility of utilizing these plants in a nuclear power station can be judged. For spezialized purposes, such as in astronautics, it may be an advantage that generating devices of a high degree of compactness can be built. From these statements it follows that for the near future nobody in the Federal Republic believes in the dispensability of one of the conventional units of energy conversion between the reactor core and the electric current that is ultimately to be generated.

2.2 Arguments:

Threemethods of direct conversion must be distinguished: Thermocouples, thermionic converters, and magneto-hydrodynamic (MHD) generators.
At the present stage of development the first two devices have only a very low efficiency. For the next 10 or 20 years they will hardly attain any importance for nuclear power stations. MHD generators seem to offer better efficiencies, especially when they are set up in series with turbine power stations. Yet, here as in the first two devices the necessary operating temperatures are very high, about 2,000^{o}C. This requires the development of fuel elements having correspondingly high surface temperatures so that cooling will have to be effected by gas. These conclusions for nuclear power stations are not contradicted by the fact that for special purposes, e.g. space vehicles, a compact aggregate as on the basis of thermocouples has some chance of being utilized.
For the MHD generator the Jülich Nuclear Research Establishment expects efficiencies exceeding 50 percent, if the development of sufficiently strong magnetic fields is successful, e.g. of hard super-conductors.

The generation of these magnetic fields is regarded with optimism. Thus, the development most probably will be, first, to develop gas-cooled high temperature reactors, e.g. of the UHTREX type (Ultra High Temperature Reactor Experiments) in Los Alamos which is intended to operate at an outlet temperature of 1,600°K of the cooling gas helium; at the same time, the MHD generator will be developed independently. Only after conclusion of these developments it will be possible to decide whether their combination offers any economic advantages.

3. How is the problem of effective utilization of nuclear fuels regarded for the coming decade?

3.1 Summary of comments:

The majority of comments points out to the investigations about this problem currently conducted by a joint study group at Karlsruhe. It is generally recognized that there is a genuine problem. It is also generally recognized that an important improvement is possible and necessary by utilizing the plutonium produced in converters not only in fast breeders, but perhaps even earlier in fuels for thermal reactors. In general, however, the biggest hopes are devoted to the development of breeder reactors. It is pointed out that with respect to the most favorable fuel cycles for each reactor line a separate investigation would be necessary. A tremendous development is envisaged in the field of fuel utilization, in particular, if in later decades the cheap deposits of uranium will be exhausted. As stated above, a comprehensive reply to this complex of questions will not be possible in the Federal Republic until the work of the Karlsruhe study group has become available.

3.2 Arguments:

Under the leadership of the Karlsruhe Nuclear Research Center the "Studienkreis Kernenergiereserven" (Nuclear Energy Reserves Study Group) investigates the problem of efficient utilization of nuclear fuels. Among the members of this study group are NUKEM, SSW, AEG, INTERATOM, BBC-Krupp, Rheinisch-Westfälisches Elektrizitätswerk AG (RWE), Aachen Technical College, Jülich Nuclear Research Establishment, Karlsruhe Nuclear Research Center.

The work of the study group is not yet finished, but it will be available most probably for the FORATOM Congress. The work has three aims. First, material balances will be drawn up, i.e. the consumption of natural uranium taking into account the fact that there are U-235 losses by the necessary tail-end decrease from separating plants as well as losses in chemical reprocessing and fuel element fabrication. Consumption as well as investment requirements are taken into account. Then a reactor economy is considered consisting of two types of reactors, for example of fast breeders and Magnox reactors. Here the attention is focused on the problem of plutonium demand, or plutonium surplus, respectively. Closely linked is the question for a reasonable doubling time and the optimum starting point of fast breeder reactors. In addition, a reactor economy having three types of reactors is regarded.

In the second stage costs are attributed to the material balance. For this purpose a fuel cost scheme is elaborated. In addition, a plant scheme is worked out calculating plant costs in a logically flawless manner by the Present Worth Method. The magnitude of available uranium resources is not explicitly taken into account, but a price level for natural uranium is considered. In this second stage of the investigations it would be possible to answer the question in how far the errection of breeder reactors of especially short doubling time at increased plant cost is reasonable.

In a third step it is intended to investigate how far it is possible on the basis of the demand for minimum electric power costs to make statements about an optimum distribution of the demand for nuclear energy on the individual types of power stations. These considerations will start from the available uranium resources, the total demand for nuclear and fossile energy, and the load factor of power stations to be adjusted. It is not yet clear whether all input data necessary for an investigation of this type can really by procured.

4. What are the arguments in favor of or against the introduction of breeder reactors, either on the basis of the thorium uranium-233 cycle or on the basis of the U-238-Pu-239 cycle?

4.1 Summary of comments:

In a more general way the introduction of breeder reactors is deemed necessary in the long run by the majority of the participants. Apparently, the Pu-U-238 cycle is given more chances by the manufacturers as well as by the utilities; one of the reasons is the fact that Pu is produced in present converters. However, there are also strong arguments advocating the thorium-U-233 cycle. One of the arguments used in favor of this cycle is that it operates on thermal neutrons and in its physical and technical structure is more closely related to present nuclear power stations. From the different comments it seems to appear that both types of breeders will have to be given a chance and that only the future can decide whether one of the two types is really superior. Detailed arguments in favor of the fast breeder were, e.g. submitted by the Karlsruhe Nuclear Research Center.

4.2 Arguments:

From the side of the Karlsruhe Nuclear Research Center arguments in favor of introducing fast breeder reactors with the U-238-Pu-239 cycle are advanced.

4.2.1 Fast breeder operate at fuel costs which will be definitely below 0.4 DPf/kWh ($\sim$ 0.001 $/kWh).

4.2.2 Fast breeders will be compact reactors. There is the chance of lower capital costs than for thermal reactors. For large plants of 1,000 MWe and above plant costs amounting to DM 400/kW and less seem to be feasible, not including the expenditures made by the owner.

4.2.3 The use of fast reactors avoids the necessity of radiation-sensitive moderators, thus permitting the use of structural materials impossible to use in thermal reactors because of their neutron capture cross sections. For instance, nickel alloys might be employed on a larger scale.

4.2.4 Fast breeders need plutonium which may well contain larger amounts of Pu-240. The Pu arising in thermal reactors is about 40% more valuable when used in fast reactors than in thermal ones. There is the possibility of starting up fast breeders also on U-235, but it is hoped that this will be necessary only in exceptional cases.

4.2.5 In effect, fast breeders burn the abundant by available U-238. Thus, in principle, the well-known economic resources of uranium are better utilized by a factor of about 100 and poorer uranium deposits become worth to be extracted. A reactor economy based on fast breeders does not require any enriched uranium or plutonium for fuel. The Federal Republic intends to build one or two prototypes with different coolants (sodium, helium gas, or water vapor) and about 200 to 300 MW of electric power each between 1968 and 1972. Afterwards, one or two demonstration reactors of 1,000 MWe are to be erected by 1980 at the latest (cf. also 3rd Geneva Conference A/Conf.28/P/539).

5. What is the opinion on future reactor variants?

5.1 Summary of comments:

The comments by manufacturers of power stations as well as by the utilities are very careful regarding the chances of future developments, the breeders excepted. Fused-salt reactors, suspension reactors and the like are judged with reserve. It is recognized that all reactors supplying superheated steam are interesting. However, they ought to turn out to continue the familiar development lines known so far. Generally, the future proper is seen in the development of already proven types. One argument is repeatedly used: Even a very good new technical idea is faced by the difficulty that the development up to a nuclear power station as a rule costs about DM 500 million. As long as it is still possible to improve the present types of nuclear power stations technically and in their efficiency - and this issurely the case this will be the field where the real progress is to be found. There are individual deviations from this general opinion. Especially the gas-cooled high-temperature reactor is deemed to be promising in various comments, among other reasons because of the English AGR (Advanced Gas-Cooled Reactor).

5.2 Arguments:

In judging the aspects of future reactor variants the Karlsruhe Nuclear Research Center makes a difference between large central power stations and other reactor applications. In the large power station reactors the fuel costs, plant costs, and availability of the installation are important partial aspects.

In the case of fuel costs the development tends toward some 0.3 DPf/kWh, in the plant costs to about DM 400/kW. In the fuel development the problem of the unrestricted release of fission gas into the coolant is being discussed as well as fuel of very high thermal conductivity and, finally, the problem whether continuous charging during operation will become the general practice. A reduction of the fuel cost below 0.2 DPf/kWh is hardly to be expected. So, if the development of future reactors should entail even a small increase in the fuel and plant costs beyond the values quoted, the incentive to build this type of development will be low. When regarding plant costs one has to remember that of the amount of DM 400/kW mentioned only about DM 160/kW are chargeable to the reactor. It is much more likely that by a steady and consequent development of the proven types of reactors these DM 160/kW will be reduced with time than it is probable that new variants will reach this aim.

In all the other reactor applications, for instance, propulsion reactors, space ship installations and other special developments things might be different. However, this is not the subject of this FORATOM Congress. Only the development of ultra-high temperature reactors is regarded by Karlsruhe as a line taking up a position between the present conventional reactors and a future development. The same opinion is stated by GHH, but with a special view to the development of a high-temperature reactor with gas-cooling working on a gas turbine. The gas turbine would offer the possibility of utilizing quite well the thermodynamical advantages of gas-cooled high-temperature reactors by the direct coupling of reactor and turbine. In the opinion of GHH sufficient experience with gas turbines in a closed cycle is available now. Over the past few years GHH has built several hot-air turbines in a power range between 2 and 14 MWe. The 14 MWe plant in Oberhausen reached an operating period of some 30,000 hours by the end of 1964. The development into larger units up to 25 MWe at a plant efficiency of 37 percent is believed to be possible. Combined with waste heat utilization, for instance for the desalting of sea water, a utilization of the heat input by more than 70 percent is thought possible. GHH thinks it not unlikely that gas turbine types up to a power of some 100 MWe per unit might be realized. However, this figure clearly shows the limit of development. This limit is completely on the side of the gas turbine.

6. Results and prospects:

On the basis of the comments to question 1 regarding small nuclear power stations one is certainly not wrong in assuming that they will form no center of a future development, mainly for cost reason. One will also not be wrong in the assumption that the so-called direct conversion is not going to achieve any direct significance for large nuclear power stations in the coming decade. For the future development then the major questions of fuel utilization, fuel cycles, and breeder reactors remain to be solved. Moreover, it must not be excluded that a future reactor variant yet might become interesting some day because of its favorable technical and economical aspects. Excluding this possibility one may ask the question whether we really have gained an overall impression of the development in the nuclear field merely by the problems just mentioned. First, let me say that we would have to restrict this question to the field of power reactors because, undoubtedly, there will be a series of spezialized developments which have been mentioned occassionally also in the previous sections and the outcome of which cannot even be estimated. With regard to the economic utilization of nuclear fuel we are, I think, at the beginning of a long development. This includes the complex questions of fuel cycles; these again include reprocessing of nuclear fuels.

The rapid promotion of development of the reactors proper sometimes has caused these questions to appear to be of a secondary nature. Closely related to these questions are those of reactor materials, especially so of fuel element canning materials. The development of canning materials in turn influences the reprocessing plants.

Another field of problems relates to reactor safety. The public is still under the impression that nuclear power stations ought to be built far from all human settlements under special precautionary measures and only on special sites. One of the main goals of the development ahead of us for conventional present-day nuclear power stations as well as for future types will be to make these plants increasingly independent of site problems. We may be very confident in this respect. Reactor development sees the nuclear power station of the future arising at the horizon, independent of nuclear safety considerations it may be built on virtually every site which appears to be suited under conventional aspects. This type of power station will know nothing of the main concerns of conventional coal-fired power stations: Storage and transportation of its fuel do not cause any problem, the emission of smoke will be unknown, and even the discharge of radioactive contamination into the atmosphere will be practically nil. To reach this aim the research laboratories of the industry and the national centers will have to combine. Envisaging this development the German Atomic Energy Program takes care of that trend by demanding the cooperation of government leadership, scientific research, and private industry.

One of the most interesting questions is whether, in addition to the present type of converters on a light-water basis, the boiling and the pressurized water reactors, there will be an intermediate generation of reactors operated on thermal neutrons offering either better conversion and utilization of the fuel or higher steam temperatures, or using fuel easier to procure, e.g. natural uranium, which would thus stand out among the present types of power reactors.

Among these types there is the organic moderated reactor promising certain cost advantages, the heavy-water moderated type permitting better conversion and the use of natural uranium for fuel, the spectral shift reactor which is to supply higher conversion and longer burnup, the sodium-graphite or the sodium-zirconium hydride reactors, both of which promise high steam temperatures and, finally, the gas-cooled high-temperature reactors with the prospect of good conversion along with high temperatures.

All these variations of thermal reactors still have to prove their economy and their reliability in operation, i.e. their availability. Work is conducted on all these types of reactors at a tremendous expense of funds in various countries. This expenditure of funds and the right of testing these types stem from the fact that the present light-water reactors leave much to be desired with respect to steam temperatures as well as to their conversion. Light-water reactors have inherent limits, especially in their utilization of fuel.

With respect to steam temperatures it can be hoped that there will be improvements. The present experiments mainly carried out in the United States but also in the Federal Republic of installing superheater parts in light-water reactors or of joining them in separate stages are aims in this direction. However, the general idea is that within one decade at the latest this generation will be followed by the breeder reactors proper, which are intended to fulfil all the wishes mentioned above which one would have to demand from the present types of reactors, i.e. above all good utilization of the fuel, in particular complete combustion of uranium-238 and thorium as well as lower capital costs in the end. It still has to be proved that these reactors, too, can be operated with a sufficient safety and satisfactory reliability. The present development is concerned with these questions.

The Federal Republic will soon be confronted with the decision whether the government is to approve the funds for the development of the first prototype installations of breeder reactors. The American as well as the German Atomic Energy Program are in favor of this development. In the United Kingdom, France, EURATOM, and in Russia large funds are spent on the development of breeders. At the present time a safe forecast as to whether there will be a transition from the present light-water converters directly to the breeders or whether the generation of advanced reactors I mentioned will come in between, is still impossible. The German Atomic Energy Commission and the Federal Ministry of Scientific Research will have to devote their full attention to these questions in the coming years.