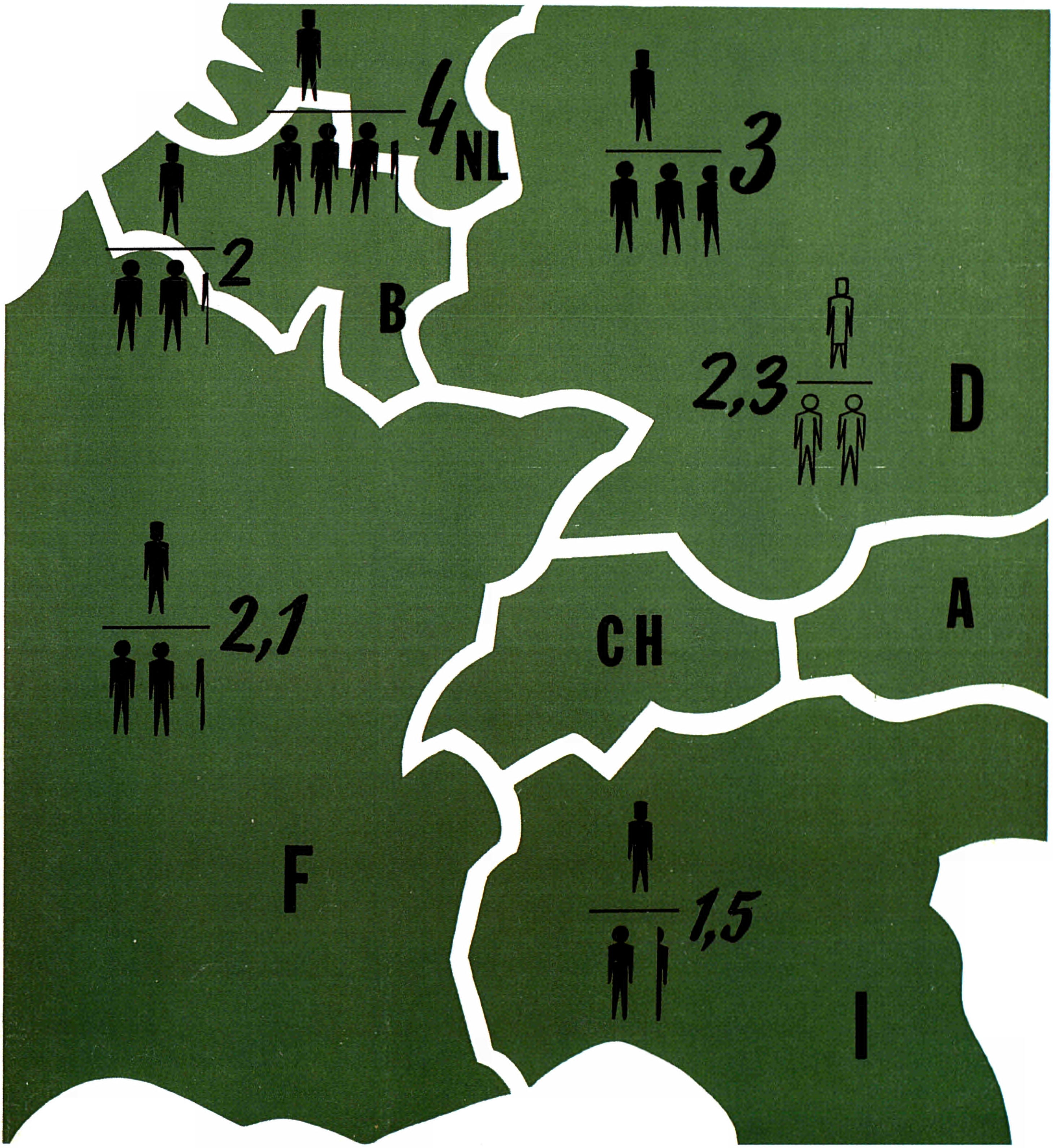
euratom

review of the european atomic energy community

December 1968 vol. VII no. 4



Do the scientists engaged on biological research in the Community have enough supporting staff? *See pages 114-116.*

CONTENTS

Quarterly Review of the European Atomic Energy Community (Euratom)

1968-4

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).

A few weeks ago, the first annual meeting was held at Ispra of the "Working Group on Liquid Metal Boiling", set up as a result of a decision taken a year earlier at Aix-en-Provence, during the International Conference on Fast Reactor Safety. The participants included some 30 experts from Belgium, France, Germany, Italy, the Netherlands and the United Kingdom.

Liquid metals, which are among the most suitable coolants for fast reactors, raise a great many problems which need to be solved both in order to advance the technology of these rather unusual materials and to ensure that reactors using them operate safely—as is explained at length in one of the articles contained in this issue.

That the Aix-en-Provence initiative has been given practical effect is undoubtedly a matter for considerable satisfaction, in two respects. Firstly, this will lead to an increase in the sum of knowledge in a leading sector; secondly, and even more important, the Working Group on Liquid Metal Boiling is a permanent body, which may be expected not merely to stimulate exchanges of information but also to achieve that true co-ordination of research which has so frequently been advocated.

What future for pum

MICHEL VAN MEERBEECK
Directorate-General for Energy

MICHEL GIBB
Editor

By the end of the century, our electricity may well be produced mainly by a network of nuclear power plants and pumped storage stations working in combination.

IT IS WELL-KNOWN that the irregularity of electricity consumption during the course of the day, the week and the year results in great differences in utilisation between one electrical power plant and another. Some run for only a few tens of hours while others operate annually at full power for more than 8,000 hours.

The structure of the production costs of the various units makes each unit more or less suitable for meeting different load demands. Broadly speaking, low-cost units will be installed to act as peak-load plants, even though the proportional costs, i.e. mainly the fuel costs per kWh, may be high, or else use will be made of old units which are already amortised and whose efficiency is poor; on the other hand, machines with low proportional costs will be sought as base-load units, even though they may entail larger investments. Nuclear power plants of course, come under this latter category.

During a study on the integration of nuclear power plants in electricity production and distribution grids, the results of which were published in 1965[1], it emerged that, while the number of nuclear plants was on the increase, two factors tended to go counter to this trend. Firstly, the new nuclear power plants, having the lowest proportional costs, fill up the base of the production diagram and displace the first plants to be installed towards the top to a zone where the load factor decreases. Secondly, the operation of base-load nuclear and conventional thermal power plants in a low utilisation zone of the production diagram raises technical problems of load modulation. Hence the idea of modifying the production diagram to the benefit of the base-load plants by storing the electrical energy they produce.

At present the only method of storage which is economically viable is that of pumping water from one reservoir into another one higher up. The water thus accumulated is brought down again through a turbine during peak hours (figures 1 and 2).

Economic justification of pumped storage

The economic justification for pumped storage schemes is based on the following considerations.

The cost of the energy fed into a grid varies greatly according to the overall load. When the load is low, only the base-load stations with low proportional costs are in service. The unit cost of this energy is thus relatively modest. On the other hand, at peak hours, practically all available plant is operating, including stations whose proportional cost is very high.

It is thus economical to store cheap energy, produced at night or at week-ends by base-load units, and to return it at peak hours in place of costly production (see figure 3 and figure 4 left), on condition, of course, that the cost of the energy returned, taking into account efficiency, is lower than that of the energy which would have been produced by the peak-load units which the pumped storage station is replacing. In this case the benefits to be derived from the pumped storage scheme during the whole of its lifetime must moreover be sufficient to offset its capital and maintenance costs.

The large-size nuclear power plants thus seem to enhance the economic viability of pumped storage. While the high capital costs of the nuclear plants penalise them as soon as their utilisation falls below 5,000 hours, their low proportional costs make their large-scale use particularly economic (figure 4 right).

Let us see in more detail what are the advantages of pumped storage.

Its advantages . . .

Although the cost of building a pumped storage station is not low (e.g. about 6,000 BF/kW installed for the Coo station, in Belgium, and 5,000 BF/kW at Vianden, in Luxembourg), the fixed annual cost per kW installed is relatively modest, for the following reasons:

– *The plant operates in the cold state*; it therefore has the advantage of not needing parts capable of withstanding high temperatures and pressures, the fabrication of which would necessitate the use of expensive special materials and the lifetime of which would in any case be fairly short; maintenance is therefore inexpensive.

– *The lifetime is considerably longer* than that of other production units, a figure of 60 years being set for the civil engineering structures and 40 years for the electrical and mechanical components. The amortisation payments are thus distributed over a longer period, reducing their share in the fixed annual costs.

– *Operation* is very simple and *does not require a large staff*. At Vianden, despite the fact that the most economical solution from the labour angle has not been adopted, 52 men are required to run and maintain the station, i.e. 0.06 man per MW. At the Coo station there is a fully automatic control scheme which would reduce the

1. Report EUR 2453f

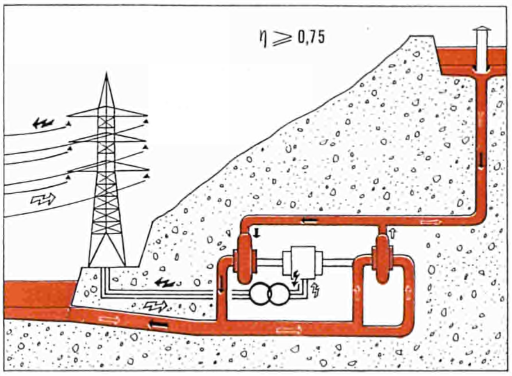


Figure 1: Principle of operation of a pumped storage scheme. Cheap energy available at certain hours is used to pump water into the upper reservoir (white arrows). At peak hours the energy is restored by the turbines (black arrows).

ped storage?

staff to 0.025 man per MW. By comparison, about 1 man per MW is needed on the average for a conventional thermal plant of 250 MW and approximately 0.4 man per MW for a nuclear power plant of 600 MW.

Only turbojet units have a lower installation cost, but with the drawback of a rather high proportional cost, which makes them economic only for operation during extreme peak-load periods.

Another advantage of pumped storage stations is their very great flexibility of adaptation to the load. At Vianden, for example, it takes less than two minutes to start the turbines or to switch over from pumping to turbine operation. This is equivalent to having a virtually instantaneous reserve of about 1,600 MW. This property is very useful in the event of failure of one or more base-load units, for the start-up of stand-by base-load units is particularly long and difficult, thus necessitating a considerable spinning reserve, which, moreover, is bound to increase with the commissioning of large nuclear units of 600 MW and over in the next few years.

Furthermore, like all hydraulic installations which work cold, pumped storage stations are simple and reliable. For this reason their availability factor is higher than that of conventional thermal units – 95 as against 80-85%.

One advantage of pumped storage plant which must not be overlooked is the particularly beneficial influence on other plant of the steadier load conditions which it brings about.

The effect on the base-load units of pumping during the off-peak night hours is to permit the operation of units which it would otherwise have been necessary to shut down, and to enable others to operate at more economic loads.

This leads to a reduction in the start-up and fuel costs of these units, as well as to savings on the maintenance costs attributable to the thermal and mechanical stresses caused by sudden variations in load. A further effect is to lengthen their life, mainly through the reduction in the frequency of start-ups; it is difficult to give statistics owing to the limited experience as yet gained with recent sophisticated units of 125 and 250 MW and with nuclear power plant, but it is certain that these plants are lacking in flexibility and emphatically not intended for discontinuous operation.

Yet another effect is that the utilisation of units with very high proportional costs is lessened, thus reducing the specific cost of electricity produced.

The most unusual advantage of the pumping stations is their "self-modern-

Figure 2: Aerial view of the upper reservoir of the Vianden scheme, Luxembourg.

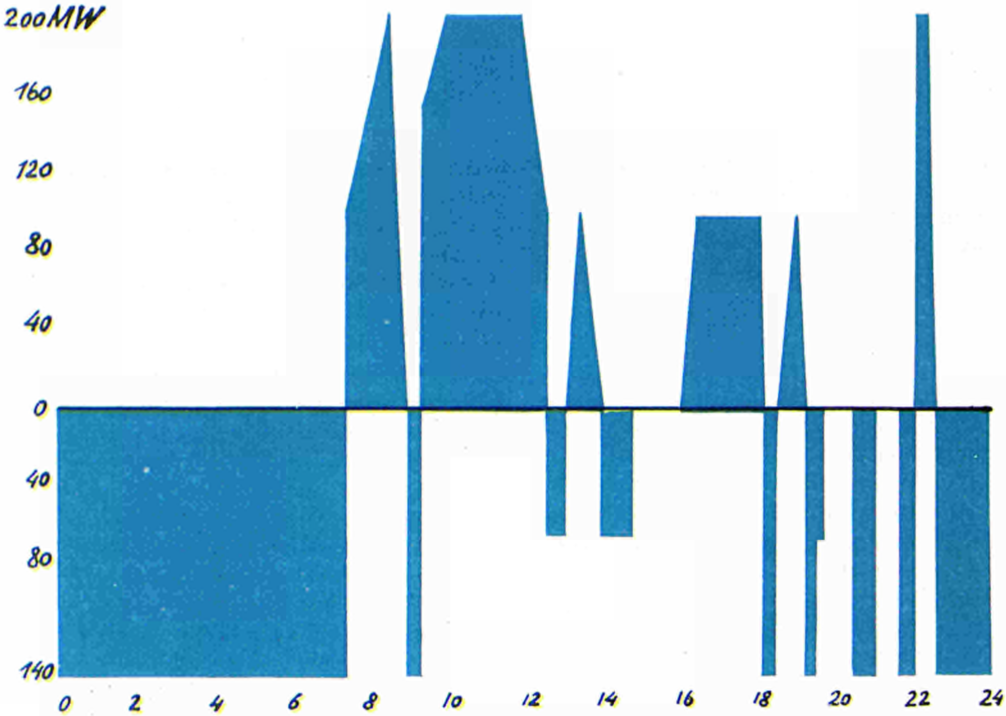


Figure 3: Typical daily load diagram of the Vianden pumped storage station after the commissioning of the first two groups.

ising", for since they use energy supplied by base-load units, they profit by all the improvements in the design of these units, particularly the reduction in proportional costs. The coupling of pumped storage with nuclear power plants thus seems to be of immediate interest, since the proportional cost of the latter plants is extremely low.

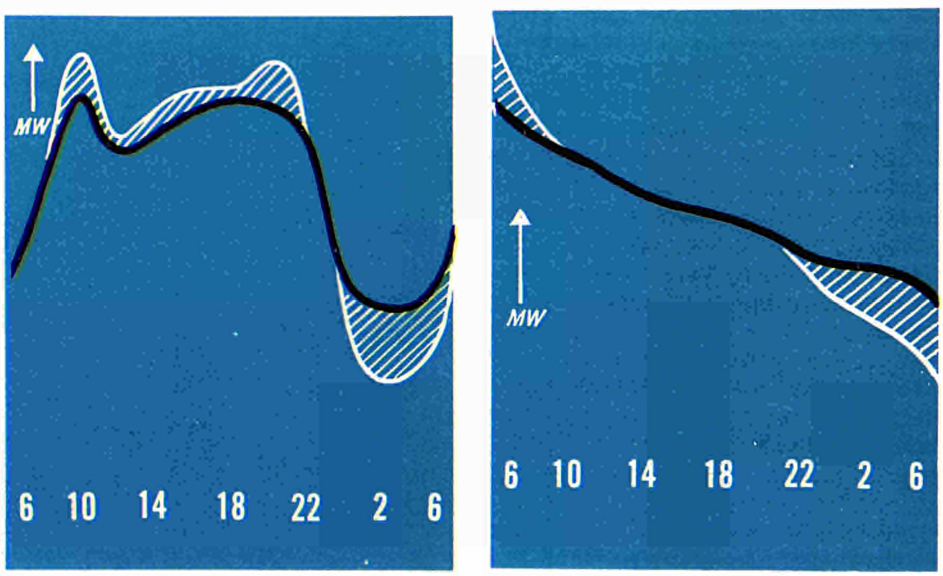
. . . and its disadvantages

Firstly, owing to the numerous transformations undergone by the energy supplied to a pumped storage station, *its efficiency is only about 70%* (figure 5).
Secondly, the profitability of a pumped storage scheme is largely *dependent upon the site*. The choice of a site is therefore generally very limited, mountainous regions remote from the high-consumption areas usually being selected. This entails investing heavily on high-tension lines and transformer stations to carry the energy produced. Moreover, in spite of the high voltages used, it is not possible to avoid energy losses due to the long distances covered.
In contrast to other peak-load units, which can feed their energy into the medium-tension grid (the site being judiciously chosen on the basis of the geographic distribution of the load), the pumped storage station, although a peak-load unit, must pass through the entire grid system before its energy can be consumed.
In addition, it is dependent upon the load diagram, since the slack night hours are used for pumping and the peaks for turbine operation. If the slack night periods become less marked or the peaks flatter (as a result of a better utilisation of energy by consumers), there will be less need for pumped storage power. However, it must be said at this juncture that in spite of the efforts of producers to improve it, the load factor has remained relatively constant as a result of the rapid increase in low tension demand.

Repercussion on nuclear power plants

As has been seen, the coupling of nuclear power plants and pumped storage stations seems a priori well justified from the economic angle. This is why in 1966 Euratom asked the Belgian companies *Electrobel* and *SOBEMAP* (*Société belge d'économie et de mathématique appliquées*) to carry out a study aimed at elucidating in detail the effects of the construction of pumped storage stations on the economic situation of nuclear power plants. An attempt is made here to summarise its main conclusions.

Figure 4: Daily load diagrams (typical of the Belgian grid). On the left a chronological diagram; on the right the corresponding diagram of the classified power outputs.
In both diagrams the effect of the introduction of a pumped storage station has been indicated. In particular, the right-hand diagram shows that the installed power able to operate under base-load conditions is thereby increased.



The Vianden and Coo schemes

At the end of 1966, eleven pumped storage stations were in service within the Community, representing a total installed power of 1,950 MWe.
Nine of them were situated in Germany (967 MWe in all), while the Grand Duchy of Luxembourg had the Vianden power plant with an output of 900 MWe. The Coo power plant (near Stavelot in Belgium), which is still under construction, will represent a turbine power of 720 MWe. The study devotes particular attention to the Vianden and Coo stations.
The Vianden plant, of the underground type, works mainly in conjunction with the German grid. The lower reservoir consists simply of a barrage on the river Our (figure 6); the water of this reservoir is thus continuously renewed and the losses due to evaporation and infiltration are automatically compensated.
The solution adopted for the turbo-pump units is that of independent pumps and turbines mounted on a horizontal axis on either side of the alternator (figure 7). This solution, adopted because at that time the technology of turbo-pumps of this size was not yet perfected, has the disadvantage of requiring the excavation of an underground gallery 330 metres long, and thus entailing major additional capital costs, and the advantage of being extremely flexible and hence particularly well adapted for synchronous compensation.
The Coo power plant, also of the underground type, is under construction in the Ambleve valley and has the characteristic of possessing two genuine reservoirs, in the sense that the lower reservoir, instead of being, as in the majority of schemes, a simple dam over the river (which would have submerged the town of Coo), will be a distinct entity like the upper reservoir. This arrangement has a double disadvantage: it is always the same water which is used, hence a risk of fouling of the machinery and, secondly, additional pumping is necessary from the Amblève river for the first filling and also to make up losses.
For this plant the solution of reversible groups has been adopted, so that the dimensions of the underground cavern (the Coo gallery is only half the size of

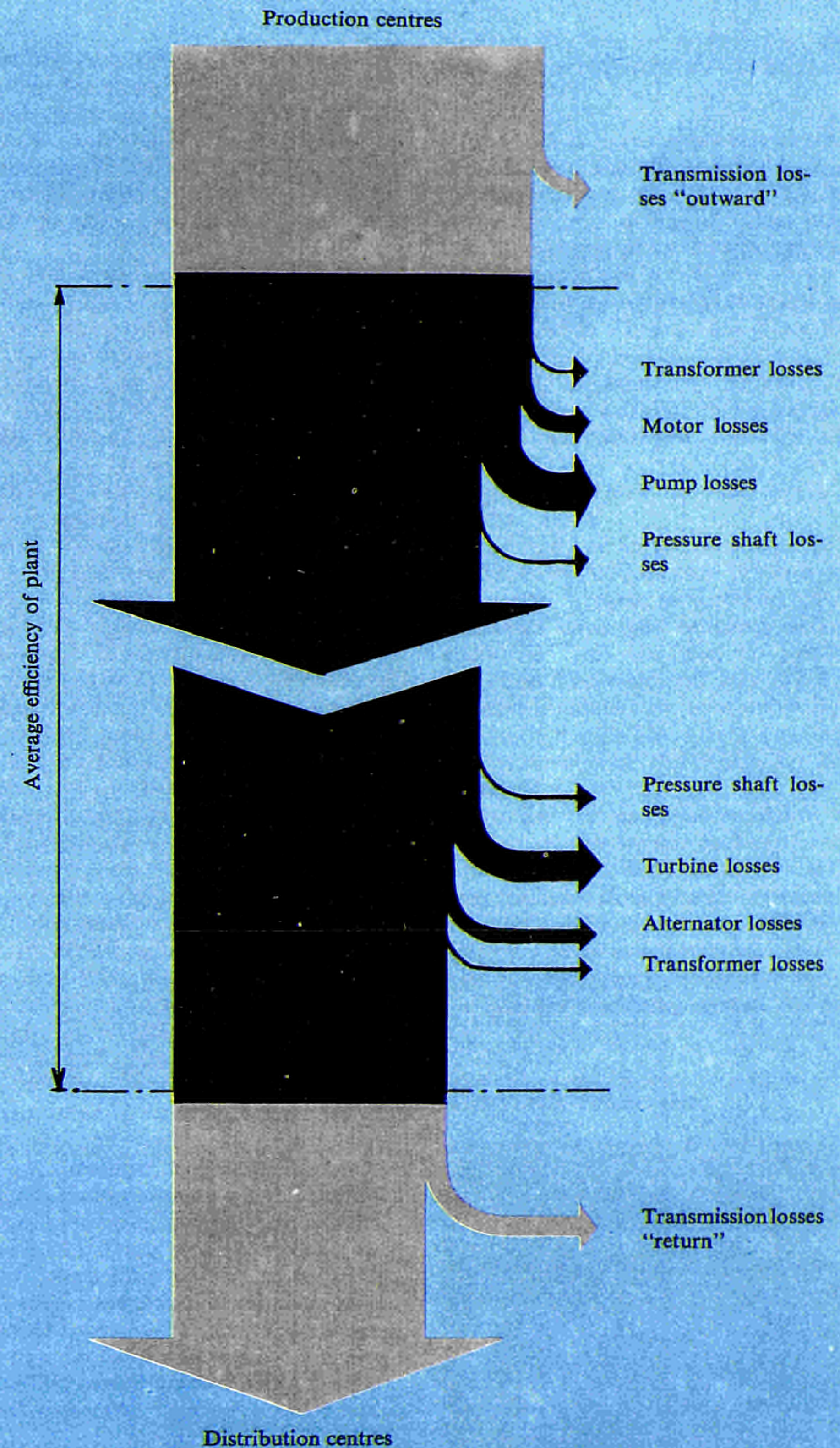


Figure 5: Breakdown of the losses for the Coo pumped storage scheme (according to the Syndicat d'étude de centrales de pompage en Belgique, *July 1964).*

that at Vianden for example) and hence capital costs can be considerably reduced. On the other hand, operation will be less flexible, a drawback which, however, will be without importance so long as the station is used only for peak-load energy and not as a synchronous compensator.

Calculation of operating costs

One of the most important parts of the study carried out by *Electrobel* and *SOBEMAP* consisted in an evaluation of the difference between the operating costs of an electricity producing system with and without pumped storage.
In order to be valid, such an evaluation must be based on an actual example. The example chosen is largely drawn from the situation of the Belgian grid, assuming completion of the Coo scheme.
The calculations were made first of all for the "ideal case", i.e. the operation of an installation situated in a perfect grid (without losses and without bottlenecks), made up of ideal machines (capable of coping with load variations from zero to maximum instantaneously and producing each unit of electricity at the same cost, regardless of load) and supplying power to a grid the demand of which is considered to be perfectly predictable at any given moment. If the overall management of the various power units is simplified in this way, the problem is essentially to calculate what it would have cost, with the aid of the other peak-load stations, to produce the energy supplied by the storage scheme, and to subtract from this sum the cost of the energy required in order to raise water from the lower into the upper reservoir. The result represents the gain afforded by the pumped storage station.
The factors which distort the ideal situation were then taken into account. In assessing their effect on the management of the station during the different phases of its existence, the study was limited to a small number of days distributed through time. Thus for each year considered (1973, 1983 and 1993), a "strong", a "medium" and a "weak" day were chosen.
The calculation proper was performed on the Mercury Ferranti computer at the *Centre d'étude de l'énergie nucléaire*, Mol, using a programme prepared by the *U.C.P.T.E. (Union pour la coordination de la production et du transport de l'électricité)*.
The results showed that nuclear power plants will not be used for pumping until after 1983 and then only on off-peak days such as Sunday, and that we must wait until 1993 for them to enter into an area of the production diagram where a daily shut-down is necessary. Thanks to pumped storage stations, these shut-downs are reduced but not entirely eliminated, because the load variation costs of such power plants are less than those of conventional steam units.
It is found that when account is taken of operating restrictions, the advantages

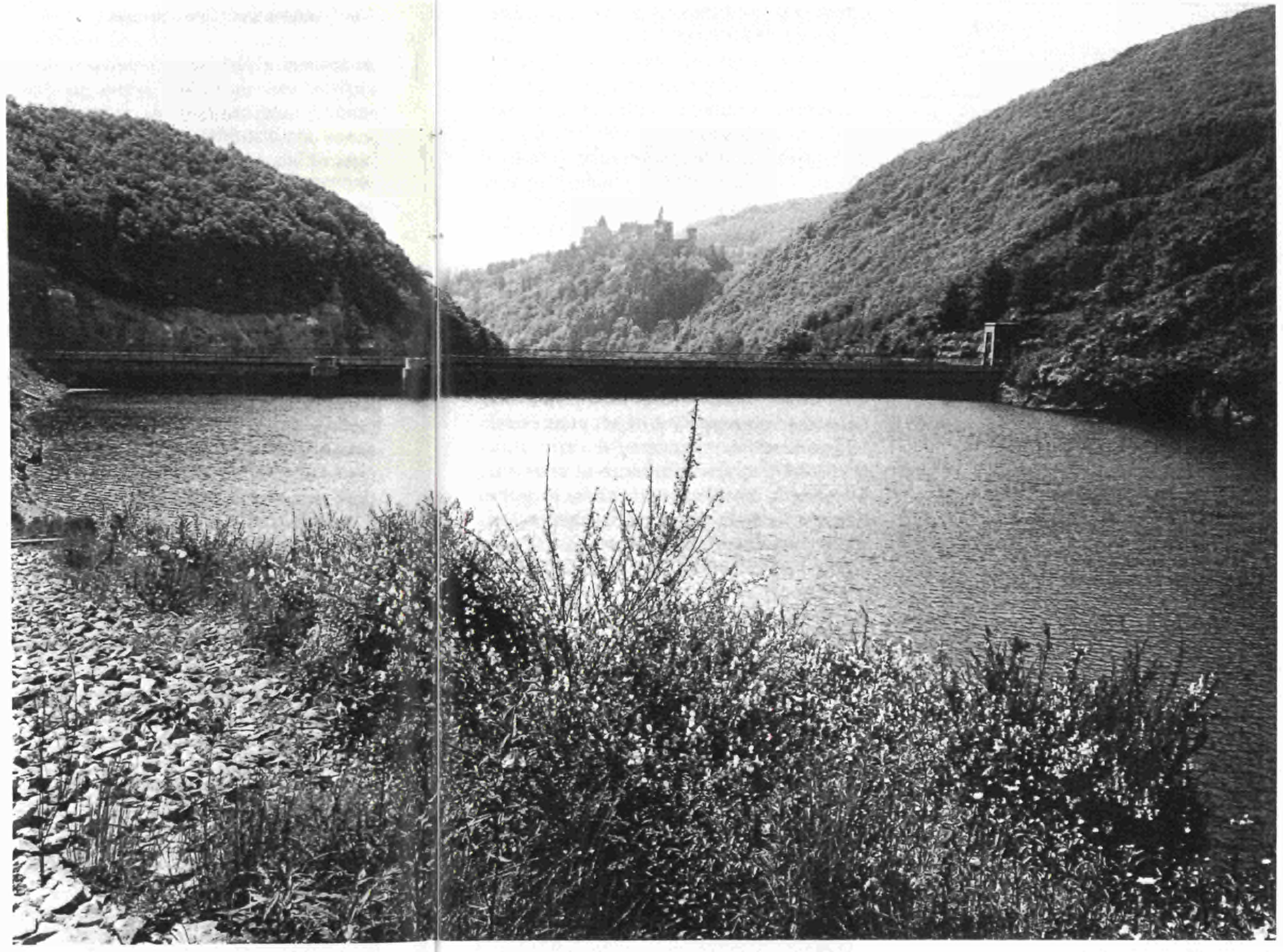
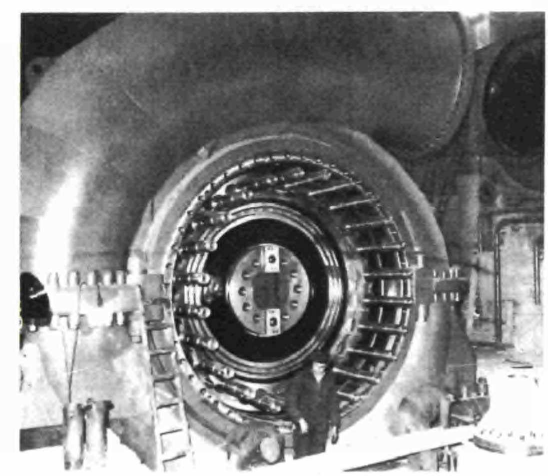


Figure 6: The dam on the river Our, which forms the lower reservoir of the Vianden scheme.

offered by pumped storage increase considerably. The causes are mainly an appreciable rise in the utilisation of base-load steam plants, which reach their maximum, and the drop in start-up costs.
Although the pumped storage station becomes less and less important relative to the total installed power, it affords a steadily-increasing absolute gain over the years.
The differences in the figures obtained for operating cost gains attributable to pumped storage between the complete calculation and the simplified calculation were so large (see Table I) that a more thorough analysis of their causes was thought necessary. For this purpose, a day in mid-December 1983 was chosen.
Between these two calculations—the calculation corresponding to the ideal simplified situation and the complete calculation on the computer—four sorts of difference can be observed to account for the gain of 987,000 BF/day in the complete calculation as against 490,000 BF/day in the simplified case:
1. The pumped storage station has a lower utilisation in the complete calculation: the pumping energy is identical (6,500 MWh), but the energy obtained from operation of the turbine is 4,550 MWh in the ideal case (the efficiency being assumed to be 0.7) and 4,462 MWh in the complete calculation.
The loss of efficiency in pumping is almost nil since pumping takes place at optimum power, which is not true of turbine operation, which takes place most frequently at intermediate power.
Consequently an additional 88 MWh must be produced in the first case. Since these are produced by peak-load machines, their mean cost is about 0.57 BF/kWh. The penalty is thus 50,000 BF/day in the actual situation as contrasted with the ideal situation.
On the other hand, the other terms are positive.
2. The fuel cost in the ideal case corresponds to the full-load cost. In the detailed calculation account was taken of the additional costs due to idling and the additional fuel cost due to part-load operation. The calculated gain is 843,000 BF/day. It would have been only 776,000 BF/day if the kWh had been counted at their nominal cost. The penalty for idling is thus 67,000 BF/day.
3. By dint of its great flexibility, the pumped storage station enables the ideal economic load distribution to be approached more closely, since it lessens the effect of certain restrictions such as the minimum power at which the various plants must run, the time they require for start-up, the need for a spinning reserve, etc. Since

Figure 7: Assembly work in progress in the gallery of the Vianden plant.



Day	Total cost—simplified case		Total cost—complete calculation with computer	
	without p.s. (10^6 BF)	with p.s. (10^6 BF)	without p.s. (10^6 BF)	with p.s. (10^6 BF)
Dec. 73	18.393	18.137	19.112	18.505
Sept. 73	14.856	16.692	15.346	14.737
Dec. 83	29.442	28.941	30.546	29.560
March 83	21.989	21.625	23.515	22.682
Dec. 93	49.228	48.114	52.480	51.112
Sept. 93	37.513	36.695	41.171	39.506
June 93	31.771	30.961	34.994	33.641

Table I: Operating costs with and without pumped storage (for the Belgian grid; pumped storage station of 720 MW).

the simplified calculation fails to reveal these advantages clearly, they constitute the major difference between the two calculations. Allowing for the fact that the loss related to the station's efficiency reduces the corresponding gain, this difference may be estimated at 336,000 BF/day.

4. The cost of start-ups, although relatively small, forms an appreciable part of the advantages afforded by pumped storage. The calculations give a gain of 144,000 BF/day.

The real economic gains due to pumped storage thus appear much greater than those indicated by a simplified calculation.

Optimum composition of a system including pumped storage plant

We have seen above how an *existing* pumped storage station should be operated in order to obtain the maximum benefit. The fixed costs due to the existence of the station were, of course, disregarded.

On the other hand, when considering the question of whether to construct a *new* station, the fixed costs must also be taken into account and compared with those of rival types of equipment. Furthermore, the use of pumped storage, since it has an influence on the utilisation factors of the various units making up the system, may call into question the entire equipment programme.

We will not go into the details of the study carried out by *Electrobel* and *SOBEMAP*, but will merely give some of the major results.

A detailed examination of the different technical and economic parameters makes it quite clear that the pumped storage station is an intermediate utilisation unit and must play a part similar to that of units such as gas turbines. Secondly, taking as the hypothetical optimum composition of a system—here again for the Belgian grid—that worked out during the previous study already quoted (Report EUR 2453 f —see Table II), it is possible to calculate the influence which the use of a pumped storage station has on the energy production cost.

A numerical example based on the inclusion of a 720 MW pumped storage station in this system gives the following figures:

— cost of the station: 3,567,750,000 BF and cost of the lines 678,000,000 BF; fixing the annual capital charges at the rate of 11.3%, conversion to present worth over 20 years at 8% gives 6,285,000,000 BF.

— assuming that the non-installed units correspond to 220 MW of gas turbines and to 500 MW of turbojets, a saving on fixed costs of 4,819,000,000 BF is obtained, also converted to present worth over 20 years.

— the saving on the fuel and start-up costs converted to present worth over 20 years has been assessed at 1,700,000,000 BF.

The benefit, converted to present worth, of the introduction of the pumped storage station is thus equal to

— 6,285 + 4,819 + 1,700 = 234 million BF.

The value of pumped storage stations being thus definitely proved by the calculations, the optimum part which they ought to play in the composition of the system must now be determined.

In order to solve this problem, it was necessary to simplify it by adopting certain hypotheses. For example, the cost structures of the various production units were assumed to correspond to those shown in figure 8. These costs were calculated, as regards pumped storage stations, for the case in which the energy supplied to the

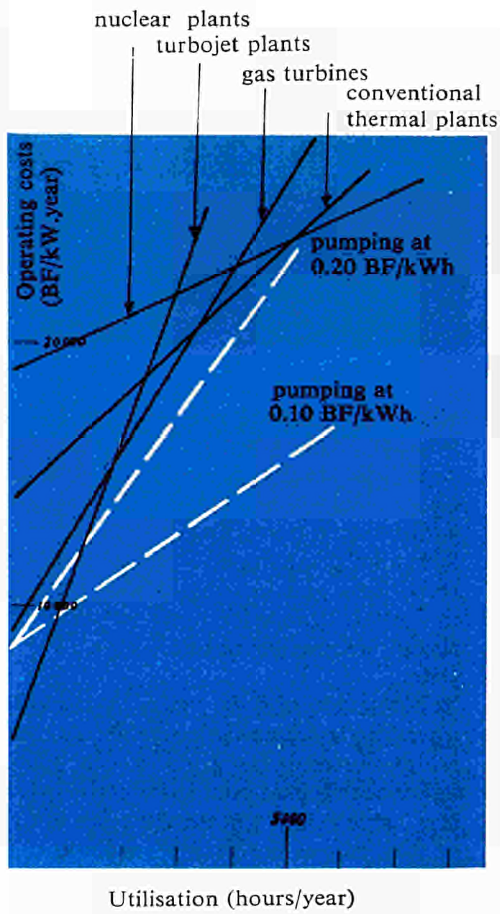


Figure 8: Annual operating costs of the various electrical production units as a function of their utilisation time. (This graph, based on target data, serves essentially to show the effect of different cost structures.)

Type of unit	Power		Fixed cost BF/kW. year	Energy produced kWh/year	Proportional cost BF/kWh	Total BF	Utilisation (hours)
	% max. power req.	% max. inst. power					
Nuclear plants	53	65,7	1.900	4.418	0,10	1.690	6.724
Conventional steam plants	17	21,1	1.400	897	0,20	474	4.250
Gas turbines	13	16,1	900	419	0,35	292	2.600
Turbojet plants	17	21,1	513	201	0,57	223	950
Total	100	124,–		5.935	0,45	2.679	

Table 11: Energy produced and annual cost for 1 kW of peak-load power required (assuming optimum composition of the production system as given in EUR report 2453 f).

plant would cost 10 centimes /kWh and that in which it would cost double this amount, or 20 centimes /kWh; this gives production costs of 14.3 and 28.6 centimes/kWh respectively. The fixed costs used for the pumped storage station (7,300 BF/kW and 823 BF/kW.year) include the transmission lines. One remarkable finding is that, apart from very low utilisation ratings, i.e. less than 1,000 hours per year, pumped storage stations are the most economical units.

Figure 9 indicates how a pumped storage station distorts the production diagram. It can be seen that the utilisation of the base-load units is increased and that, inasmuch as the capacity of the reservoirs and pumps permits, the maximum pumping energy corresponds to the surface PQRST (figure 9a).

But in actual fact a diagram similar to that in figure 9b is obtained, which only takes into account the energy which it is economic to pass through a turbine (represented by the surface MNPU). For low utilisation factors it is more economic to install turbojet machines and for higher factors to use base-load plants.

Thus there is a level PQ for which the energy available for pumping is equal to the energy which it is economic to pass down through the turbines. It has been calculated that this level corresponds to about 70% of the system.

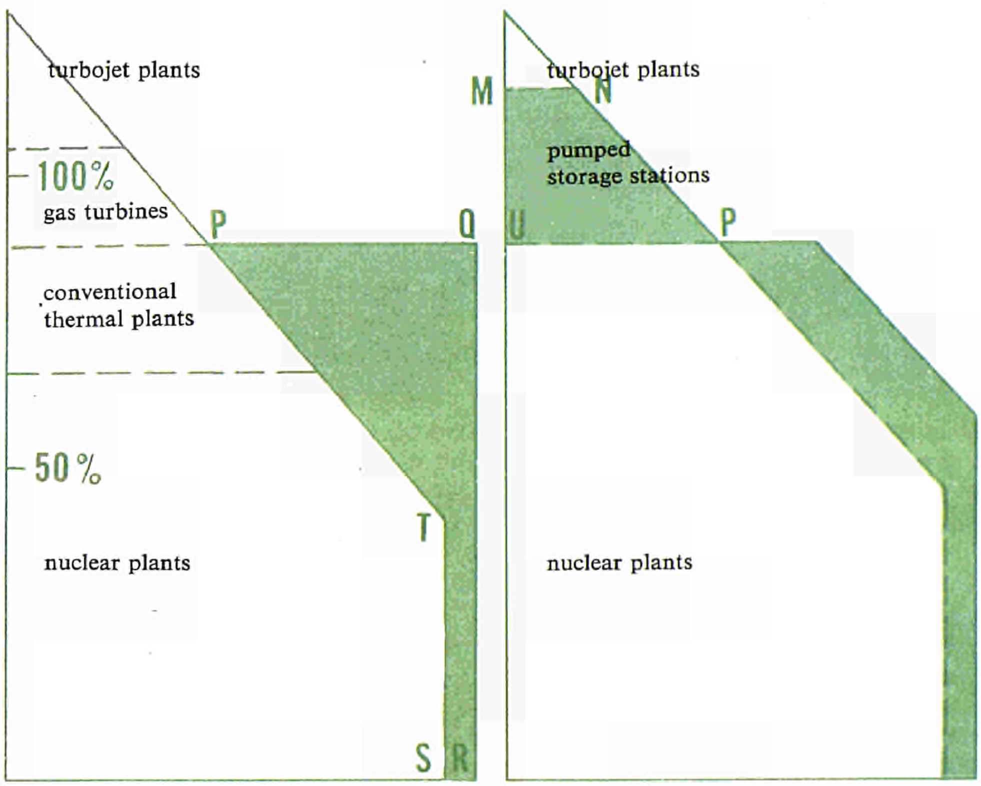
In view of this, the utilisation factor of the base-load machines remains high, never falling below 6,000 hours. Consequently there is no reason to install conventional thermal units and the optimum proportion of nuclear power plants amounts to 70%. The optimum system is then made up as follows:

— nuclear units: 70%

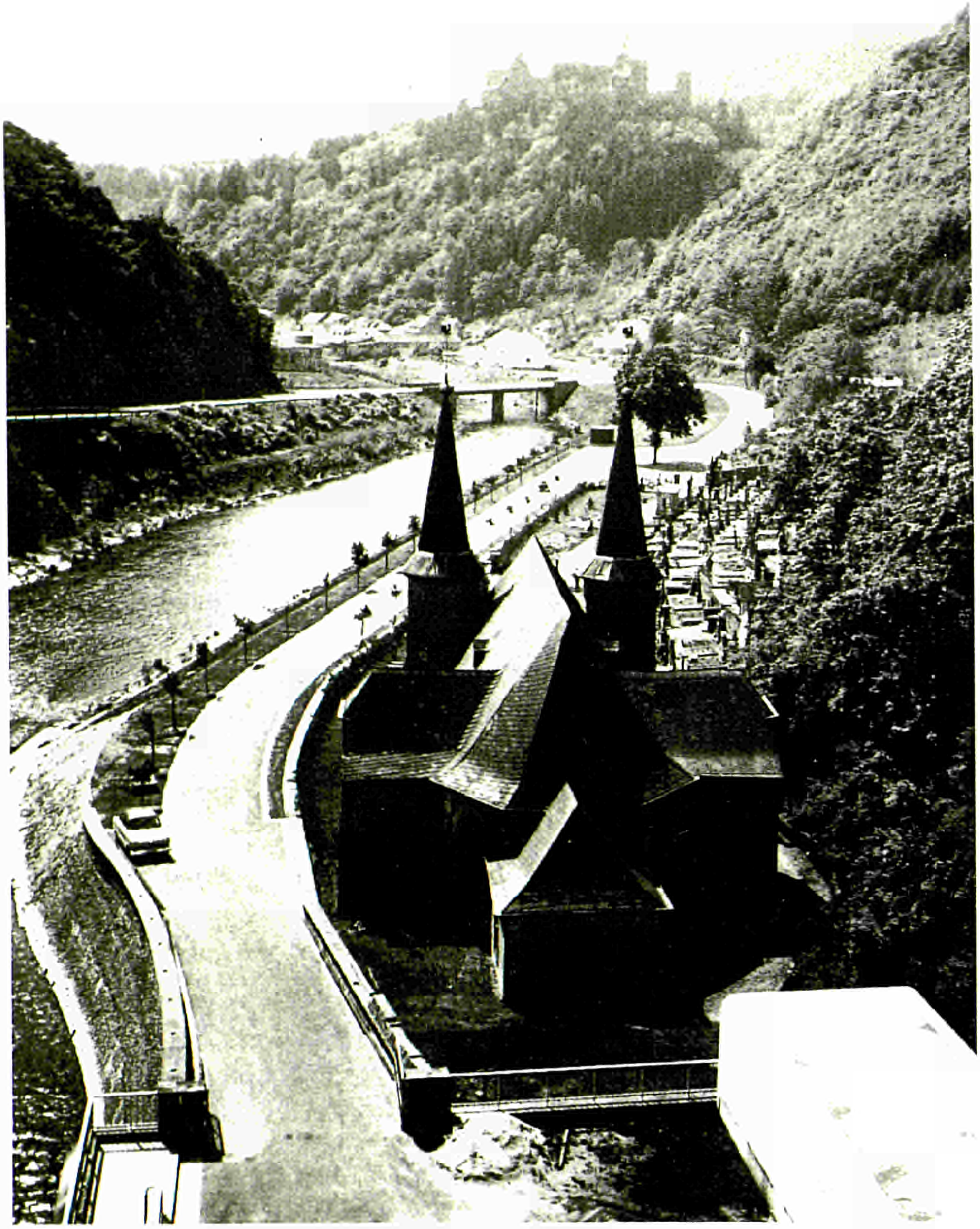
— pumped storage stations: 22%

— turbojets: 8%

It should be pointed out, however, that it is not in all parts of the world that a



Figures 9a and 9b: Modifications made to a hypothetical production diagram by the introduction of pumped storage. (It is assumed that the maximum installed power of the system is 124% of the maximum power actually required). Figure 9a represents the production diagram of a system without pumped storage and figure 9b that of a system including an optimum proportion of pumped storage.



View of the Our Valley downstream of the dam forming part of the Vianden scheme.

sufficient number of sites are available to install this kind of pumped storage capacity at the capital costs used in the calculations. In other words, the installed pumped storage power is limited in practice by natural factors.

It should be emphasised that the statistics used in the study just outlined should only be taken as orders of magnitude valid in the present economic context. However this may be, the study clearly demonstrates the attraction of pumped storage stations and shows them to be the ideal unit for use in conjunction with nuclear power plants.
(EREA-A 7-14)

The boiling of alkali metals

GÜNTHER GRASS *and* HEINZ KOTTOWSKI, *Heat Transfer Department, Ispra Establishment of the Joint Research Centre*

The design of certain reactor types, and in particular fast-neutron reactors, is based on the use of liquid metals for heat transport. This, by comparison with the centuries-old use of water for this purpose, is something entirely new. It is therefore advisable, partly for safety reasons but also in order to derive the greatest possible advantage from them, to study the behaviour of such metals very closely.

INVESTIGATIONS into the suitability of alkali metals like sodium and potassium or their alloys as coolants did not begin until after 1950. Research on the boiling behaviour of sodium subsequently received a fresh impetus, especially because of the need for accident analyses in respect of fast breeder reactors. Sodium boiling can occur in a fast breeder reactor, both in a power excursion and in a coolant flow failure. Both types of accident can result in the boiling temperature being exceeded.

Besides, in the last few years, technological development has opened up fields of application in which sodium vapour has proved superior to conventional media. The carrying-out of such projects is at the present time still limited by the reliability of suitable construction materials. Taking the present status of materials development as a starting point, it is none the less already technically feasible to build, inter alia, reliable alkali-metal vapour driven turbines for low powers (around 300 kW) and saturated steam conditions of up to 1,200°C and 5 bars, but initially their application would be confined to space travel. In addition, the feasibility of using sodium and sodium vapour in closed-cycle operation, for example in direct magnetohydrodynamic energy conversion (MHD) and for the transport of process heat in the iron and steel industry, is definitely established.

The sodium and potassium boiling studies, which started out from the safety angle, very soon developed into basic investigations into the boiling behaviour of alkali metals in general, under various conditions. While the flow pattern of water under pool boiling and forced convection conditions was quite well known, there existed at that time only theoretical models of the flow pattern in boiling liquid metals which, as it subsequently transpired, are of limited or no validity. If the hydrodynamic flow conditions are taken to be the primary characteristic of each type of boiling, the following distinctions can be drawn:

1. stagnation,
2. natural convection, } in a channel
3. forced convection,
4. film boiling,
5. transpiration and perspiration cooling (evaporation).

Cases 1 and 2 can arise if, for example, the pumps in a fast breeder cut out suddenly and reactor power is not turned off quickly enough. Case 3, boiling with forced convection in the reactor, may occur if the sodium flow rate in a reactor channel drops or if the reactor power is excessive. Film boiling takes place when a reactor cooling channel is emptied for any reason and a fluid film is left on the walls. By evaporation cooling is meant evaporation through a porous wall (e.g. sintered metal), which permits a heat transfer that is self-adjusting over a wide range.

On account of its greater interest, boiling under flow conditions 3), 4) and 5) is discussed in detail below.

Various boiling mechanisms in forced convection

By boiling in forced convection (Fig 1) is normally meant the conditions that prevail in, for example, a once-through boiler: a coolant enters the boiler undercooled at a particular flow rate, evaporates either completely or partially on its way through and accordingly comes out as pure steam or a liquid vapour mixture. The channel wall is heated with a heat flux that is constant in time but may vary locally in certain circumstances. The saturation temperature of the liquid (T_S in Fig. 1a) falls on the way through the channel in line with the decrease in total pressure, which is due to friction pressure losses and also, in the case of vertical channels, to the change in hydrostatic pressure. The liquid temperature rises in line with the flow rate and heat flux (T_F in Fig. 1a). The two curves intersect at a distance L_S from the inlet at the saturation point. Downstream of the saturation point the temperature of the mixture ceases to rise with the T_F curve, if it is assumed that thermodynamic balance conditions prevail at every point, but corresponds to the saturation temperature T_S.

In the channel, the liquid/vapour mixture goes through a number of flow conditions which in particular cases may be wholly or only partially present, depending on the pressure, mass flow, steam content at outlet and other parameters (Fig. 1b):

A: pure, undercooled liquid;
B: surface boiling;
C: nucleate boiling;
D: slug flow;
E: annular flow;
F: fog;
G: pure, superheated steam.

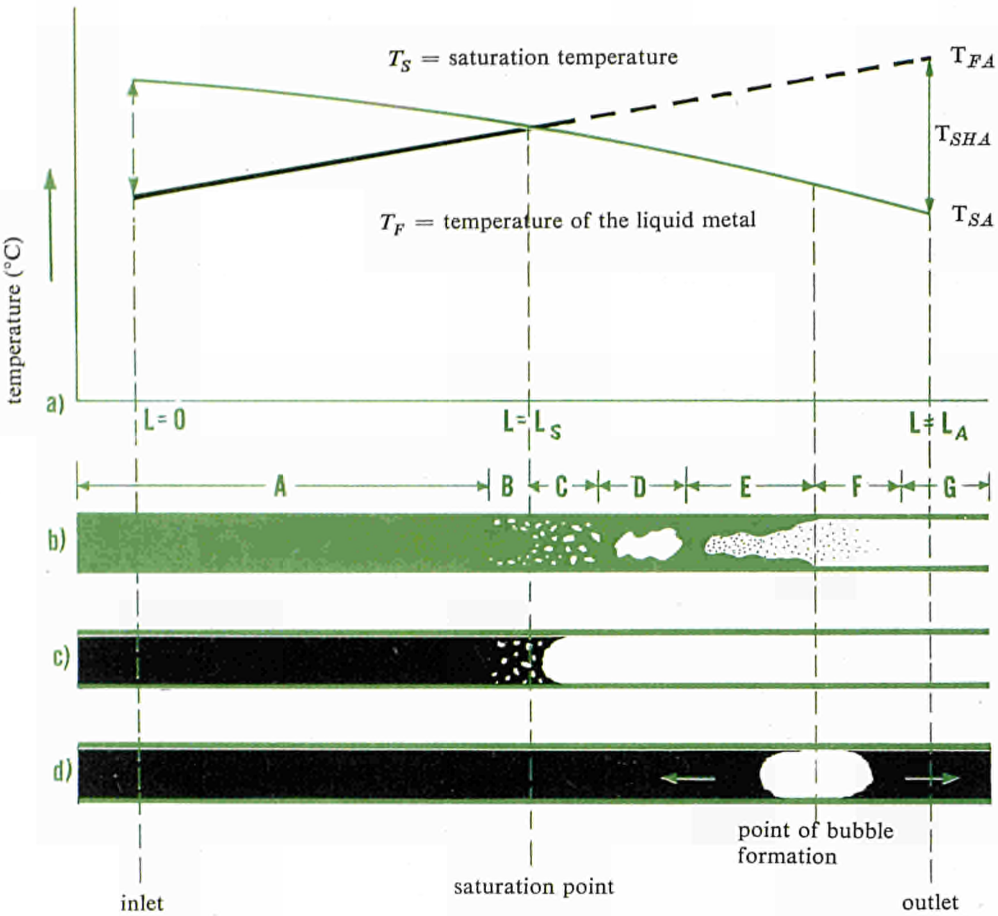


Fig. 1: The liquid metal temperature and saturation temperature in the case of forced-convection boiling in a vertical tube. At b) is a diagrammatical representation of what happens in water at a pressure of 70 bars with a heat flux of 100 W/cm², i.e. the normal conditions in a boiling-water reactor; at c) and d) is shown what happens to liquid metals at 2 bars with a heat flux of 350 W/cm² in conditions of thermodynamic equilibrium (c), and in—more usual—delayed-boiling conditions (d).

Fig. 1b illustrates in the most general way what occurs at every point during "steady" boiling under forced convection conditions typical of a boiling water power reactor (70 bars). The steam content rises constantly, the state of the mixture at every point is clear-cut and virtually constant in time.

The boiling of liquid metals, on the other hand, is totally different at low pressures[1], where the vapour and liquid density differ by about a factor of a thousand, i.e. a small volume of evaporating liquid produces a very large volume of vapour. Furthermore, pure liquid metals contain exceptionally few physical or chemical boiling nuclei, in addition to which they apparently neutralise to a large extent surface irregularities, which also act as boiling nuclei. This results in a very marked tendency toward retardation of boiling. (In potassium at its purest, superheating up to 830°C has been measured.) The good thermal conductivity of liquid metals entails, under forced convection conditions, radial temperature gradients which are slight in relation to the possible superheat, i.e. the superheat in liquid metals can be uniformly very high throughout the volume considered.

Because of all these factors, liquid metal boiling follows a different pattern from that usually observed in water. The

1. In the typical case of alkali metals, confinement to low pressures results from the limitations set by the properties of the construction materials at the high boiling temperatures involved.

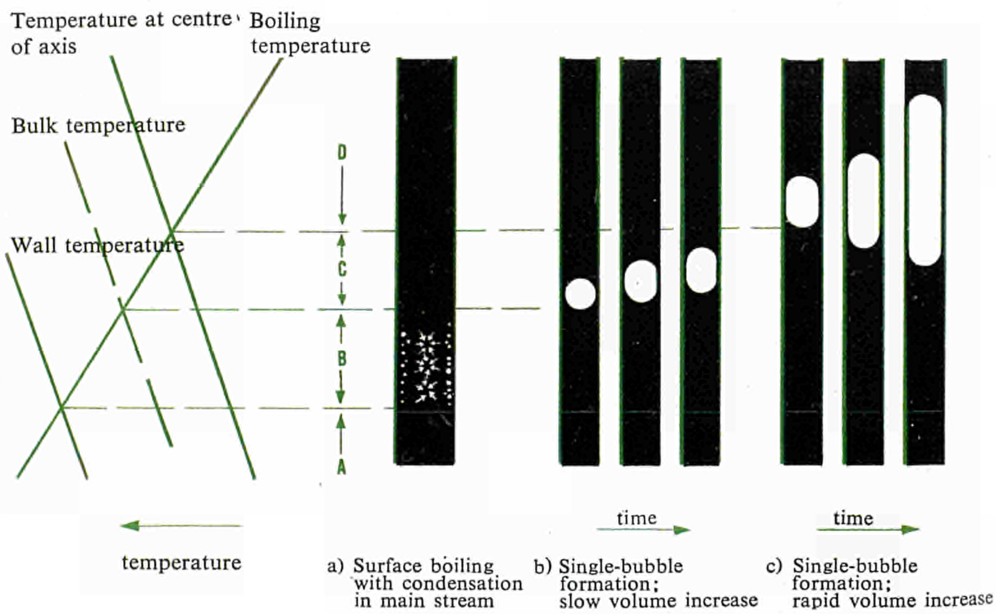


Fig. 2: Liquid metal boiling during forced convection with superheat.

temperature T_F of the liquid metal (Fig. 1a) continues to rise downstream of the saturation point L_S (up to a maximum of T_{FA}), so that at the outlet a superheat of $\Delta T_{SHA} = T_{FA} - T_{SA}$ can occur without boiling taking place at all. An analysis of the physical properties of sodium and potassium (see Table I) shows that superheating and hence retardation of boiling is a characteristic property of sodium and potassium. Initiation of boiling in the superheated range L_S to L_A leads to the formation of large separate vapour bubbles (Fig. 1d).

If, on the other hand, we assumed the same boiling mechanism as for water, the transition from liquid flow to vapour flow in liquid metals at low pressures would be so rapid, owing to the high specific vapour volume, that the ranges B, C, D and E in Fig. 1b would disappear completely. While in boiling water channels these ranges may take up lengths of about 30-50 cm at 70 bars and a heat flux of 100 W/cm², in liquid metals this transition would theoretically take place over a few millimetres at 2 bars and 350 W/cm², as illustrated in Fig. 1c.

On the basis of the experimental data which are available today it is already possible to make reliable predictions about the boiling behaviour of sodium and potassium for the conditions permitted by the present state of technology (i.e. up to 5 bars and 1,200° C). Two quite distinct stages must be considered, namely a) the actual onset of boiling and b) boiling some time after the onset.

The critical phase in the boiling of sodium and potassium (and with other alkali metals it will be similar) is the onset of boiling. In the transition from the subcooled to the superheated condition, either of the following two boiling processes are possible (shown in Fig. 2), namely surface boiling and retardation of boiling with the formation of separate bubbles.

The form in which boiling sets in depends on the activation of the boiling nuclei on the wall surface. The types of boiling shown in Fig. 2 will occur with equal probability. Surface boiling (Fig. 2a) is possible even if the liquid is superheated downstream. Surface boiling does not, however, remain stable for any length of time. It changes into another form of boiling (Figs. 2a and 2b: slow or fast growing separate bubbles) and the surface boiling is inhibited. When separate-bubble formation occurs, a residual film remains behind on the wall, its thickness depending on the velocity and acceleration of the liquid in the channel. Cooling is maintained by film evaporation.

After a transitional period characterised by the alternate formation and condensation of bubbles, the flow conditions shown in Fig. 1c are established. The amount of liquid present in the boiling channel varies according to the heat flux and the mass flow of the coolant. In this case, too, superheating can cause retardation of boiling, accompanied by an ejection of columns of liquid, resulting in the build-up of a new film on the wall surface. This flow pattern, too, is of an unstable character, owing to the high superheating capacity of alkali metals. The channel may even be completely flooded with superheated liquid metal. Boiling breaks out in the superheated liquid (because of boiling nuclei on the wall surface, say) and this leads on again to retardation of boiling and the formation of large separate bubbles.

It is seen that in liquid metal boiling delayed boiling with the formation of large separate bubbles is the prevailing mode, unless mechanical or chemical expedients are adopted to prevent superheating. Thus a graphic picture is afforded by the use of the term "separate-bubble ejections" in order clearly to distinguish this form of boiling from both steady-state boiling and ejection phenomena in the form of two-phase mixtures.

The properties of sodium

Table 1 shows the properties of sodium and, for comparison purposes, of potassium and water. It is the physical properties which determine the velocity and temperature profiles. They also determine boiling behaviour.

In detail, it can be said that the tendency boiling with ejection of separate bubbles is all the greater:

— the lower the number of boiling nuclei per unit volume,

— the higher the liquid vapour density ratio and hence the volume occupied by the proportion of the liquid which is evaporating,

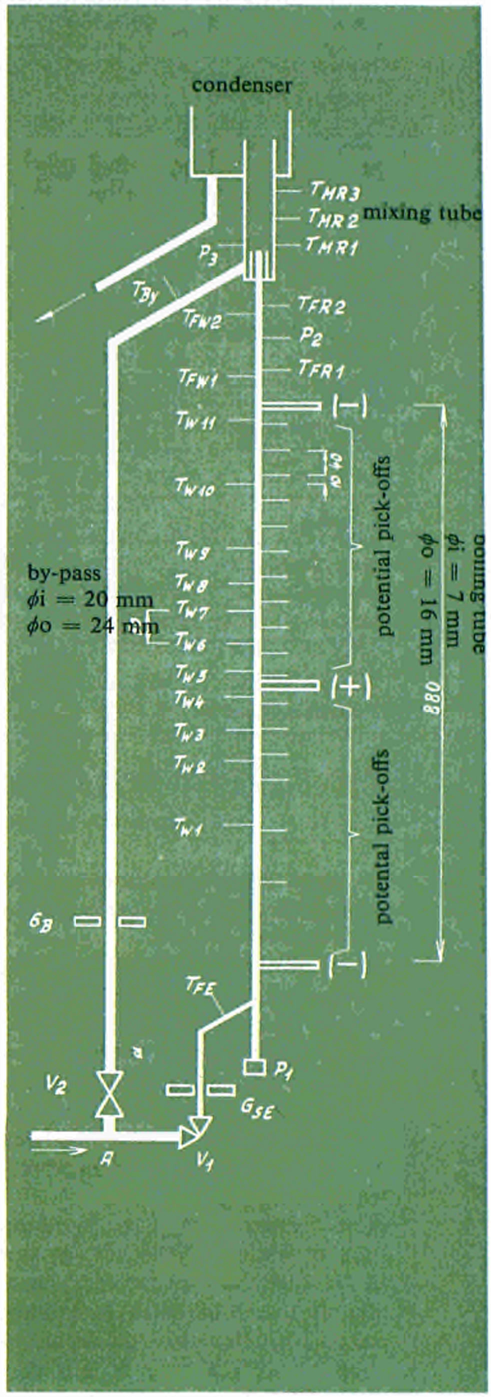


Fig. 3: Experimental loop for boiling tests with liquid metals installed at Ispra. At the various points shown, measurements are made bearing on velocity (v_1, v_2), mass flow (G_{SE}, G_B etc.), pressure (P_1, P_2 etc.) and temperature (T_{w1}, T_{FR}, etc.).

Description	Quantity	Unit	Na 2.0 bar	Na 1.3 bar	K 0.55 bar	H_2O 1.3 bar
Saturation temperature	T_S	°C	962	913	685	107.2
Density of liquid at sat. temp.	ρ_F	kg/m³	713	745	679	955
Density ratio	ρ_F/ρ_V		1240	2440	2340	1265
Surface tension	σ	N/m	0.106	0.108	0.07	0.059
Superheat	ΔT_{SH}	°C	30-400	30-400	30-400	3.0
Thermal conductivity	λ	W/m°C	43.7	46.3	32.5	0.68
Heat diffusivity	α	m²/sec	$47.0\cdot10^{-6}$	$48.0\cdot10^{-6}$	$61.0\cdot10^{-6}$	$0.17\cdot10^{-6}$
Specific heat	Cp	J/kg°C	$1.31\cdot10^{3}$	$1.29\cdot10^{3}$	$0.78\cdot10^{3}$	$4.20\cdot10^{3}$
Latent heat	A	J/kg	$3.7\cdot10^{6}$	$3.74\cdot10^{6}$	$1.95\cdot10^{6}$	$2.23\cdot10^{6}$
Ratio of stored heat to ejection heat	$\frac{Cp.\,\Delta T_{SH}}{A}.\frac{\rho_F}{\rho_V}$		22.0 $\Delta T_{SH}=50°C$	42.0 $\Delta T_{SH}=50°C$	46.8 $\Delta T_{SH}=50°C$	7.2 $\Delta T_{SH}=3°C$
Viscosity	η	kg/m sec	$1.6\cdot10^{-4}$	$1.65\cdot10^{-4}$	$1.4\cdot10^{-4}$	$2.65\cdot10^{-4}$
Prandtl number	Pr		$0.48\cdot10^{-2}$	0.4610^{-2}	0.3410^{-2}	1.63

Table 1: Physical properties of sodium, potassium and water at saturation.

— the greater the tendency toward superheating and hence the ratio of stored heat to latent heat,
— the flatter the temperature profile in the stream before the onset of boiling, i.e. the higher the proportion of the total volume which is subjected to high superheating,
— the greater the thermal conductivity and hence the possibility that the evaporating fraction can utilisě the heat stored in the surrounding fraction which is not evaporating.

The deficiency of pure liquid metal in boiling nuclei is well known. But, even aside from this, perusal of Table 1 shows plainly that there must be a tendency in liquid metals toward separate-bubble ejection; indeed, this is almost equally true of sodium as it is of potassium.

The technique of experimental investigations into boiling

Experiments with boiling sodium require considerable expenditure owing to this metal's high boiling point (962°C at 2 bars). The loop initially used for this purpose at Ispra (Fig. 3) was thus kept as simple as possible as regards handling while, on the other hand, great stress was laid on the best possible leaktightness. The leak rate was less than 5×10^{-6} torr l/sec.

In consequence, the purity of the metal, which was fresh before the experiment, hardly altered over the course of the experiments. The pattern followed by the experiments was exactly the same at the beginning and end of the series of tests.

The experimental section (Figs. 3 and 4) consisted of two tubes, one in which boiling was conducted, the other arranged to form an unheated by-pass, both installed vertically with the flow from bottom to top. The metal vapour was mixed with subcooled metal in the mixing section of the experimental equipment and condensed largely through direct contact. Heat was applied straight to the boiling tube using direct current in order to maintain the necessary heat fluxes.

Direct heating, in which the current flows in the same way through both the liquid metal and the tube wall, also makes it possible to establish the electrical resistance of any desired number of tube sections of any desired length by means of potential pick-offs.

Since a fairly constant heating current is passing through the sodium-filled (or locally non-filled) boiling section, any considerable vapour formation between two potential pick-offs results in a reduction in the voltage drop owing to the increase in the electrical resistance. Thus it is possible to ascertain, precisely and satisfactorily, when the portion of tube between the relevant potential pick-offs is empty or full. By this means, the exact moment at

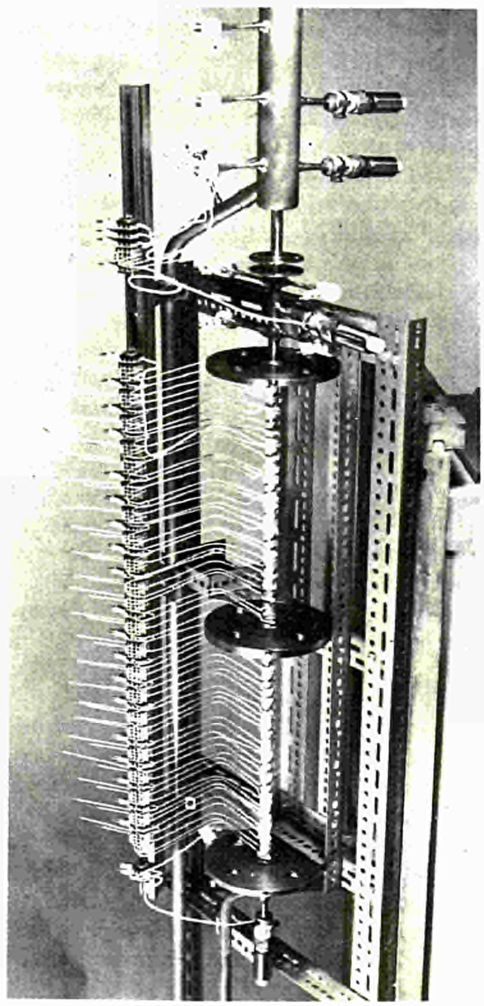


Fig. 4: View of the loop sketched at Fig. 3

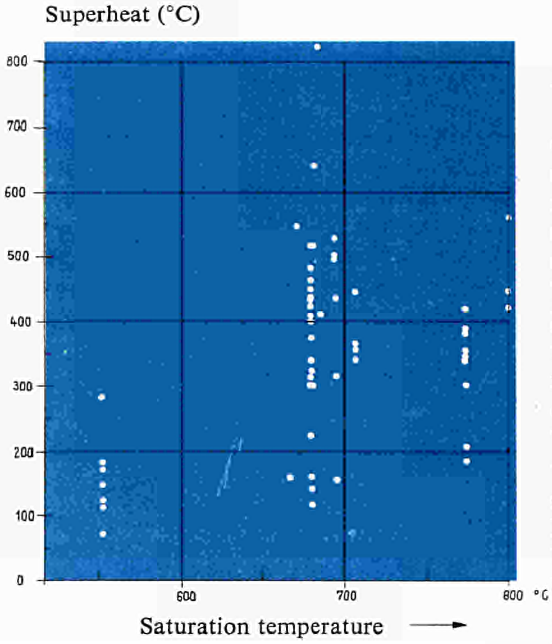


Fig. 5: Measured superheat in potassium.

which a bubble boundary (i.e. a liquid/vapour phase boundary) has passed through this portion of tube can be pinpointed. By interpreting the recorded potential values obtained by this method of measurement, therefore, the distance covered by the columns of liquid metal can be determined with very great accuracy and (by double differentiation of the distance) the velocity and acceleration can be calculated.

Superheating and separate-bubble ejection

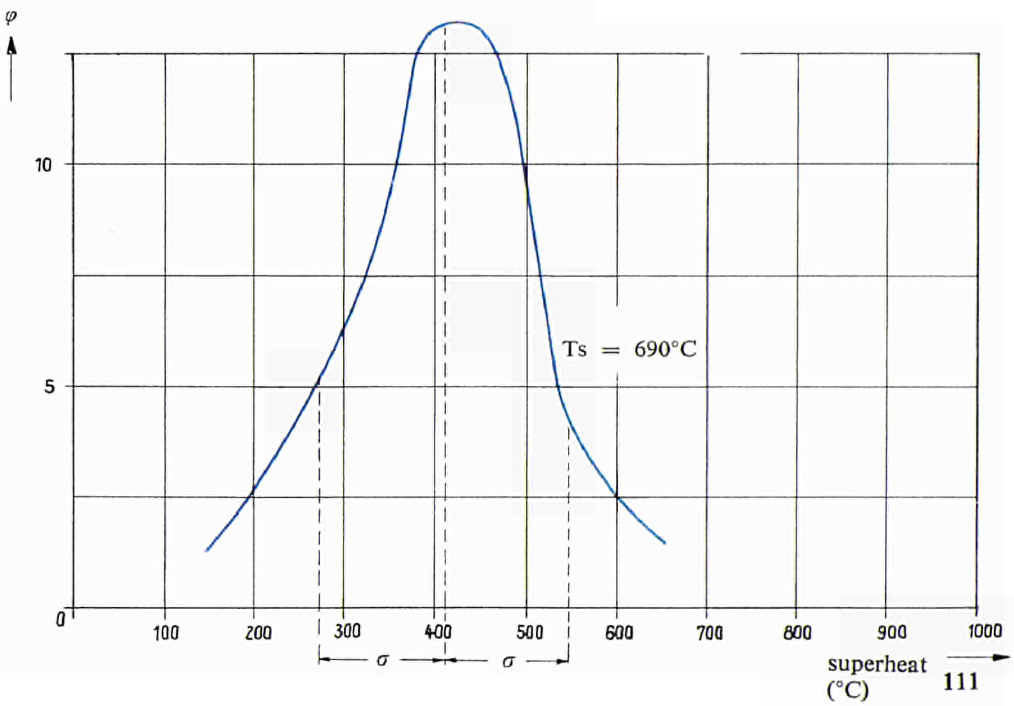
Measurements of initial superheating are particularly important because this is a determining factor in separate-bubble ejection. By way of example, Fig. 5 shows the superheat measured at Ispra in very pure potassium. Fig. 6 gives the statistical distribution of these experimental results — which is approximately Gaussian. The scatter of the measured superheat is characteristic of liquid metals and is caused both by their physical properties and by the random distribution of the active boiling nuclei along the tube wall.
It was also observed that the measured superheat tends upwards with the passage of time (Fig. 7). This can probably be attributed to the fact that wall cavities which are filled with extraneous gas or vapour will become filled with metal in the course of time and so cease to be active boiling nuclei. The behaviour in time is dependent in very large measure upon the experimental conditions and the leaktightness of the installation.
The maximum possible level of superheating of a liquid metal is therefore anything but a constant property of the material and must be viewed as a variable quantity.
The growth, and hence the ejection, of the vapour bubble will proceed at a greater or lesser rate depending upon the superheat, i.e. the temperature differential between the liquid temperature and the boiling point at the place where retardation of boiling occurs. Inside the vapour space of a bubble taking up the entire cross-section of the channel is set up a pressure approximately in line with the temperature of the film adhering to the wall[1]. This pressure is superimposed on the system pressure and ejects the column of liquid from the tube.

1. The time for thermodynamic equilibrium to appear in the vapour space of a 7 mm diameter tube is of the order of 10^{-4} sec.

Film boiling

As said above, a residual film of liquid metal is left on the wall during each ejection. Owing to the increasing area of the residual film during ejection, the rate of evaporation increases with the length of the bubble. Only this makes possible the high ejection and expansion velocities observed. If the walls were dry and only the small surfaces of the ejected volumes of liquid metal could contribute to evaporation, then the bubble's internal pressure would certainly drop during ejection, which would be delayed thereby.
Film evaporation is thus a determining factor in the ejection sequence. But it is also interesting from another standpoint: it enables liquid metals to be vaporised without superheating, and hence a more stable evaporation process can be ensured. How to secure sufficiently steady conditions in an evaporation film, e.g. a trickle film, forms the subject matter of various projects in hand at Ispra, amongst other places, and has considerable relevance to the possible practical utilisation of liquid metal evaporation for cooling or vapour-generating purposes.

Fig. 6: Distribution of superheat measured in potassium.



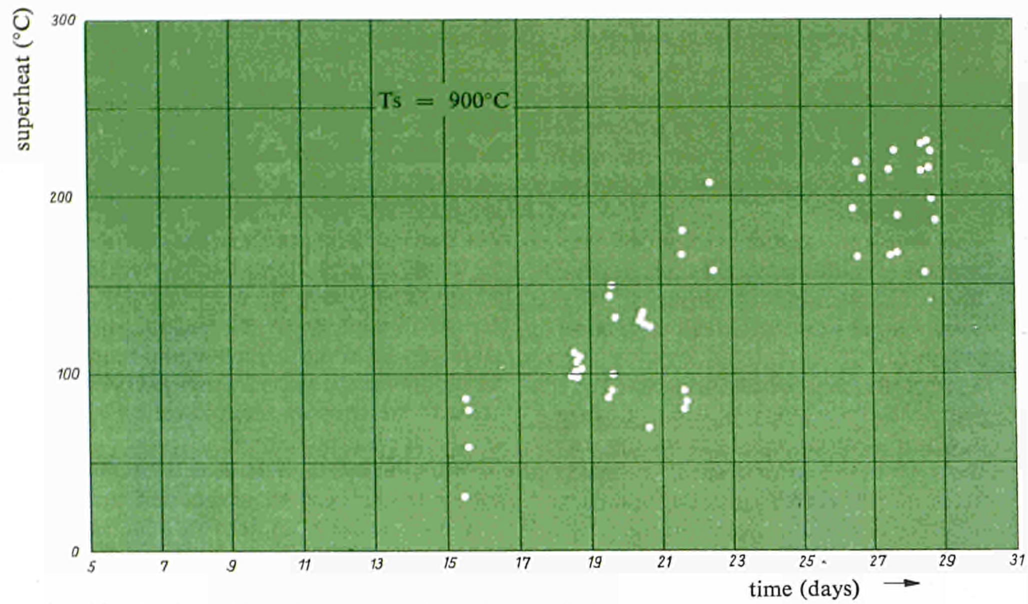
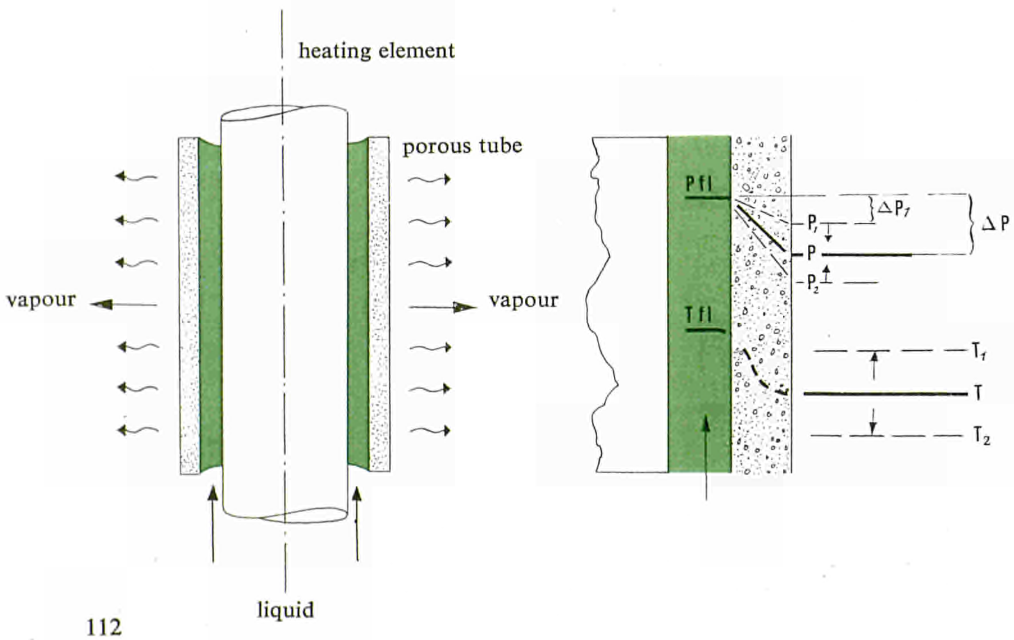


Fig. 7: Rise of superheat measured in sodium with time.

Fig. 8: Perspiration cooling. An increase in pressure from P to P_1 in the space filled with vapour entails a reduction in mass flow through the wall and at the same time a rise in the saturation temperature. As a result, the evaporation process is slowed down and the pressure can return to its original level. Should the pressure drop from P to P_2, the phenomena are reversed.



Transpiration and perspiration cooling

Liquid metals can also be evaporated through small pores and this process can be used to cool a surface, just as in the case of the human body. Depending on whether the heat of evaporation is supplied to the evaporating surface from inside or outside, this is termed "transpiration cooling" or "perspiration cooling". The former is used, in engineering, on rocket nozzles and the heat shields of satellites and may be considered as relatively well understood.

If, on the other hand, it is desired to remove a considerable amount of heat originating from within, another problem arises, namely that of transferring the heat from the inside to the outside without the liquid metal further inside beginning to boil.

For instance, if it is assumed that a rod-shaped fuel element (Fig. 8 left) is to be cooled in this way, it can be encased in a porous tube and the annular space filled with liquid metal. As soon as heat is generated in the element, a temperature gradient is set up between the rod centre and the outer surface of the porous tube. When the outside temperature of the porous tube corresponds to the saturation temperature, the liquid diffusing through the porous wall evaporates at the surface without being superheated. This process is currently being further investigated at Ispra. It is especially attractive because it constitutes a self-regulating cooling system (Fig. 8 right).

Burn-out

A further problem in connection with the evaporation of alkali metals must finally be mentioned; this is the phenomenon known as burn-out. The term burn-out is generally used to describe the very rapid rise in the temperature of liquid-cooled surfaces following a failure or reduction, for any reason, in their cooling. By extension of this definition, burn-out also occurs in the case of separate-bubble ejection. During the time of ejection, a coolant channel may be filled temporarily with only vapour instead of liquid. As a rule, a residual film of liquid metal continues to adhere to the wall and maintains cooling by evaporation for a varying length

Fig. 9: Hot spot due to local temperature excursion.

of time. This film may, depending on the heat flux, be totally evaporated before fresh liquid is fed to the surface by a restored flow or reverse flow. If we define the start of burn-out as the point in time at which the residual film of liquid on the heated wall has just been completely evaporated, then the ensuing rapid temperature rise can be equated with the well-known phenomenon of burn-out.

In the case of liquid metals, therefore, the presence of a critical heat flux is not a sufficient indication as to whether or not burn-out can occur, unlike the well-known case of boiling water. Fig. 9 shows a hot spot due to a local temperature excursion and Fig. 10 an experimental tube after a burn-out. (EREA-A 7-15)

Bibliography (1) G. GRASS, H. KOTTOWSKI, B. MILLIOT: Beitrag zur Untersuchung des Siedens von Flüssigmetallen bei erzwungener Konvektion. *Nukleonik* 8, S. 273-282 (1966). (2) G. GRASS, H. KOTTOWSKI, R. WARNSING: Das Sieden von flüssigen Alkalimetallen, *ATKE* 12-16 (1967), p. 101-110. (3) R. C. NOYES, L. LURIE, A. A. JARRET: The Development and Growth of Incore Voids due to Boiling during Fast Reactor Gradients. *Proceedings of the Conference on Safety, Fuels and CoreDesign in LargeFast Power Reactors*, Oct. 11-14 (1965). *Argonne National Laboratory*, p. 881. (4) W. PEPPLER, E. G. SCHLECHTENDAHL, G. F. SCHULTHEISS, D. SMIDT: Sodium Boiling and Fast Reactor Safety. *Report KFK* 612, paper presented at the "Conférence internationale sur la sûreté des réacteurs à neutrons rapides, (1967). Aix-en-Provence. (5) A. M. JUDD: Boiling and Condensation of Sodium in Relation to Fast Reactor Safety. *Conférence internationale sur la sûreté des réacteurs à neutrons rapides.* Aix-en-Provence. (6) G. GRASS, H. KOTTOWSKI, K. H. SPILLER: Measurement of the Superheating and Studies about Boiling Phenomena in Liquid Metals. *Conférence internationale sur la sûreté des réacteurs à neutrons rapides.* 1967, Aix-en-Provence.

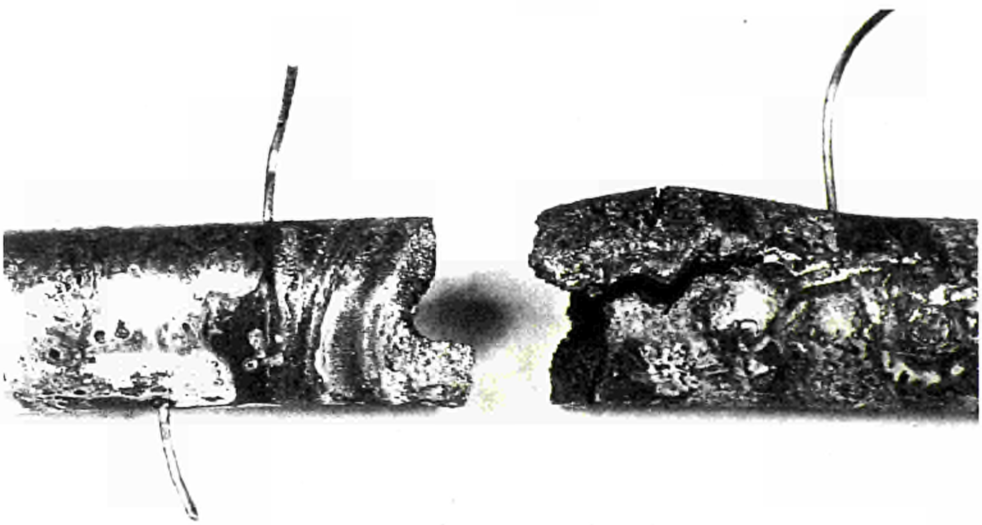


Fig. 10: Actual burn-out.

The anatomy of biological research in the Community

AN ENQUIRY recently conducted by the Commission of the European Communities has yielded interesting data on the state of research in biology, medicine, and agriculture in the Common Market countries. The study was carried out under the terms of Article 5 of the Euratom Treaty.

During 1966 and 1967, questionnaires were sent to some 2,700 research centres, institutes and departments of the Community. A total of 1,179 replies were received, of which 756 were very detailed.

Although the overall result was not representative in every respect, a fairly precise picture emerged after analysis of the replies. In particular, the statistical part of the investigation contained data on the personnel and funds available for research in the three sectors under study.

Expenditure per scientist

Figure 1 shows a breakdown of the *average expenditure per scientist* in the institutes which answered the questionnaire. This includes not only personnel costs (i.e. the salaries of the scientists themselves, engineers, technicians, assistants, administrative staff, etc.), but also running expenses and investment costs.

The most marked difference is seen between the university and research institutes: in all member countries the average expenditure per scientist is much higher in the research institutes.

On the other hand, regardless of whether institutes were engaged in research into biology, medicine or agriculture, the statistics revealed only slight differences between the various fields. Figure 1 therefore shows merely the overall situation.

Expenditure per employee

In figure 2 also, which shows expenditure per employee, no distinction has been made between the three sectors. Contrary to the average expenditure per scientist, it varies surprisingly little from one member country to another, and (with the exception of French institutes) lies between 4,100 and 5,100 u.a. in university institutes and between 5,900 and 6,300 u.a. in research institutes.

Composition of staff

Apart from the funds available to the scientist in order to do his job satisfactorily, the composition of staff in itself is particularly interesting. Figure 3 shows the ratio between scientific personnel and other employees.

Again, one is first struck by the fact that in all cases the research institutes have considerably more staff per scientist than the universities. Actually the figures do not give the complete picture, in the sense that, at the university, a scientist has to spend more time teaching than he does in a research establishment, while his assistants are solely occupied in research work. Besides, the calculations do not take into account any rôle played by the students.

It was worth finding out whether there are any significant differences in staff composition between the various sectors. Figure 3 shows that there is hardly any disparity between the scientific research establishments working on biology and medicine. In both types of establishment the requirements, methods and available resources are very similar. However, it was observed that agricultural research requires more assistant personnel than do the other two sectors. Finally, it is worth pointing out the differences from one country to another, particularly in university institutes.

Staff expenses

Staff expenses come under figure 4 and are expressed in terms of average salary per employee. So that these statistics make sense, the personnel breakdown given in figure 3 must be taken into account. Although the number of scientists, and

1. 1 EMA u.a. = 1 US dollar.

Figure 1: Average expenditure per scientist (in thousands of u.a.[1]) for biology, medicine and agriculture.

university institutes

research institutes

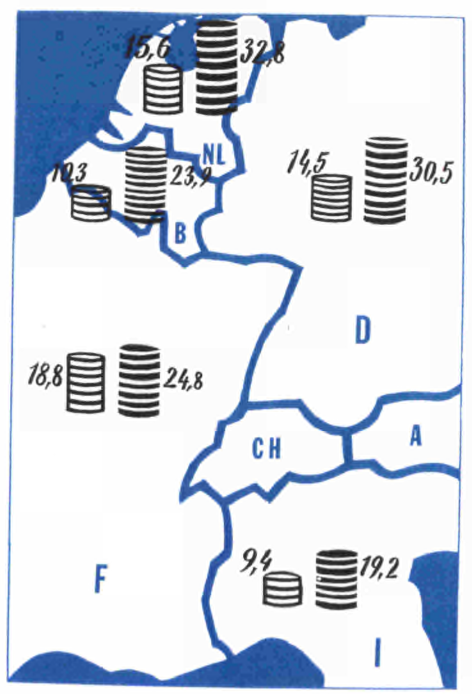


Figure 2: Average expenditure per person engaged in biology, medicine and agriculture (in thousands of u.a.)

university institutes

research institutes

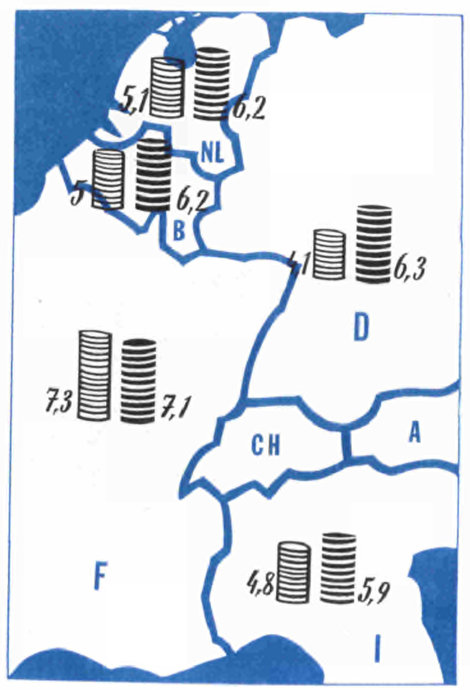
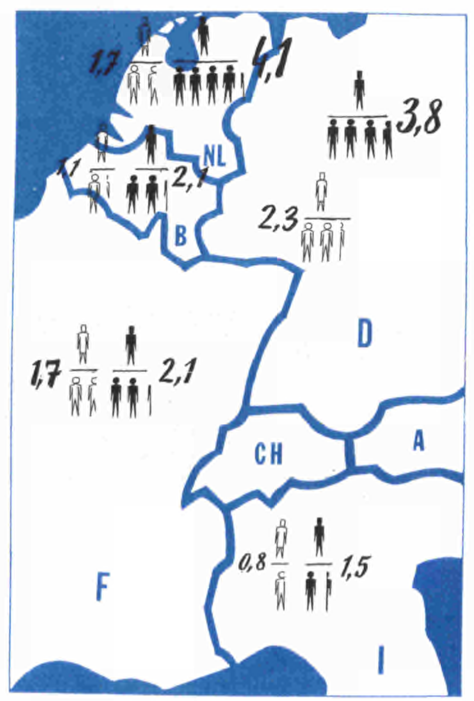


Figure 3: Staff breakdown—relation between scientific personnel and other employees (NB: in some cases no statistical analysis was possible).

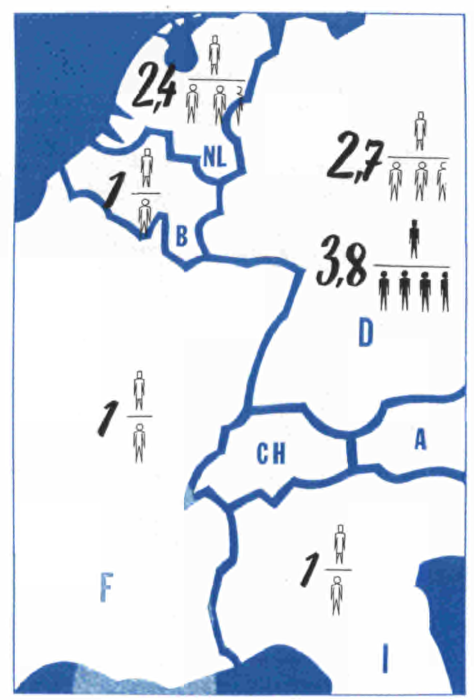
university institutes

research institutes

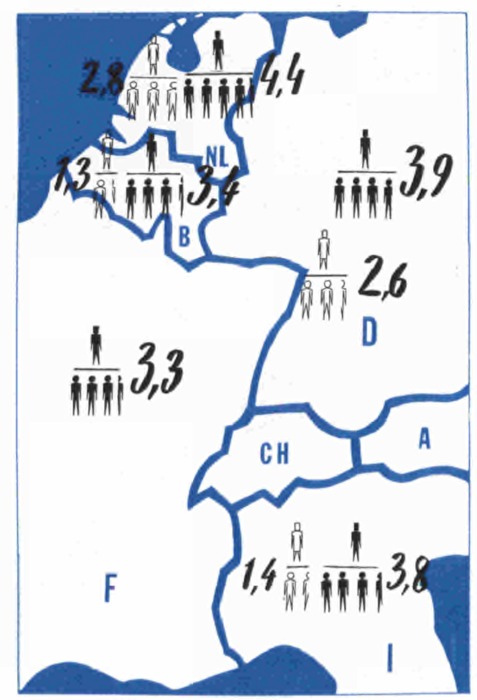
a) Biology



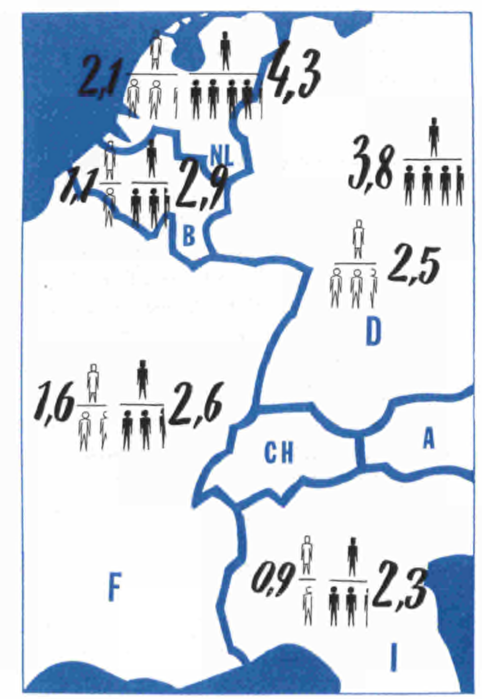
b) Medicine



c) Agriculture



d) Mean for biology, medicine and agriculture.



Country	B	D	F	I	NL
Average staff per institute					
– university institutes	15.8	29.4	27.2	25.3	34.7
– research institutes	24.9	90.3	39.9	41.8	75.7
Average number of scientists per institute					
– university institutes	7.7	8.3	10.5	7.9	11.3
– research institutes	6.4	18.7	11.4	12.8	13.9
Average expenditure per institute (in thousands of u.a.)					
– university institutes	79	121	198	74	177
– research institutes	154	570	283	245	445

Table 1: The relative size of university and research institutes.

therefore the number of more highly-paid personnel, is greater, the average salaries are lower in the universities than in the research institutes (except in France).

Other costs

Under this heading are included running expenses and investment costs. Figure 5 shows the other costs as a percentage of the average expenditure per scientist. In the Community countries this percentage is generally between 30 and 50% of the total costs.

Size of institutes

From the angle of attempting to determine the size of the institutes, the concept itself of an institute is somewhat ambiguous owing to the fact that replies were received from vastly different establishments. Thus, in drawing up Table 1, only independent institutes and individual research institutes were taken into account, the larger establishments which administrate these smaller institutes being ignored.
In each Community country, the university institutes differ considerably from the research establishments as regards staff size and overall expenses. On the other hand, the number of scientists in all the countries is, with one exception, virtually the same in both university and research institutes.

The use of nuclear techniques

Some of the questions put to these institutes dealt with the importance of nuclear techniques in their research. The number of establishments in the different member countries of the Community which use or are interested in nuclear techniques can not be worked out exactly, because of the lack of information on institutes which did not reply to the questionnaire or did not receive it. However, the percentage of biological, medical and agricultural research institutes which are interested in or use nuclear techniques can be put at 20 or 30%.
Among the institutes which filled out the questionnaire, the percentage of those using nuclear techniques varies from country to country between 30 and 40%. Of these, about 70% use these techniques to a limited extent, 20% use them to an extent which may be considered as medium in relation to the institute's other activities, and 10% use them on a large scale or even exclusively.

Michel GIBB

(EREA-A 7-16)

Figure 4: Average salary per person (mean for biology, medicine and agriculture in thousands of u.a.).

4,7 university institutes

4 research institutes

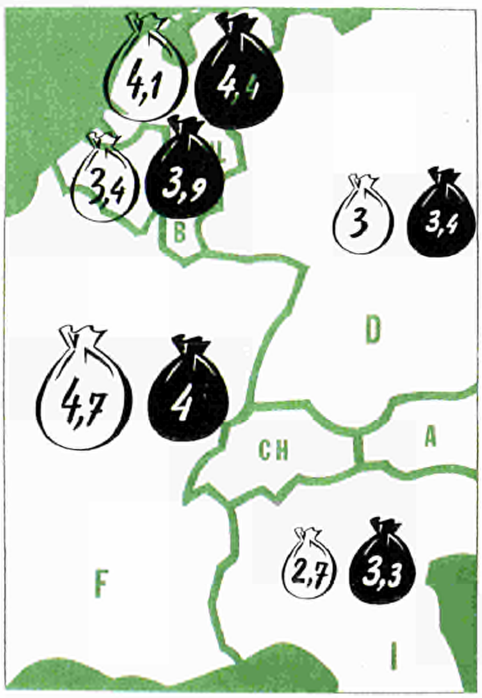
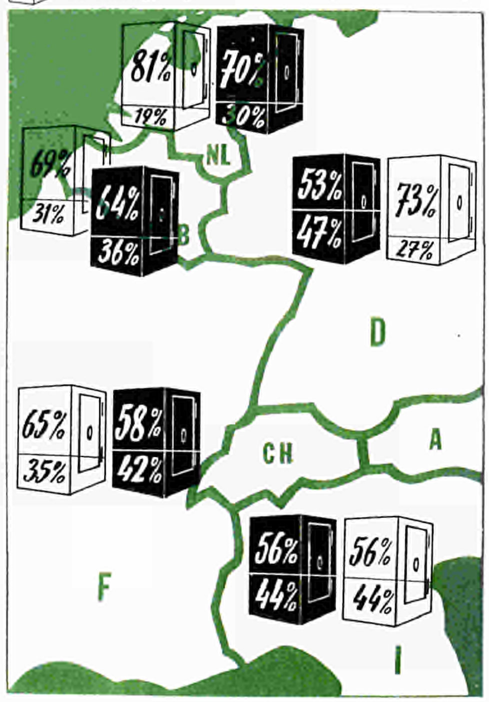
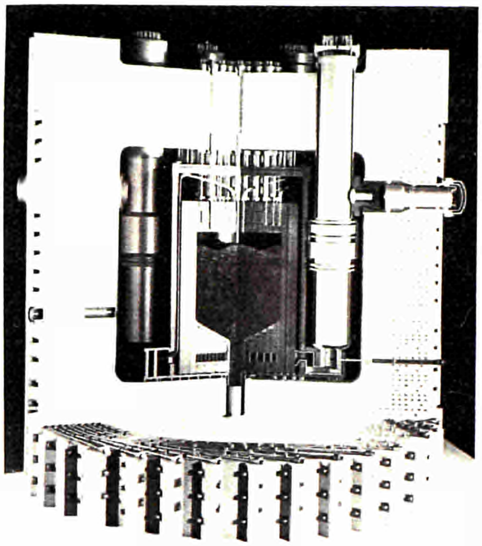


Figure 5: Breakdown of expenditure (mean for biology, medicine and agriculture).

university institutes
58% personnel costs
42% running expenses and investment
research institutes
65% personnel costs
35% running expenses and investment





Model of prototype 300 MWe high-temperature pebble-bed reactor proposed by Brown Boveri/Krupp Reaktorbau GmbH.

The pebble-bed reactor - something of its background

In most nuclear reactors, the fuel is in the form of static elements; once inserted in the core, they stay put until they are removed. In pebble-bed reactors, on the other hand, the core is a moving, one might almost say heaving mass of spherical elements, which circulate in accordance with the laws described in the following article.

This idea was first put forward by Farrington Daniels *in 1944 as part of a general survey of high-temperature helium-cooled reactors.*

Subsequently, various patents were published between 1945 and 1954, but they did not lead to any large-scale development work.

Since then, more detailed studies have been undertaken by several organisations, of which the Australian Atomic Energy Commission *was the first, contemplating the use of beryllium oxide as a moderator.*

Then the firms of Brown Boveri et Cie, *Mannheim and* Friedrich Krupp, *Essen, formed a working group on the pebble-bed reactor, under the direction of Professor Schulten.*

The firms of Sanderson and Porter *and* Alco Products Inc. *commenced studies with the active support of the* United States Atomic Energy Commission, *which culminated in two reactor designs.*

However, only the German programme was pursued, firstly to the experimental reactor stage, and then on an industrial scale. It concerns a high-temperature system (see Euratom Bulletin, *Vol. IV (1965) No. 2, pp. 44-48 and* Euratom Review, *Vol. VII (1968) No. 2, pp. 42-45), in which the fission heat is removed by forced helium circulation.*

By 1959, the work done by Brown Boveri/Krupp (BBK) *was so far advanced that the* AVR *firm, a joint enterprise combining about fifteen utilities, decided to commission* BBK *to build a 15 MWe power plant at Jülich, near Aachen. The reactor went critical in August 1966 and was first connected up to the German grid on 18 December 1967. Since then, the reactor has been run up to and maintained at two thirds of its rated power (apart from a short period at full power). Its performance has fully demonstrated the soundness of the pebble-bed reactor concept, in spite of the scepticism of certain engineers.*

In order to ensure the industrial development of the system, the Euratom Commission, the KFA (Kernforschungsanlage Jülich) *and* BBK *signed a contract of association (for the five year period 1963-1967), known as* THTR. *Apart from a programme of research and development and participation in the running of the* AVR *reactor, this association's main objective was the drawing up of a reference design for a 300 MWe reactor which could be extrapolated to higher power ratings.*

Since then, in August 1968, BBK *submitted a tender to the German government and to* Hochtemperatur-Kernkraftwerk (HKG), *which combines various utilities who provided backing for the building of the* AVR, *as well as the* Vereinigte Elektrizitätswerke VEW, *the second largest producer of electricity in Germany. The third German atomic programme provides for the construction of the 300 MWe prototype, as soon as this is warranted by the performance of the* AVR *and the results of the development work. A decision will probably be taken early in 1969.*

Denis TYTGAT, Directorate general of the Joint Research Centre.

Does a pebble-bed behave like a fluid?

DIETRICH BEDENIG, *Brown Boveri/Krupp Reaktorbau GmbH*

THE SPECIAL features of a pebble-bed reactor are to be found in the build-up of the core and the handling of the fuel.

The core consists of a cylindrical vessel of carbon and graphite construction filled with several hundred thousand spherical fuel elements in a random stack, their number depending on the reactor power rating. The lower part of the core is conical and terminates in one or more discharge tubes through which the fuel elements are withdrawn from the core. The elements then pass through a scrap separator, which removes from the cycle those which have undergone mechanical damage, after which their burn-up is measured. According to the result of these measurements they are then either lifted pneumatically and fed back into the core at various radial positions or removed and replaced by fresh elements.

Figure 1 shows the fuel element cycle in diagrammatic form and Table I displays the main data on core structure and fuel circulation in the *AVR* reactor and the *THTR* prototype.

Thus, after the spherical configuration of the fuel and its random stacking in the core, the most important feature of the high-temperature pebble-bed reactor is the fact that the fuel elements are continuously circulated through the core and pass through a series of inspection systems. Downward motion is due to gravity and upward motion is effected by a pneumatic elevating system.

The most important of the characteristics arising from this feature are as follows:

— *the distribution of fuel and fertile material over a large number of "differential" elements*, causing both uniform burn-up in the individual fuel element and increased safety, since damage to one fuel element causes only very slight contamination of the primary circuit;

— *the continuous on-load charging of the core*, leading to a saving of fuel, since excess reactivity to compensate for burn-up is unnecessary; at the same time this entails a further raising of the nuclear safety level, as the reactivity reserve on which power excursions can draw is smaller by this amount than in other reactors; furthermore it is possible, with particular flexibility, to adjust the fuel flow to suit the fissile and fertile material market;

— *the continuous inspection of the fuel elements, only a tiny proportion of which are out of the core at any one time*; this results in optimum fuel utilisation and opens up the possibility of using beryllium oxide moderating spheres; the advantage of introducing beryllium into thermal reactors is twofold: after neutron capture beryllium disintegrates into two helium nuclei and two neutrons, so that it operates as an additional neutron source; secondly beryllium is a better moderator than graphite, which leads to a reduction in "protactinium-losses" (see *Euratom Review*, Vol. VII (1968) No. 3, pp. 74-81) and fast neutron leakage; for these reasons it looks as though it should be possible, through the use of beryllium, to raise the conversion factor to such an extent that a thermal breeder is obtained; in the present state of the art only the pebble-bed reactor has this capability, since, owing to the lithium poisoning and embrittlement of the material which occur, a condition of the use of beryllium oxide is that it can be subjected regularly to heat treatment about every six months.

Investigating the pebble-bed flow behaviour

Before full advantage can be taken of the above inherent merits of the high-temperature pebble-bed reactor, it is essential to acquire as much knowledge as possible of the pebble-bed flow pattern in the core. Investigations along these lines were carried out as part of the *THTR* programme; they constitute the true substance of "pebble-bed mechanics". Attention also had to be paid to questions regarding the *THTR* absorber rod system, in which the rods are inserted freely into the pebble stack so that the bed is displaced like a fluid. The present article, however, is confined to the classical field of pebble-bed mechanics.

It should only be added, to complete the picture, that in addition to the analysis of the flow pattern in pebble-beds, a series of further investigations were carried out in which the general characteristics of spheroid stacks were determined, for instance the spatial arrangement of the balls, characterised by the space factor, which describes the occupation of the space by the spheroid stack, and by the co-ordinate

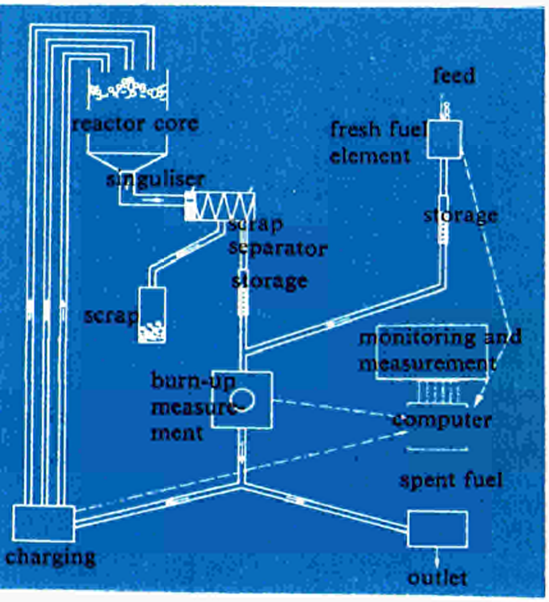


Figure 1: Diagram of fuel element cycle in the 300 MWe THTR *prototype.*

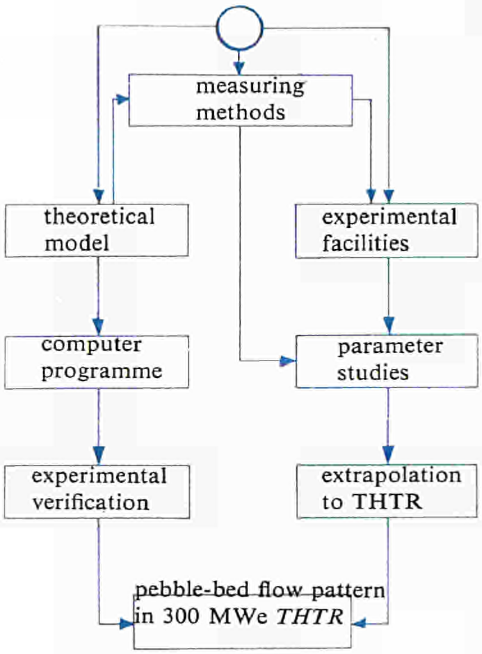


Figure 2: Block diagram of the different stages into which was divided the investigation of the pebble bed flow pattern in the core of the 300 MWe THTR *prototype.*

distribution, the tendency for orderly structures to form along smooth vessel walls, the formation of bridges in discharge tubes and the pressure distribution inside the stack and on the walls of the vessel.
Figure 2 shows in block diagram form the individual stages into which the investigation of the pebble-bed flow pattern was divided.
Methods of investigation and measurement, as well as the corresponding instrumentation, first had to be developed and tested. Once suitable methods and experimental equipment had been selected, comprehensive parametric studies were carried out to examine the influence on the pebble-bed flow behaviour of the individual parameters, such as the specific gravity or the friction of the balls.
Concurrently with the experiments a theoretical model was constructed for the purpose of calculating the pebble-bed flow pattern, and a computer programme was developed on the basis of the model.
The next stage was to verify empirically the results given by the computer programme. This verification was completely successful, so that the computer programme could be used to calculate the flow pattern in the *THTR* core under steady state conditions. The input data required for this purpose were obtained by extrapolation from the results of the parametric studies.

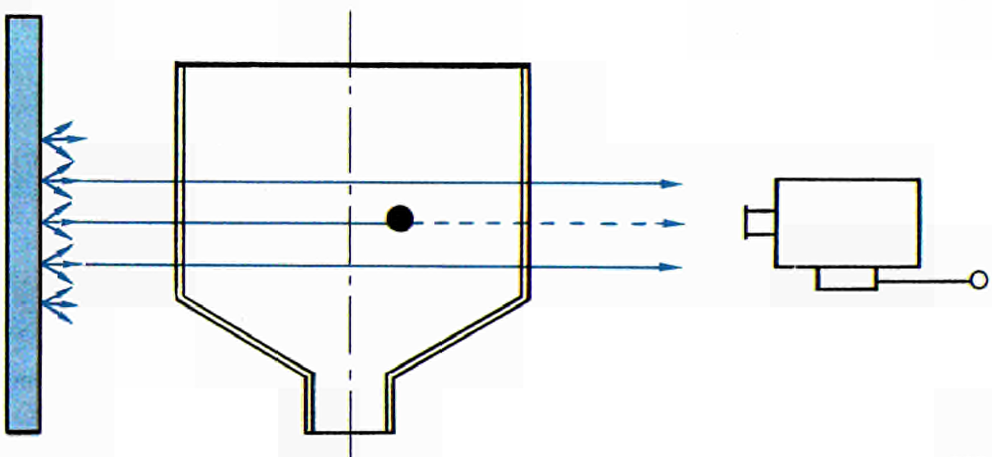
	AVR	*THTR*
Core diameter		
Diameter	300 cm	560 cm
Height of cylindrical section	350 cm	580 cm
Angle of conical bottom section	30°	30°
Number of discharge tubes	1	1
Discharge tube diameter	50 cm	80 cm
Number and diameter of spheres		
Number (steady conditions)	100.000	657.000
Diameter	6.0 cm	6.0 cm
Fuel handling		
Number of self-contained identical charging facilities	1	2
Number of elevator tubes per facility	5	8
– number of tubes feeding into core centre	1	2
– number of tubes feeding into core periphery	4	6
Circulating capacity of singuliser (FE = fuel element)	50 FE/h	500 FE/h
Mean residence time of fuel elements in core	0.5 y	0.5 y

Table 1: Data on core structure and fuel circulation

Measuring methods . . .

The measuring methods developed for the experimental determination of the pebble-bed flow pattern in model cores are either of the direct or indirect type. The direct methods involve the immediate

Figure 3: Schematic representation of the so-called absorption method for investigation of pebble-bed behaviour. The monochromatic light source is represented on the left.



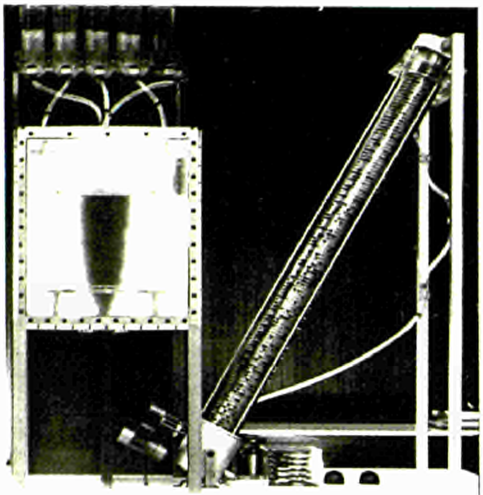


Figure 4: Glass sphere model of the AVR *core, showing the creation of a two-zone core after appropriate charging (inner zone: black spheres; outer zone: transparent glass spheres).*

location of special test balls by means of radiation. The indirect methods of measurement consist in determining the speed at each point in the core from measurement of integral quantities, like the balls' residence times in the core.

. . .direct. . .

The most important of the direct methods is the "absorption method", in which visible light is used. A model core of transparent material is employed (glass and perspex in fact). The spaces between the glass balls and between the perspex walls of the model core and the rectangular container housing the model are filled with an immersion fluid having the same refractive index as the glass spheres. This produces an optically homogeneous block with flat areas of contact. Monochromatic light from a plane source is then passed through it (figure 3). Spheres of black glass or aluminium are used as absorber test balls and their movement through the core can be observed and photographed directly.

Such a glass sphere model is primarily suited for determining flow profiles and sphere paths. Figure 4 shows a glass sphere model of the *AVR* core exhibited at the United Nations conference on the peaceful uses of atomic energy in Geneva in 1964. It can be recognised as representing a two-zone core (black spheres in the inner zone, transparent glass ones in the outer). The boundary between the two zones can be varied to any desired radius by altering the ratio between the number of spheres loaded via the centre and the number loaded via the peripheral charging tubes.

Figure 5 shows some sphere paths as photographed in a glass model. Such paths

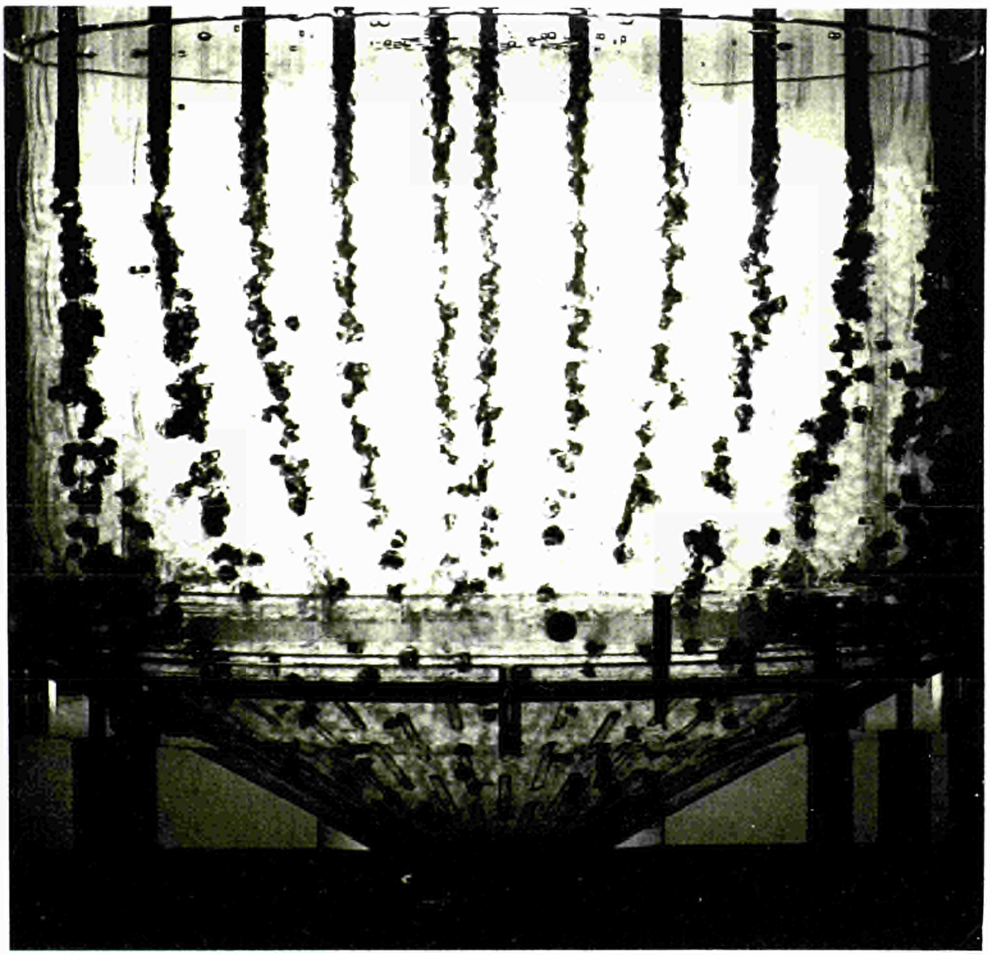


Figure 5: Sphere paths as photographed in a glass sphere model.

must be known in order to calculate the velocity distribution in the "flowing" pebble-bed.

Glass ball models can be used to advantage not only in these obvious cases but also in a number of others. Thus each phase of start-up and power operation in the *AVR* reactor was visualised as regards pebble-bed motion and fuel charging by simultaneous tests on a 1:7.5 scale model. Indirect measurements carried out during start-up demonstrated the excellent agreement between model tests and actual conditions in the core.

In addition to the absorption method used in the glass sphere model, other direct measuring methods were developed, e.g. procedures involving test balls labelled with radioactive substances.

. . . and indirect

In the case of the indirect test methods, various versions were also developed. Here again, only the most important will be discussed, namely the residence spectra method.

This method leads to the determination of the time-dependent distribution function in accordance with which test balls initially distributed evenly over the levelled surface of the pebble-bed leave the core. Figure 6 shows an example of such residence spectra. The proportion of the test ball layer found at the point of discharge of the core at different intervals during circulation is plotted against the ordinate. The abscissa is the time axis. Since the circulation speed was selected arbitrarily, it is more meaningful to use a relative unit of time instead of real units of time. In the case of the pebble-bed core the most suitable units would be the number of balls or the number of complete core volumes circulated.

The model cores with which the residence spectra illustrated in figure 6 were determined differ only by the fact that the transition between the cylindrical wall and conical base is angular in one case and rounded in the other. The difference between the spectra is clear. Residence spectra are therefore obviously suitable for characterising the pebble-bed flow pattern. The more such a spectrum stretches out over the time axis, the less uniform the flow pattern in the core will be, i.e. the

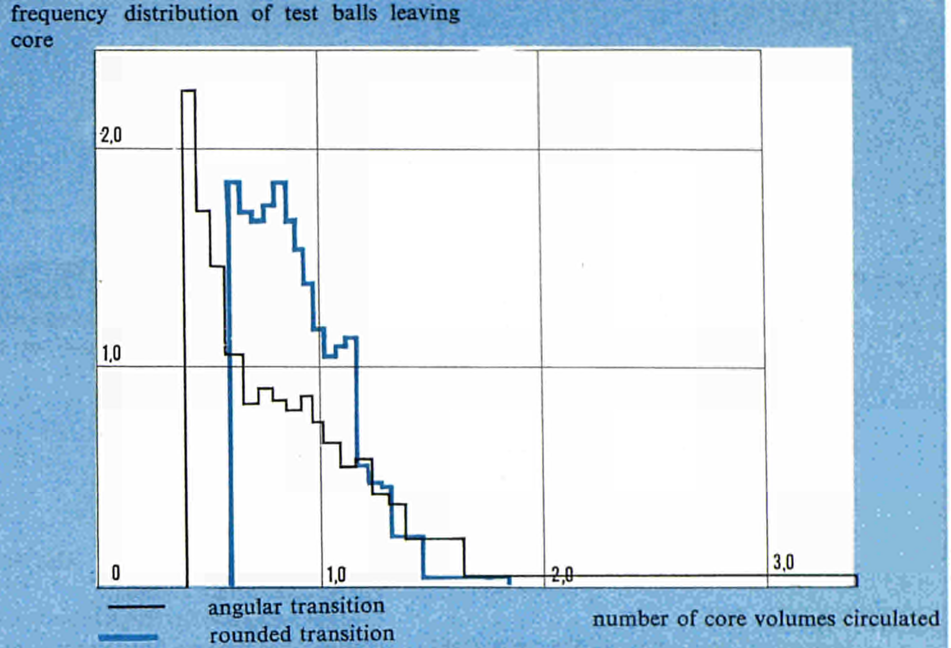


Figure 6: Residence spectra, measured on a 1 : 15 model of the THTR *core; the effect of the transition between the cylindrical wall and the conical base is shown. The frequency distribution in accordance with which test balls initially on the top surface leave the core is plotted.*

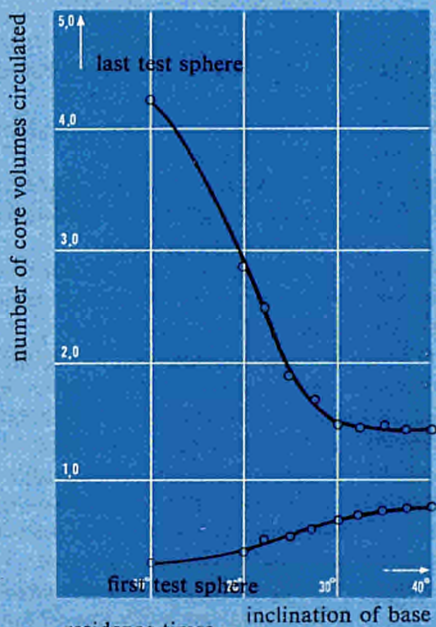


Figure 7: Influence of the base inclination on the pebble-bed flow pattern.

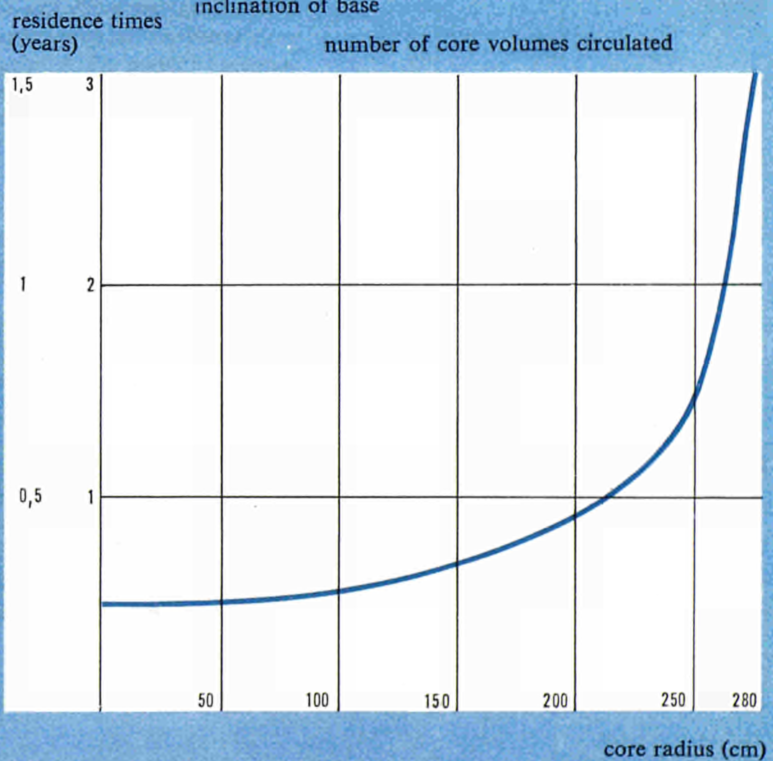


Figure 8: Residence spectra of spheres in the THTR *core as a function of initial radial position.*

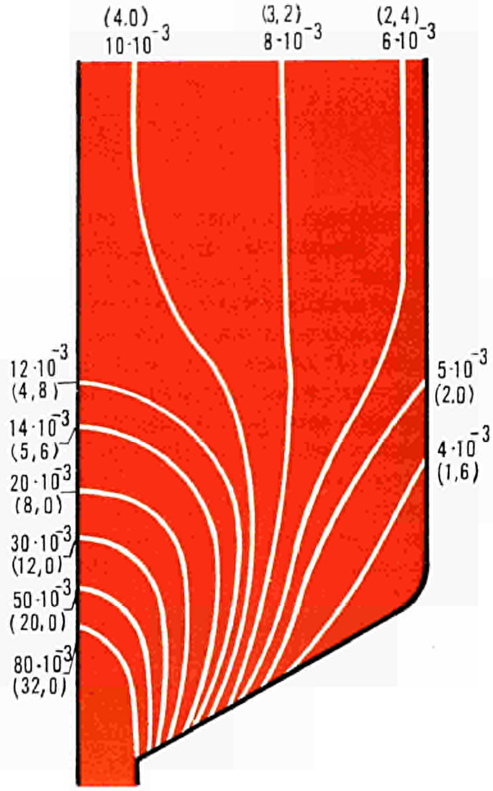


Figure 9: Isotach diagram for the THTR core; the curves shown are those of equal vertical velocity, in cm per circulated sphere (figures without brackets) and cm per day (figures in brackets).

greater will be the difference between the residence times of balls positioned near the periphery and those which are near the centre.

Residence spectra provide not only a clear picture of the pebble-bed flow behaviour. Under certain conditions their information content also enables the velocity distribution in the whole core to be determined, as well as other functions derived therefrom and describing the flow pattern.

Theoretical description of the pebble-bed flow pattern

The theoretical model briefly described below was developed with a view to determining by means of a computer programme, and working from easily measurable data, all quantities of interest in connection with the pebble-bed flow pattern.

The theoretical basis used for the development of the computer programme was the model of incompressible laminar flow subject to friction. The input data were the sphere paths and residence times in relation to the initial radial position on the core surface. From these data the programme can be used to work out the velocity distribution in the core, flow profiles and mass flow distributions.

The successful empirical verification of the theoretical model has already been mentioned.

Parametric studies

It was not possible to simulate all the conditions prevailing in the core during reactor operation simultaneously. For this reason comprehensive parametric studies had to be carried out. The following parameters were studied:

— the radius of the transitions between the cylindrical wall and the conical base, and between the base and the discharge tube;
— the angle of taper of the base;
— the height of the core bed in relation to its diameter;
— the ratio between the sphere diameter and the core diameter;
— the ratio between the discharge tube diameter and the sphere diameter;
— the sphere density;
— the friction between spheres;
— the friction between pebble-bed and wall;
— the influence of the cooling gas flow.

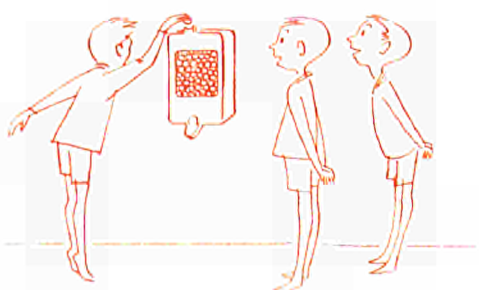
It was difficult to establish the effects of the individual parameters because virtually all the parameters influence each other.

Figure 7 gives an example taken from the many parametric studies carried out, namely the influence of base inclination on the pebble-bed flow pattern. It shows the number of times the core must be circulated before respectively the first and the last sphere from the original surface layer have passed through. The measured values were obtained from residence spectra, only the initial and terminal points of the spectra being given here for the sake of clarity. It is obvious that the flow pattern is very dependent on the angle of the base taper. The closer the two curves lie, the greater the uniformity of the pebble-bed flow pattern.

From one point of view, it is desirable to obtain the most uniform flow pattern possible, but on the other hand the reactor should not, for nuclear reasons, have too sharp a cone; this is why the cone angle on the 300 MWe *THTR* prototype was fixed at 30°. With smaller angles the flow pattern becomes distinctly less uniform while larger angles bring about no improvement worth mentioning. The value selected for the inclination of the base thus represents an optimum in the above sense. One of the applications of the parametric studies was that the flow pattern in the *THTR* prototype core could be established by means of the computer programme. Another was that information was obtained with regard to the influence of the core geometry on the flow pattern, particularly with respect to higher power units.

The pebble-bed flow pattern in the THTR core

The ball residence times in the THTR core as a function of the initial radial position are shown in figure 8. The residence times are shown on both a relative and an absolute time scale. As already stated, the relative scale, which refers to the number of balls circulated, is more relevant to the real problem. An absolute scale was nonetheless added to give an idea of the spheres' residence times in the core in terms of the more familiar time-scale. It was assumed that the mean residence time should be about six months. The mean residence time corresponds to the circulation of the contents of a core, i.e. 675,000 balls. Hence 4,000 balls are circulated each day. This will be achieved by operating the fuel charging facility, which has a capacity of 500 balls per hour, for eight hours a day.



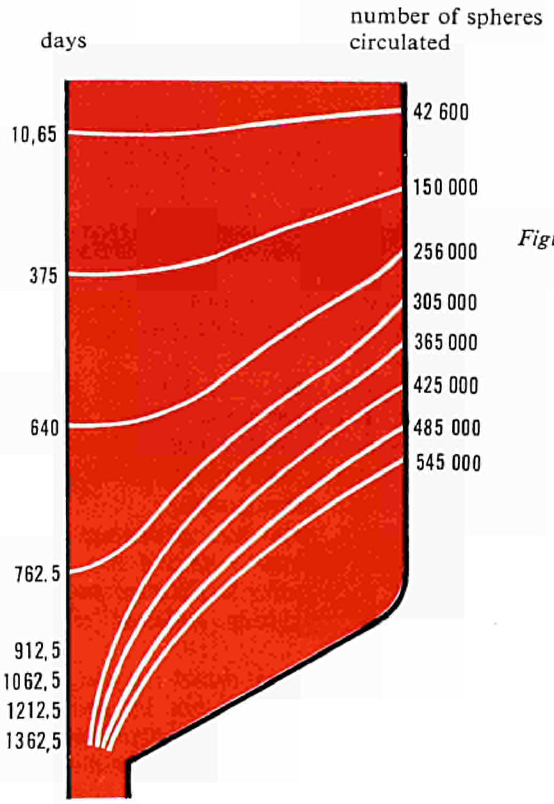


Figure 10: Flow profiles in the THTR *core.*

With the help of the computer programme, the flow pattern in the *THTR* core was calculated from the residence times given in figure 8. As an example of this figure 9 shows an isotach chart, in which the curves are those of equal velocity (in this case, the vertical velocity component only). It is clear that the cylindrical portion of the pebble-bed initially sinks very uniformly. Both in a vertical sense and in terms of radial position the velocity differentials are small.

As the discharge orifice is approached a major velocity increase takes place, while the velocity towards the wall-base transition area decreases in the vicinity of the wall. There is however no area of the core in which the spheres stagnate.

As a further example of the flow pattern in the *THTR* core, figure 10 shows some of the flow profiles, i.e. the positions of an initially horizontal surface layer as a function of the number of spheres cirlated.

The measuring methods used in pebble-bed mechanics and the results obtained, of which this article gives a selective report in condensed form, are not applicable solely to high-temperature pebble-bed reactors. A number of basic questions which arise here are similarly relevant in other technical sectors. This was clearly shown on the occasion of a symposium held by the *THTR* Association at the Jülich Nuclear Research Centre in March 1968 on "Problems with the pebble-bed and granular material". The meeting was attended by over 300 specialists in a wide variety of disciplines, such as silo construction, mining, soil mechanics, chemical and mechanical process engineering, reactor technology and so on. In spite of this unusual heterogeneousness, the discussions were very fruitful, as the basic problems were the same for all the participants. (EREA-A 7-17)

Bibliography: (1) W. RAUSCH: Non-destructive Testing of Fuel Elements in Pebble Bed Reactors. *Paper presented at the 13th Metallurgical Congress, Centre d'études nucléaires de Saclay*, June 24-26, 1968. (2) D. BEDENIG: Experimentelle Untersuchungen zum Strömungsverhalten eines Kugelhaufens im Hinblick auf den Brennelementkreislauf im Core eines Kugelhaufenreaktors. EUR 3283 d. (3) D. BEDENIG: Ein theoretisches Modell zur Beschreibung des Kugelhaufen-Fließverhaltens im Core eines Kugelhaufen-Reaktors. *Nuclear Engineering and Design*, no. 6 (1967), pp. 479-488. (4) D. BEDENIG: Messung der Kugelbahnkurven in der Spaltzone eines Kugelhaufenreaktors. *Kerntechnik*, Vol. 10 (1968), no. 4, pp. 230-232. (5) Proceedings of the symposium "Problems of the Pebble Bed and Granular Material", Jülich, March 6-8, 1968, EUR 4190 d/e.

High-temperature reactors and the steel industry

The last few years have seen a downward trend, often spectacular, in the cost of the installed nuclear kW, linked with the constant growth in power plant ratings. It is only natural, therefore, that a sector with such a high energy consumption as the steel industry should look into the prospects offered by this new form of energy (see *Euratom Bulletin*, Vol. VI (1967), No. 4, pp. 115-120).

That is why the Commission of the European Communities recently asked a group of experts to carry out a technical and economic study, with the object of giving an initial estimate of the cost of producing steel by processes in which conventional energy would be replaced by nuclear power. This working party comprises iron and steel experts and metallurgists such as Professors Schenck and Wenzel of *Technische Hochschule Aachen* and officials of the *Centro Sperimentale Metallurgico* and the *Società Italiana Impianti* on the one hand, and nuclear power plant constructors such as *SOCIA* and *Brown Boveri/Krupp* on the other.

The conversion of iron ore into crude steel involves three essential stages, namely the reduction of ferrous oxide to iron, removal of the insoluble ore components, and separation of the soluble impurities contained in the iron. For the first two operations, two processes are at present competing—the blast furnace method, which is practically the only one employed today on an industrial scale, and the direct reduction method. The traditional blast furnace process uses coke to produce both the necessary heat and the reducing gas. As to the direct reduction process, not only does it dispense with coke, an expensive material, but it does not require such high temperatures.

A particularly attractive feature of this latter process is that the part of the energy which is used to provide heat for the reaction, amounting in the blast furnace method to two-thirds of the coke burned, can be replaced by a cheaper energy such as nuclear power. The temperatures required virtually impose the use of a reactor of the high-temperature helium-cooled type.

Generally speaking, the reduction processes convert the iron ore into a substance known as sponge iron, which has a lower sulphur and carbon content than the pig iron usually produced in blast furnaces. For the purposes of the study mentioned above it is assumed that the refining operation which follows, involving the separation of the soluble impurities contained in the iron, will be carried out in electric furnaces powered by an electricity-generating plant installed on the reactor primary circuit, in parallel with the smelting process.

By assigning this dual function to the reactor, a higher power rating can be achieved, and this of course tends to bring the costs down, very sharply in the particular case of nuclear power.

Two direct reduction processes were considered separately during the study, each of them using a different reducing agent and requiring different coolant temperatures.

The first process is based on the direct reduction of the iron ore by means of lignite or pit coal (figure 1). Here the production of reducing gas from the solid fuel and the reduction reaction take place simultaneously in the same furnace, the heat transfer needed for both operations being effected preferably by spraying with lead droplets. A secondary circuit with lead as the heat-transfer medium must therefore be employed. As high temperatures (1,200°C) are necessary, such materials as graphite had to be considered for the heat exchangers.

The second process is based on direct reduction of the ore by means of methane (figure 2). In this case the production of the reducing gas (essentially hydrogen) from methane and the actual reduction reaction are carried out in two separate reaction towers. The heat transfer from the helium primary circuit takes place inside these reaction towers; the temperature required here is not so high (900°C), which means, amongst other things, that more usual materials such as Ni-Cr 20-25 steels can be employed for the heat exchangers.

In the case of the methane process, preference was given to the conventional type of turbine, because steam is necessary to the chemical reaction. With the other

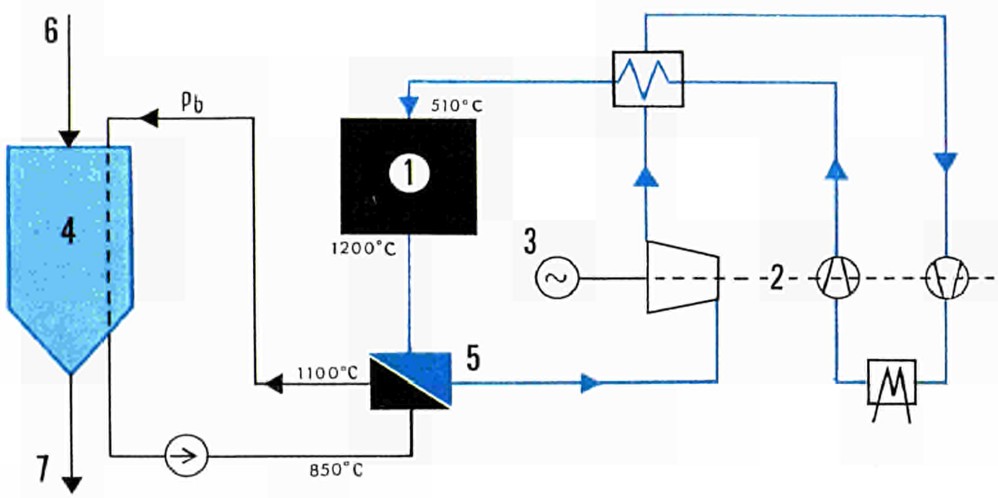


Figure 1: Direct reduction of iron ore with solid reducing agents.
1. Reactor
2. Gas turbine
3. Alternator
4. Reducing furnace
5. Helium/lead heat exchanger
6. Iron ore + lignite
7. Sponge iron

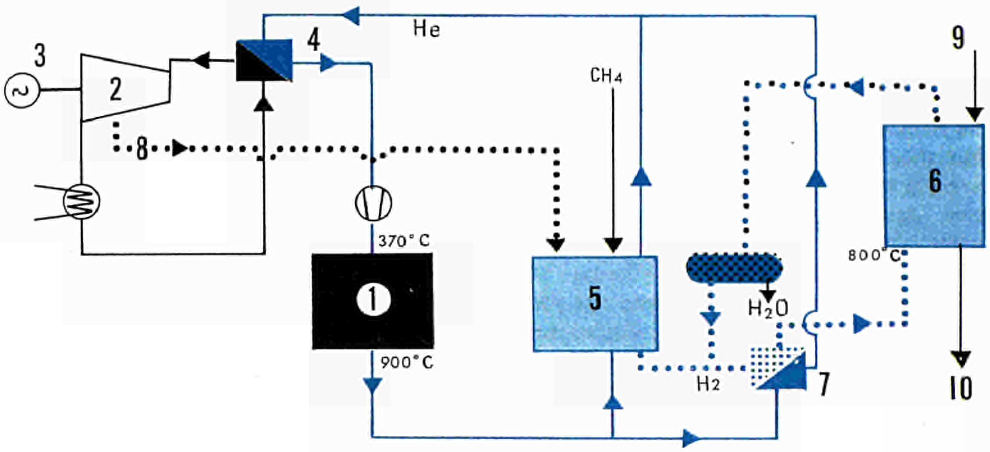


Figure 2: Direct reduction of iron ore with gaseous reducing agents.
1. Reactor
2. Steam turbine
3. Alternator
4. Helium/H_2O heat exchanger
5. Reducing gas (essentially H_2) production unit
6. Reduction tower
7. Helium/reducing gas heat exchanger
8. Steam bled for production of reducing gas
9. Iron ore
10. Sponge iron

process, however, which uses solid reducing agents, a gas turbine mounted on the helium primary circuit could be used.
In both cases the specific characteristics of the steelworks had to be carefully defined for costing purposes.
The basic assumption is that 1978 should be set as the threshold year for an estimate, with due allowance for all the foreseeable technological developments by that time. This is particularly important for the nuclear reactor. As things stand at present, the coolant leaves the reactor at a temperature of 850°C. For the two processes envisaged, this value will have to be raised to 900 and 1,200°C respectively, a requirement which raises a number of technological problems, especially as regards the 1,200°C level. These problems, though they involve no fundamental difficulties, call for numerous technical improvements, which there is every reason to suppose can be achieved within ten years.
It was further assumed that the nuclear steelworks would be sited on the European coast, so as to ensure optimum conditions as regards ore supplies, on the understanding that large ore-carriers will be in service around 1978. A nuclear reactor, being relatively free of siting restrictions, provides the best answer to this economic requirement.
It was decided to plan for a production capacity of 3.6 million tonnes of steel a year, which will probably be regarded as a normal capacity in ten years' time. The energy requirements for a steelworks of this kind correspond to a nuclear reactor of about 2,000 MWth, i.e. roughly the equivalent of a 750 MWe nuclear power plant.
The first findings of the study currently in progress, which concerns only a comparison with the conventional blast furnace process with LD refining by oxygen, show that the conventional process loses marks on certain items such as initial expenses and the various energy supplies required (coke, blown air, oxygen, electricity). On the other hand, the operating costs for such conventional plant emerge as slightly lower. The end result shows a difference in the production cost per tonne of steel of at least 10% in favour of the nuclear direct reduction process. It should also be noted that the price of coke is tending to rise today and such technological improvements as might be introduced in blast furnaces will not suffice to set off this increase.
Admittedly these part-results are not completely representative. For instance, a comparison must still be effected with the most economical methods of direct reduction by conventional processes. These findings will incidentally serve to show what development efforts need to be undertaken in this field.

Manfred SIEBKER and Henri MARTIN

First list of technical notes

Since the beginning of 1967, the Commission of the European Communities has been publishing "Technical Notes" giving a brief description of patented inventions and proprietary information stemming from Euratom's various research programmes (see *Euratom Bulletin*, Vol. VI (1967), No. 2, p. 64 and *Euratom Review*, Vol. VII (1968), No. 2, p. 64a).
A list was recently issued giving details of all the notes published during 1967 and part of 1968. A copy can be obtained by writing to:
Commission of the European Communities
D.G. XIII – Directorate A
European Centre Kirchberg
Luxemburg.
These technical notes appear to have aroused a certain amount of interest in industrial circles, which has resulted in an appreciable increase in the number of licence contracts concluded in 1968 in comparison with previous years.

Industrial application of a process developed at Ispra

Several new licence contracts have been concluded covering the sputtering process for surface-coating developed at Ispra and described in *Euratom Bulletin*, Vol. VI (1967), No. 4, pp. 121-124. The German companies *Leybold-Heraeus* and *W. C. Heraeus* are now licence-holders in addition to the French company *STEL*.

Plutonium recycling in the Garigliano power plant

In the early 'seventies, plutonium output in the nuclear power plants of the Six Community countries will be roughly two tonnes a year. This rate will climb fast, reaching 15-20 tonnes a year towards the end of the decade.

Some of this plutonium will certainly be reserved for the development of fast breeder reactors, and particularly for constructing prototype reactors and the first commercial unit of this type. Even so, a large proportion of the plutonium output will still be available, either for recycling in thermal reactors or to be stockpiled for future use in fast breeders.

If the second solution is to be economically acceptable, the value of the stockpiled plutonium will have to double at least every eight years so as to cover the interest on the capital involved and the storage expenses. This means that, assuming that the plutonium destined for consumption in the breeders were bought towards the end of the 'eighties at a price of about 12-16 $/g, its value on leaving the reprocessing plant at the start of the 'seventies, i.e. some sixteen years earlier, might well be as low as 3-4 $/g.

This would place an intolerable handicap on the fuel cycle of the present thermal reactors; for, assuming that plutonium is recycled in thermal reactors, its industrial value is at present assessed at 7-10 $/g, depending on the type of reactor and the cost of manufacturing the plutonium fuel.

In the search for an answer to this major economic problem, numerous and worldwide studies are in progress to develop efficient techniques of plutonium recycling in thermal reactors.

As early as 1960 Euratom started work on the problem by way of research contracts with various Community organisations. Experiments were also carried out in American reactors, under the United States/Euratom Agreement for Co-operation.

More recently, two research programmes were launched with a view to the industrial use of plutonium in two Community nuclear power plants, namely the *SENA* Franco-Belgian plant at Chooz and the *ENEL* plant on the Garigliano river, in Italy. The studies are complementary, since one concerns a pressurised water reactor and the other a boiling water reactor.

The first study is being conducted as part of the United States/Euratom Agreement by the *CEN/BelgoNucléaire Association*, under a shared-expenses contract with Euratom. The object of the programme is to find the optimum plutonium recycling strategy with specific reference to the Chooz power plant, and to carry out a complete study of the solution adopted. This work also includes a series of critical and sub-critical tests designed to perfect the neutron computer codes for plutonium-containing lattices, and a programme for improving fuel fabrication processes.

The object of the *ENEL* programme is to seek out all the factors, both technical and economic, that will enable the Garigliano reactor to be fuelled exclusively with a mixture of natural uranium and plutonium from 1972 onwards. The programme includes tests on critical assemblies and the irradiation of prototype plutonium elements in the Garigliano reactor.

The Garigliano power plant, after its annual maintenance period, started up again on 11 October 1968 with a core in which, out of a total of 208 fuel elements, 12 contained plutonium. The plutonium content in these elements amounts to 40 kg; it was produced in another *ENEL* power plant, the Latina plant, which has a gas-graphite natural uranium reactor. The fissile isotopes (Pu 239 and Pu 241) constituted 85% of the total weight of the plutonium charge.

The elements used to refuel the Garigliano reactor are each composed of 64 rods arranged in a 8×8 square lattice (figure a). Whereas the standard uranium elements each contain two different enrichments (1.84% for the 12 corner rods and 2.41% for the 52 others), the prototype plutonium elements contain three or even four. This system of multiple enrichments was adopted in order to keep the hot spots—a trickier problem with plutonium than with uranium—within the normal limits during irradiation. Of the 12 prototype elements inserted in October 1968, eight contain natural uranium blended with three different percentages of fissile plutonium (figure c). The four other prototypes are composite elements, containing enriched uranium rods and two central zones of natural uranium blended with fissile plutonium (figure b). All the rods were fabricated by the usual pellet method, with the exception of 12 rods made by vibrocompacting UO_2-PuO_2 powders.

Before the 12 prototype elements were finally loaded into the Garigliano reactor, a series of critical assemblies made up of these elements were installed, in August 1968, in the actual reactor pressure vessel. For this purpose all the fuel elements had previously been discharged from the north zone of the vessel and special nuclear instrumentation installed.

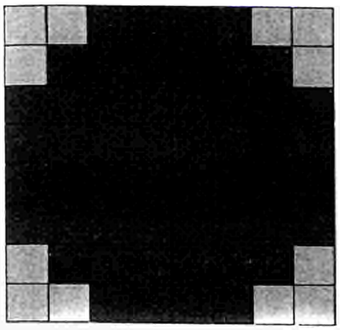
The first critical configuration was achieved with seven standard uranium fuel elements. Then, in the three following tests, a plutonium-containing element was inserted in three different positions in turn in the critical assembly.

Next, a critical experiment was performed with six standard elements and one plutonium-containing composite element.

A final critical experiment was carried out on a 3×3 configuration, comprising four standard enriched-uranium elements, four composite plutonium elements and, in the central position, one normal plutonium element. After an hour's critical operation at a power of 2-3 kW, the optimum activation level, determined in the course of preliminary experiments, was achieved and the critical test was terminated. The nine slightly irradiated fuel elements were removed to the pond for two weeks' cooling

After that, three of the nine elements that had formed the critical assembly were transferred to the fresh fuel storage room, where a gamma-scanning facility had been installed. These elements (one standard, one plutonium and one composite) were dismantled and some of their rods gamma-scanned to ascertain the power distribution. The three elements were

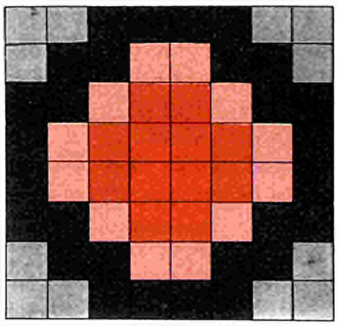
Enrichment distribution in the rods of three types of fuel element used in the plutonium recycling experiments at Garigliano nuclear power plant.



a) standard uranium refuelling element

uranium enriched to 1.83 %

uranium enriched to 2.41 %



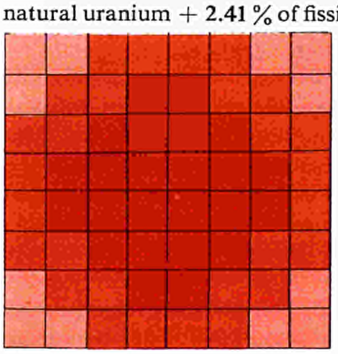
b) composite plutonium element

uranium enriched to 1.83 %

uranium enriched to 2.41 %

natural uranium + 1.80 % of fissile plutonium

natural uranium + 2.41 % of fissile plutonium



c) normal plutonium element

natural uranium + 0.74 % of fissile plutonium

natural uranium + 1.40 % of fissile plutonium

natural uranium + 2.85 % of fissile plutonium

then reassembled and were finally loaded into the reactor.
The results of the measurements performed on the different mixed critical configurations are still being processed. A first analysis indicates that the gap between the experimental and calculated values is in every case less than 0.3%, which confirms the soundness of the calculating methods developed by *ENEL* under this Euratom contract.
During the coming year the computer codes will be developed and improved. A post-irradiation examination, now being carried out at the laboratories of the Institute for Transuranium Elements, Karlsruhe, on a standard uranium element irradiated in the Garigliano reactor, will provide additional information on the power distribution inside an element and on the isotopic composition of the plutonium build-up.
It is also proposed to place the order for a second set of prototype plutonium elements, to be loaded in during the next scheduled shut-down of the Garigliano power plant, in the spring of 1970. During that shut-down further gamma scans will be carried out in an attempt to check the computer codes at increasing burn-ups. That step will conclude the development work on methods of recycling plutonium in thermal reactors which *ENEL* has performed under its research contract with Euratom.

Armand COLLING

Implementation of a nuclear policy in the Community

During October, the Commission of the European Communities forwarded to the Council of Ministers three documents relating to the implementation of a nuclear policy within the Community.
The first of these documents is a general report outlining the framework of the Commission's proposals, the second a suggested programme of research and education to extend over several years and the third the draft budget for the 1969 financial year.
The aim of the first document—the "Survey of the Community's Nuclear Policy"—is to sum up the current state of affairs and in particular to pinpoint the causes of the Euratom crisis, and then to plot guidelines for a future policy.
It should be noted that this report is being published, in a very slightly abridged version, as a special edition of the *Euratom Review*.
This special number is, however, not limited solely to our subscribers, and a free copy can be obtained on request by anyone interested.

Co-operation in the field of iron and steel research

As part of its relations with non-member countries the Commission has recently held discussions with Sweden, Japan and Austria on the possibility of co-operation in various fields of technology, notably iron and steel research.
A meeting was held between Commission representatives and those of Japan in Brussels on 7 and 8 October. A similar meeting took place on 26 September with the representatives of Sweden, followed by a visit from 21 to 26 November by a Commission delegation to various Swedish organisations working in the field of iron and steel research. Finally there was a meeting in Vienna on 28 and 29 November at which the Austrian research programmes were compared with those of the Community.

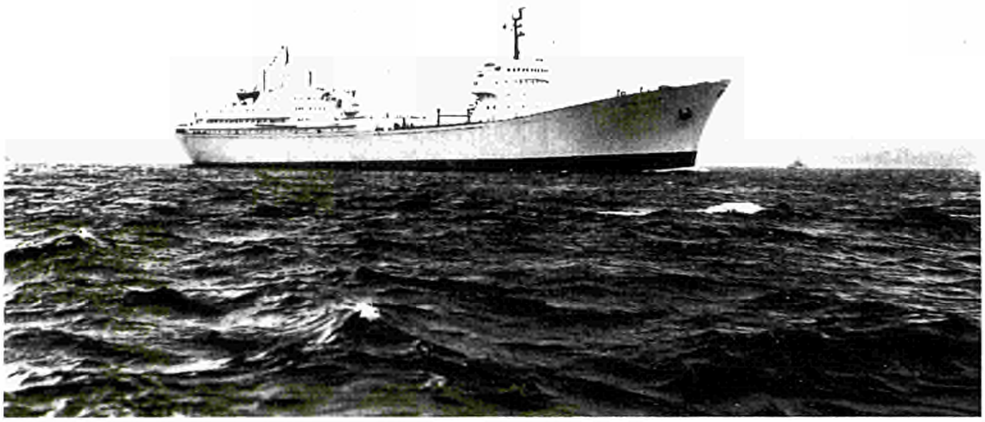


Figure 2: The Otto Hahn *during its maiden voyage in October 1968.*

Maiden voyage of "Otto Hahn" under nuclear power

In January 1968 the nuclear research vessel "*Otto Hahn*" was handed over at Kiel to the *Gesellschaft für Kernenergieverwertung in Schiffbau und Schiffahrt mbH* by the *Howaldtswerke – Deutsche Werft AG*. It was built under a contract of participation between Euratom and the GKSS (see *Euratom Bulletin* Vol. IV (1965) No. 1, pp. 12-23) and is powered by a reactor of the integrated type built by the *Arbeitsgemeinschaft Deutsche Babcock & Wilcox Dampfkesselwerke AG* and *Interatom*. It is the first reactor of this kind to be constructed; the key feature of its design is that the heat exchanger is mounted inside the pressure vessel.

During the first six months, while a critical experiment was being performed at the GKSS Centre at Geesthacht, a vast test programme on the nuclear plant was carried out on board. During July the fuel elements were installed, after which the control-rod drive mechanism was fitted (figure 1).

The reactor went critical for the first time on 26 August. A further series of zero-power critical tests was then performed, this time with the main object of checking on the nuclear instrumentation and calibrating the control rods, and of determining the reactivity coefficients at various temperatures. In the second week of September on-load testing began, the power being gradually raised to 60% of rated. Throughout these operations the ship remained moored to the shipyard jetty.

The first trial voyage under nuclear power took place in the Baltic on 11 October (figure 2). About 200 guests were on board; they included Mr. Stoltenberg, West German Minister for Research and Mr. Hellwig, Vice-President of the European Communities. The second trial voyage followed on 12 October. During the two days at sea the behaviour of the reactor was tested at various power levels and under conditions of rapid load change. During the first day the continuous maximum reactor power was 60% of rated. On the second day it was increased to 80%, being temporarily stepped up to 100%, corresponding to 38 MWth.

The reactor installation functioned very satisfactorily, and in general the dynamic behaviour characteristics were better than expected.

The ship is due to make a voyage of about eight weeks in the Atlantic and in tropical waters in early 1969. It will then be used for carrying ore between Narvik and ports in Germany and the Netherlands. The main purpose of these voyages will be to check the performance of the nuclear plant under normal operating conditions. A measurement and research programme will also be carried out on the reactor.

Under the contract of participation it is possible for public or private undertakings within the Community to profit from these voyages by seconding personnel to the ship. Those interested can apply to the responsible department of the Commission (Directorate-General XII), which will inform them as to the various projects to be conducted during these voyages. The nuclear ship "*Otto Hahn*" will thus enable marine and nuclear engineering circles to familiarise themselves with this new means of propulsion.

Hans BOOS

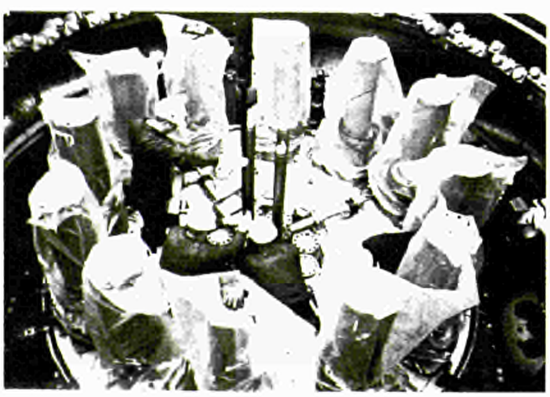
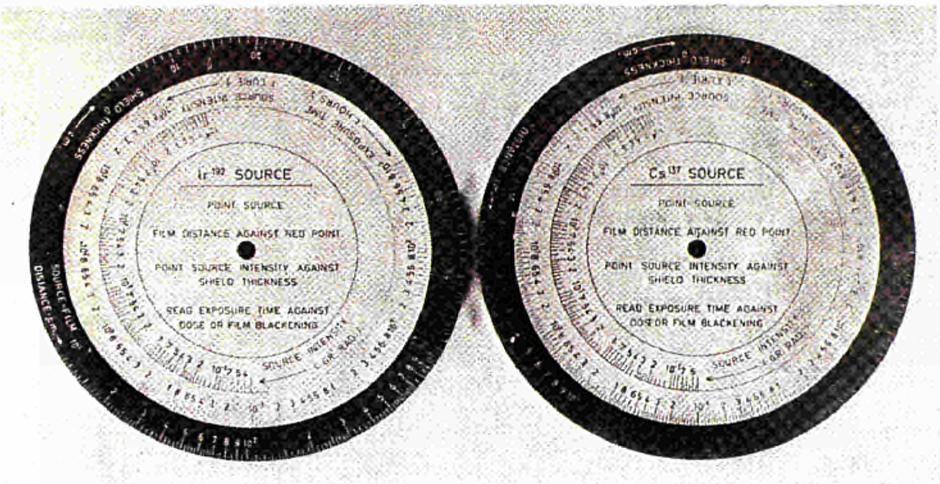


Figure 1: Erection of the control rod drive system in the Otto Hahn.



A slide rule for gamma radiographs

A slide rule using experimentally and theoretically determined absorption coefficients has been developed by *CETIS*, the computer centre of the Ispra Establishment of the *Joint Research Centre*, under a development contract concluded between Eurisotop and the firm of *Appareils Gamma Siar*, France, on the application of gamma radiography to the inspection of prestressed and reinforced concrete.

This slide rule is only for use with concrete. It is designed for Co^{60}, Cs^{137} and Ir^{92} radiation and is suited to the most widely-used films.

It correlates the following quantities: activity (0,1-100 Ci), exposure time (0.1-100 hours), distance between film and radiation source (for a mean concrete density of 2.36 g/cm^3) and the film density or dose rate.

The slide rule consists of a series of concentric rings and discs 15 cm in diameter which are interchangeable depending on the type of source.

Recent publications by the Information and Documentation Centre

—Shock structure interactions in reactor vessels

This book is a record of a meeting held by the European Nuclear Energy Agency (O.E.C.D., Paris) and the Joint Research Centre *of the European Communities at Ispra on June 27-30, 1966. It consists of 17 papers dealing with the following subjects: Initiation and propagation mechanisms of pressure waves; instrumentation for measurements in rapid transients; shock effects on structures.*

EUR 4101 f, e
Price: B. Fr. 500, $ 10

—Thermionic Electrical Power Generation

This book is a record of the second international conference on Thermionic Electrical Power Generation held in Stresa, Italy, on 27-31 May, 1968, under the auspices of the Joint Research Centre (Ispra) of the European Communities. Papers were presented under the following headings: Converter Performance; Integrated Systems; In-Pile Testing; Heat Pipe Systems; Materials; Converter and System Design Analysis; Theory of Converters; Converter Performance Analysis; Plasma Properties; Surface Phenomena; Survey of Experimental Work in the USSR; Panel discussion on "Present and Future of Thermionic Energy Conversion"

EUR 4210 f, e
Price B. Fr. 1000, $ 20

We have pleasure in announcing that Euratom Review *is now being indexed in the* Science Citation Index, *published by the* Institute for Scientific Information *of Philadelphia.*

---

topi radioisotopen s
hip propulsion schiffs
antrieb propulsion na
vale propulsione nava
le scheepsvoortstuwi
ng biology biologie
biologie biologia bio
logie medicine medi
zin médecine medicin
a geneeskunde healt
h protection gesundh
eitsschutz protection
sanitaire protezione s
anitaria bescherming
van de gezondheid
automatic data proces
sing automatische inf
ormation information
automatique informa
zione automatica auto
matische verwerking
van gegevens insura
nce versicherungswes
en assurances assicura
zione verzekeringen
economics wirtschaft
économie economia e
conomie education
and training ausbildu
ng enseignement inse
gnamento onderwijs
en opleiding power
reactors leistungsreak
toren réacteurs de pu
issance reattori di po
tenza energie reactor
en nuclear fusion ke
rnverschmelzung fusi
on nucléaire fusione
nucleare kernversmel
ting radioisotopes r
adioisotope radioisot
opes radioisotopi ra
dioisotopen ship pr
opulsion schiffsantrie
b propulsion navale
propulsione navale
scheepsvoortstuwing
biology biologie biolo
gie biologia biologie
medicine medizin mé
decine medicina gene
eskunde health pro
tection gesundheitssc
hutz protection sanit
aire protezione sanita
ria bescherming van
de gezondheid auto
matic data processing
automatische informa
tion information auto
matique informazione
automatica automatis
che verwerking van g
egevens insurance v
ersicherungswesen as
surances assicurazioni
verzekeringen econ
omics wirtschaft éco
nomie economia eco
nomie education and
training ausbildung
enseignement insegn
amento onderwijs en
opleiding power reac
tors leistungsreakto
ren réacteurs de pu
issance reattori di po
tenza energie reactor
en nuclear fusion ke
rnverschmelzung fusi
on nucléaire fusione
nucleare kernversmel
ting radioisotopes r
adioisotope radioisot
opes radioisotopi ra
dioisotopen ship pr

CDAA68004ENC