EUR 85.e

EUROPEAN ATOMIC ENERGY COMMUNITY - EURATOM

ORGEL
A EUROPEAN POWER REACTOR DESIGN

by

J. C. LENY,
S. ORLOWSKI
J. C. CHARRAULT, F. LAFONTAINE

1962

ORGEL PROGRAM

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ORGEL Program

Brussels, October 1962 — pages 26 + figures 10

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The main aspects of this plant are discussed, such as the fuel element, the organic coolant, the reactor structure, the fuel handling system and the conventional part. The method used to optimize these various components on the economical view point is indicated. The results of these optimisation studies show how the economy of the reactor is influenced by such parameters as flux flattening ratio, reactor height, moderator to fuel volume ratio, radial reflector thickness, organic coolant flow and velocity, rod clearance in the fuel cluster. Finally a table gives the present set of values for the Power Plant characteristics.

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C O N T E N T S

LIST OF FIGURES

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SUMMARY

This paper describes the general features of the ORGEL Power Plant as well as the various parts of the Research and Development Program associated to it. The ORGEL (ORGanique - Eau Lourde) Program was started by Euratom at the beginning of 1960. An important part of the researches are performed by the services of the C.C.R. of Ispra, while the project will have the use of specialized installations at BR-2, Mol, Belgium, in H.F.R. Petten, Holland and in Grenoble, France. Particular mention should also be made of three special contracts with European Industries, of the ECO critical experiment to be built in Ispra, of the specific test reactor ESSOR and of the ORGEL Power Plant Reference Design.

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I. ORGEL PROGRAM

The ORGEL (ORGanique-Eau Lourde) program is the name given to the study of organic-cooled, heavy water-moderated reactors. This study was initiated by EURATOM at the beginning of 1960 and is scheduled to last throughout the entire period of the second five-year plan (1963-1967).

I.1. General aspects

ORGEL represents one of EURATOM's own actions. It is aimed at the development of a European power reactor system, i.e. :

1) which can be operated in Europe without any outside help : the need for enrichment, if it is not ruled out in every case, is however not necessary (it is not a "sine qua non" condition).
   As regards heavy water, a certain production capacity could be rapidly built up in Europe if necessary.

2) which would utilize the united resources of the six Community countries. The problem here is not only of creating a spirit of personal cooperation, but also - which is more difficult - of inducing commercial firms to work in collaboration.
   We have, however, already had some success in two major projects :
   a) the ESSOR (ESSai ORgel) reactor design study being carried out by a Franco-German group made up of the firms Groupement Atomique Alsacienne Atlantique (GAAA), France, and Internationale Atomreaktorbau G.m.b.H. (INTERATOM), Germany.

   b) the study for the ORGEL reference project, aimed at the complete design of a 250 MWe plant, on which an economic evaluation of the project could be based (determination of cost functions, etc, is now being carried out by a group consisting of the firms

BELGONUCLEAIRE (Belgium), INDATOM (France) and SIEMENS-SCHUCKERTWERKE (Germany).

However, we do not intend to stop there. Quite apart from the other EURATOM activities, where the same policy is being pursued as far as possible, the aim of the ORGEL project is to enable European industry to construct reactors of this type with the aid of the research and development infrastructure set up by EURATOM in its Joint Research Centre or by means of contracts with the Community's public or private laboratories.

3) which could be incorporated in the various national programs as harmoniously as possible, at the same time avoiding useless duplication of efforts. In this way, the heavy water lattice study supplements the projects undertaken in Germany and France, thus providing for advantages to be derived by both sides. The organic coolant studies will make a marked contribution to the organic program now in progress in Italy and Germany. These programs will likewise benefit from the research being carried out on a fuel (uranium carbide or uranium metal) and a structural material (SAP).

Resources available

It is worthwhile remembering that the date on which the project commenced was very near January 1, 1960. Since the agreement handing over the Ispra Centre to the Commission was ratified in July 1960, the date at which the Ispra services and departments began participating in the ORGEL project can be fixed at approximately January 1, 1961.

Our first goal was to design an infrastructure with a view to investigating interesting reactor solutions. Studies are being carried out by EURATOM's scientific departments and by contracts with laboratories or industrial concerns in the Community.

These contracts are being executed under the supervision of the Commission's scientific departments either in Ispra or in Brussels headquarters (which is the case of optimization, economy and dimensioning studies as well as the ESSOR design studies), or in other EURATOM centres.

The table which follows describes the project's various research phases.

ORGEL PROJECT

I. PROJECT COORDINATION

- Coordination of scientific and technical activities.
- Orientation, economy, Dimensioning and optimization studies, etc.
- Construction of ESSOR test reactor.
- Coordination of administrative, budget, contractual problems, etc.

Works carried out at EURATOM Headquarters and by contracts under supervision of Project Leader at Brussels.

II. RESEARCH & DEVELOPMENT PROGRAM

A) ORGANIC COOLANT STUDIES

1) Chemistry
- basic studies
- technological studies
- analytical methods
- search for improved products
- chemical engineering (purification, etc.)

2) Heat transfer
- heat transfer coefficients
- burn-out fluxes
- physical properties
- fouling studies

3) Physical Chemistry
- compatibility
- structural analysis of SAP
- Fission gas behavior in SAP or UC
- fuel-cladding contact resistance
- corrosion studies

B) METALLURGY
- shaping of UC and SAP
- UC studies
- fuel element studies
- corrosion
- mechanical and non-destructive tests
- active tests
- physical measurements

C) TECHNOLOGY
- pressure tube and its joints (SAP-stainless steel)
- mechanical studies (mandrelling, vibrations)
- effects on ORGEL vessel and connected tubes of pressure tube accident
- thermal insulation
- thermomechanical stability of components
- General reactor engineering problems

D) REACTOR PHYSICS

Physics & Mathematics
- neutron studies
- completion of ORGEL formula, ESSOR lattices
- Control, dynamics, regulation
- construction and exploitation of ECO critical experiment (Expérience Critique Orgel)
  EXPO experiment (Expérience Exponentielle Orgel)

Works carried out at the Ispra scientific departments and by contracts executed under their supervision

To carry out these works, the project has at its disposal the installations of the Ispra services and departments which, in most cases, are participating almost entirely in the ORGEL works (for example, the Technological and Metallurgical departments are participating for 90 % of the time).

Moreover, the project has, or will have at its disposal after construction, a certain amount of specialized installations :

- 3 loops for the in-pile irradiation of polyphenyls, two of which are inserted in the MELUSINE swimming-pool reactor at Grenoble (France) and one in ISPRA-I (Italy);
- 1 loop for the in-pile irradiation of substitutes to polyphenyls (MELUSINE, Grenoble);
- 1 loop for electron irradiation of organic products;
- 5 out-of-pile loops for heat exchange coefficient studies (2 in Ispra, 2 in Grenoble, 1 in The Hague, each one of them presenting, of course, different characteristics and objectives);
- 2 rigs for UC studies (Ispra and Petten);
- 1 out-of-pile loop for corrosion studies at Ispra;
- 1 organic-cooled thermal cycler (Ispra);
- 1 apparatus for in-pile testing of SAP creep (AVOGADRO, Saluggia);
- 1 rods and triplets irradiation loop (BR2, Mol, Belgium);
- 1 ORGEL full-scale test channel (Ispra);
- 1 thermal insulator test rig (Ispra).

Particular mention should be made of :

- the ECO critical experiment (Expérience Critique ORGEL), Ispra;
- the EXPO experiment (Expérience Exponentielle ORGEL), Ispra;
- and, last but not least, the ESSOR reactor, now in the detailed design phase, of which no further mention will be made here since it is being described in a special paper (x).

(x) American Nuclear Society Meeting, Boston, June 1962 : "ESSOR : Specific Test Reactor for the ORGEL Program", by J.C. LENY and C. CHASSIGNET.

I.2. The ECO critical experiment (Expérience Critique Orgel) - Fig. 1.

ECO is a low-power critical assembly, moderated with heavy water, a large volume of which (25 tons) is available. This will allow the accurate measurement of small buckling factors (1 to 1.5 m^{-2}) and also on unreflected lattices. The replacement method will be used, with a reference lattice consisting of clusters of 19 uranium metal rods surrounded by organic liquid (eutectic ortho-meta-terphenyl, the fusion and boiling temperatures of which range from 30 to 400°C respectively) in an aluminum tube. The reference lattice can be modified by putting the rods in clusters of 12 or 22.

One of the original features of ECO is that it will be possible to heat the substitute lattice (maximum 24 rods), which will be made up of independent cells suspended in place of the normal elements of the reference lattice. A cell is made of the cluster, its pressure tube, a circulation pump for the organic, an electric heating device (4 KW maximum) and a temperature regulation device. The pitch can be modified continuously or even can oscillate around a fixed value if the hydraulic mock-up studies now in progress provide positive results. If so, it will be possible to measure not only buckling at a given pitch but also the tangent at that point, thus considerably increasing accuracy.

The ECO reactor will have a mechanism for oscillating the central element. With this device it will be possible both to observe more accurately the effect of replacing a rod and to study long-term changes by replacing part of the centre rod, either by a section of synthetic rod simulating the state of the fuel after irradiation or by a rod section irradiated in the ECO reactor.

It is also possible to introduce a detector to observe the reactor in pulsed operating conditions by means of an electrostatic accelerator. Finally, a neutron pulse can be removed either from the vertical centre channel, either by immersing in the heavy water an empty tube coming out opposite a horizontal channel located in the shielding. The pulse may be analysed by time of flight. As detection techniques improve, a 1 KW power should be satisfactory to secure good statistical accuracy on spectrum measurements.

The ECO reactor also includes substantial mechanical improvements as compared with other reactors of this type; in particular, the heavy water circuits which make it possible to accurately determine the heavy water level in the vessel.

ECO is now in the constructional phase under contract with the Dutch concern NERATOOM. It should be operational in July 1963.

II. THE ORGEL POWER PLANT

About 6 months after the start of the ORGEL studies, it was decided to focus research on a reactor variant using a uranium carbide rod bundle with a sintered aluminum cladding as fuel; a terphenyl mixture (basically O and M isomers) was retained as coolant.

A 250 MWe plant power has been chosen, taking into account (1) preliminary economical considerations and (2) recent developments in the characteristics of power plants located in the Community.

Since then, extensive research based on the above considerations is being carried through by the project's Optimization Group at EURATOM headquarters, where the results furnished either by the Ispra scientific services or by contracts with industrial concerns in the Community, are being worked out. A mathematic model of the plant is being continuously adapted to technical developments; the latest version has been entirely programmed on the IBM machine 7090 under the code name ORION I.

II.I. Reactor

The reactor is a vertical axis cylindrical assembly consisting of either a stainless steel or an aluminum double-bottom vessel stiffened by zircalloy or aluminum calandria tubes. The organic coolant flows from top to bottom in the channels containing the fuel elements. This channel is composed of a sintered aluminum tube, co-axial with the calandria tube, the insulation of which is ensured by an insulating layer. The vessel is filled up with slightly pressurized heavy water.

II.2. Fuel element

Numerous geometries have been investigated : 4, 7, 19, 22, 31 rods with structurations by sheaths, stiffeners, matrixes, shieldings, fillers, etc.

The studies were focused on an element composed of a 7-rod bundle made of natural uranium carbide with SAP cladding (Fig. 3); clearance between the rods is obtained by pressing one cladding against the other through space fins; the clearances are maintained by end grills and a thin stainless steel binding.

II.3. Organic coolant

The coolant selected is a mixture of terphenyls, the composition by weight being :

Terphenyl O : 14 - 16 %
Terphenyl M : 79 - 81 %
Terphenyl P : 3 - 5 %
Diphenyl : 1 %

A certain amount of pyrolytic and radiolytic high boilers is accepted.

The physical properties, resulting from recent experiments, are as follows for a mixture containing 30 % of high boilers :

Temperature	(°C)	300	400
Density	(g/cm^3)	0,91	0,84
Viscosity	(g/cm s)	$5,7 \times 10^{-3}$	$3,1 \times 10^{-3}$
Specific heat	(j/g °C)	2,2	2,4
Thermal conductibility	(w/em °C)	$1,21 \times 10^{-3}$	$1,12 \times 10^{-3}$
Vapor pressure	(kg/cm^2)	0,22	1,75

The melting of the mixture free from high boilers occurs in the region of 65° and ends in the region of 80°C; these values decrease according to the high boilers content; when the latter is, for example, of 30 %, the melting occurs at room temperature. Irradiation measurements have shown that the radiolytic behavior of this mixture is practically similar to that of paraterphenyl while its cost, although it is higher than that of p-terphenyl, is definitely lower than that of mixtures richer in ortho-terphenyl.

II.4. Primary circuit and heat exchangers

In the circuit, which is entirely of mild steel, the organic coolant flows from the reactor core to the heat exchangers.

At each end of the reactor, the coolant flows through 2 semi-toric headers on which are fixed individual feeding tubes ($\emptyset$ = 57 mm) for each fuel channel; the main primary circuit, which consists of 6 independent loops, is linked to the semi-toric headers through a spherical collector.

Each loop includes a heat exchanger made up of an economizer, a vaporizer and a superheater in the same container. The organic circulation pump is located at the reactor inlet.

II.5. Conventional part of the plant

The 250 MW turbine is of the action type, with a horizontal shaft which is directly connected to a three-phase alternator. It has a divided HP body and two BP bodies with three exhausts each; there are three steam extraction points, one HP and two BP; one or two wheels have special grooved blades which enable the actual moisture in the turbine exhaust to be limited to 12 %.

The condenser is of the single-pass type, with an absolute pressure of 44 g/cm2.

The condensate is pumped out of the condenser through two BP feed-heaters, one feed-heater with a degassing tank and, finally, two feed-heaters before being fed into the economizer.

II.6. Loading-unloading machine

The machine is located at the upper part of the reactor, outside the biological shielding. This arrangement makes it possible to connect the machine-nose on the cold channel connection, thereby simplifying the problems of tightness and connecting mechanisms; it also ensures easy access to the machine and does not involve any particular requirement as regards the lower part of the channel.

The machine can be shifted by means of rotating shield plugs. The very big movable weight used in this solution is a drawback, it is however compensated by the advantage of a more appropriate shielding and of shorter channels.

The machine is equipped with a fixed storage space. The hook grasps a string of elements and the assembly is lifted by a hoisting-gear. When the first element has arrived into the machine, it is disconnected from the second one, which is then hooked up and carries the rest of the string.

III. OPTIMIZATION METHODS

III.1. Study of conventional plant

The study of the conventional plant for a nuclear power plant of the ORGEL type requires special care : the temperature region of the proposed organic coolant, namely :

$$350^\circ C \qquad t_1 \qquad 425^\circ C$$
$$80^\circ C \qquad t_1 - t_o \qquad 150^\circ C$$

appears, from a thermodynamic standpoint, to be a transition region rich in possibilities; the steam cycles usually chosen for other reactor types may still be worth investigating, as is shown in Fig. 4.

The study of these cycles and the selection of the plant have been carried out with the overall aim of obtaining the minimum cost of 1 kWh supplied by the complete ORGEL power plant. The problem has been simplified by making a partial optimization in connection with the conventional plant, only along the following lines :

In the equation giving the net cost C of a kWh supplied to the network, the contribution of the conventional part of the plant is represented by a term y_1, related to the investment and by the efficiency R

$$C = A + \frac{X}{R} + \frac{y_1 + y_2}{R}$$

A : constant
X : term relating to reactor, heavy water, fuel, etc.
y_1 : term relating to conventional power plant
y_2 : term relating to heat exchangers,

where y and R depend only on two variables of a general character, the temperatures t_o and t_1 at the inlet and outlet of the reactor; however, it is necessary to introduce into the study heat exchangers characterized by an additional variable; the difference d_1 between the organic and water temperatures at the inlet of the boiler section of the steam generators (*).

Partial optimization is then performed without difficulty in accordance with the above formula, in which A is a constant and X, y_1, y_2 and R are functions of t_o, t_1 and d_1; this last additional variable can, moreover, be eliminated after a certain amount of scanning.

(a) Single pressure steam cycle

The main study was conducted into the usual single pressure steam cycle, which is considered as the reference cycle; it showed that the variations in the cost of the conventional plant, exchangers not included, as a function of the operating parameters were low and of the same order of magnitude as those due to the differences in the turbine costs due to the various technologies and labor costs in the different Community countries.

The single pressure cycle comes up against the problems raised by the excessive moisture encountered at the end of the expansion, if relatively high turbine admission pressures are to be reached.

Assuming that the turbine is equipped with 1 or 2 special moisture removal grooved paddle-wheels, the following values of net electrical efficiency of the classical plant would be obtained for a maximal moisture of 12 % in end of course :

(*) In the first approximation, it is also necessary for the difference d_o to be introduced at the superheater inlet; in the studies carried out, d_o was taken as being equal to 10°C.

r	0,335	0,346	0,359	0,371
t_1	350	375	400	425
Δ_t	95	110	120	130
p_v	62	75	90	110

The general use of special paddles or of mechanical water separators outside the turbine would bring about a considerable improve in efficiency; these methods have however not been retained since an efficiency of the same order can be obtained through resuperheating, which does not set problems of technological development.

(b) Single pressure cycle with reheating

Reheating has been studied only for some chosen numerical values of the thermodynamical parameters. From the optimization viewpoint, it has hitherto been considered as an addition, characterized by the terms R, y_1, y_2 relating to the operating point selected in the single pressure cycle with no reheating.

Reheating by the organic liquid in the heat-exchanger has proved, from both the technical and the economic viewpoints, to be preferable to reheating carried out in a separate reheater located in the vicinity of the turbine by bleeding off live steam during the expansion.

III.2. Study of nuclear parts

The ORGEL reactor design makes it necessary to make certain choices linked to the channel or to the reactor itself; a great number of variants are then possible, each one possessing an optimal solution; the most economical one is then comparatively retained.

Such an experiment is long and results would undoubtedly contain many relative uncertainties, such as the difficulty of estimating the safety of each variant. It was preferred to carry out the conceptual choice after tho_rough investigation, and to so define in advance the reactor model which now appears to hold best chances of leading to the most interesting solutions.

Among the basic solutions, mention can be made of :

a) The choice of a vertical axis reactor bound up with the fuel cycle

The natural uranium lattices are characterized by their tight neutron balance. It is necessary to make a well-advised choice of the fuel cycle in order to make the best possible use of these lattices and hence, so, reduce the marginal neutron cost.

Unloading during reactor shut-down makes it possible to use a cheap and simple unloading machine. However, either the burn-up or the specific power is low if the unloading cadence is not increased, which entails a rapid deterioration of the factor of utilization. Unloading in reactor operation, while it calls for an intricate and expensive unloading machine, makes it possible to make more appropriate use of the neutron possibilities of the lattice. Two main variants are being retained : the parallel-crossed loading and the loading by half-inversion.

The former calls for two loading machines and seems to be best adapted to a horizontal axis reactor; the latter, while it makes it possible to obtain but slightly lower burn-ups as compared to the first variant, means a single loading machine and calls for a vertical reactor. It is the latter variant which has been retained to date, with a vertical axis core.

b) The choice of independent collectors

The shield pool tank at reactor inlet has been eliminated, due, namely, to the high pressure required at the channels inlet, as well as the shield pool tank at the lower part, due to the great amount of coolant submitted to a temperature of approximately 400°C.

c) The choice of a gas-layer channel insulator

Inasmuch as organic coolant insulation was rejected for both neutronic and technological reasons, solid and gas insulation remain to be investigated. The former presents the advantage of permitting a cold pressure tube; the second, a better insulation and lower neutron absorption. Pending results of the experiments under way, the gas insulation has been retained.

d) The choice of a fuel element

As regards the fuel element, the choices are more difficult. In particular, the field of uranium carbide research is still much too unexplored and does not make it possible to rely on a sufficient volume of coherent experimental results.

Our current research programs cover the study and development of an economical process of carbide preparation, but no evidence has come out so far (*).

However, in view of the particularly good thermal conductibility of this material, it was estimated that the technological limitations of the elements would be found in the fuel element cooling itself rather than in the fuel behavior. This fact makes it possible to start overall studies; they will be adjusted - or even modified - as soon as experimental results are available.

These studies are now centred on a 7-rod bundle geometry. They are aimed at the development of a compromise between the neutronic interest of the little divided fuel and the technological advantage of a material which, when operating at reasonable temperature, would not run any risk of deformation.

Sintered aluminum has been retained as cladding (*), the

(*) American Nuclear Society Meeting, Boston, June 1962 : "Development of Fuel and Cladding Materials for the ORGEL Project", by C. Moranville.

development of which is being investigated and has already made it possible to fabricate, by extrusion, finned claddings with a 2 m length, a 0,8 mm thickness and very good size - margins (alumina ratio ranging from 4 to 7 %).

Very thin stainless steel, the development of which as cladding material remains to be investigated, and which presents the drawback of not reducing hot points, is being investigated only as a temporary "spare" solution.

In a 7-rod geometry, it is necessary to fit stiffeners playing the part of fillers in the channel zones which cannot be occupied by the fuel rods. These fillers homogeneize the velocity distribution and, as a consequence, the temperature distribution in a channel section. On the other hand, by replacing the scattering and absorbing coolant, they might improve the neutronic characteristics of the lattice. Possible choices are either tube stiffeners, which are interesting from a mechanical viewpoint, or full stiffeners, the form of which is particularly well adapted to their thermal function. In the latter case, they can be made of beryllium, which is neutronically and mechanically advantageous, but extremely expensive (*), or of graphite. The last solution has been retained in spite of the drawback of having a porous material which is filled with a little organic and which must be sheathed, and which prevents the fillers from playing their mechanical function. A program of graphite compatibility with organic liquid is in progress.

The cluster structure must therefore be provided, either by the cladding itself, or by a sheathing tube which, in order to be interesting from a neutron viewpoint, must be made of beryllium. The advantage of such a tube is that it separates the mechanical function from the heat transfer function, which is not the case as regards the first version. The latter has however been retained, especially in view of its low cost.

Since the cladding carries the loads, it is preferable

(*) raw material and machining in the required sizes.

to have it operate under traction rather than compression. The elements are suspended by series of 4 to the channel end in which, to avoid a flying-off effect, the coolant flows from top to bottom.

Variables linked to the fuel element design

Preliminary studies have shown that the interesting value is as follows :

Fuel cross section (cm^2)	25	30	35
Clearance between rod (mm)	1	1,2	1,5
Finning ratio	1,5	1,7	1,9

Reactor optimization

Reactor optimization has been undertaken within the frame of a 250 MWe power plant study; the fission power is adjusted to the gross electrical power of the plant.
In consequence, the main variables influencing the reactor size may be listed as follows :

- coolant outlet temperature t_1, velocity v and high-polymer content p;
- height of the reactor H;
- lattice pitch z;
- degree of flux-flattening x;
- thickness of radial reflector d_r.

The influence of the variables on the characteristic quantities of the reactor, such as the number of channels, the weight of the heavy water, the weight of the fuel and the fuel and organic consumption, has been the subject of various studies with the OREE and ORION I codes.

The most important conclusion from these studies is that the cost function to be minimized may, in the first approximation, be represented by a quadratic function of the 4 independent variables H, z, x, d_r. The optimization relative to these variables is an easy matter; the extremum conditions in this case are reduced to a system of four linear equations with four unknowns, provided that the existence of an extremum within the region under consideration can be shown. Such an optimization routine is included in the ORION I code. The studies now in progress will make it possible to ascertain whether this optimization technique is also applicable to the other independent variables (t_1, v, p). If so, the ORION I code will be modified in order to obtain an automatic optimization as a function of the main variables leading to the size of the reactor.

IV. SOME RESULTS

IV.1. Economical scheme

The specific investment (direct and indirect investment - design and ground cost) is inferior to $ 270/installed KW for a prototype. It might be considerably lowered in the case of a certain number of reactor plants of the same type.

The estimates have been calculated for a plant equipped with a single reactor, and may be regarded as reliable for the time being. Plant development costs are not included.

These estimates will be revised and completed at the end of 1962, based on the results of the cost estimate studies carried out in cooperation with the Community's industries.

Indirect investments have been estimated, based on the classical coefficients of uncertainty, on an overall escalation rate of 8 %, over a period of construction of 4 years, and an interest rate of 6 %.

One of the basic features of this reactor type is its relatively low investment cost. This is due, let us not forget it, to the use of organic coolant which permits low pressures and is compatible with cheap materials like ordinary steel or aluminum. To ascertain the accuracy of this point, we have launched numerous corrosion experiments in terphenyls at reactor temperatures with water contents ranging from 0 to 500 ppm. We have studied SAP, stainless and mild steel - separately, juxtaposed and electrically coupled.

While the surface treatment of steel seems to have an effect on the formation of brownish surface deposits, nothing serious has been found, on the contrary; water content encourages corrosive formation, but it is however not possible to fix an inferior limit.

Only cost functions related to the most significant items have been retained to date, namely :

for the reactor

- channels, joints, end fittings and ancillary instrumentation
- heavy water ($ 62/kg)
- fuel

for the classical part

- heat exchanger
- turbo-alternator, pumps and condenser.

Fixed charges stem from investment depreciation (total depreciation rate of 10 %, depreciation time of 20 years), and from the return payment on fuel immobilization (interest rate 6 %).

Organic consumption charges are calculated from radiolytic and pyrolytic decomposition. The price of organic OM2 is $ 0.6/kg.

IV.2. Plant total power

Preliminary studies have revealed the interest of large natural uranium reactor plants; in particular, the energy cost continues to decrease well above a 250 MWe power (fig. 5), but the unit power depends on the constructors' standards and uses for turbo-alternator groups, and on the electrical network as well as its flexibility. An ORGEL-type 250 MWe nuclear power plant is perfectly adaptable to the requirements of the various Community countries.

IV.3. Radial flux flow - Flattening ratio

Different possibilities present themselves if it is wished to switch from a non-flattened radial flux to a flattened radial flux reactor. Different ways of flattening the flux can be envisaged; we have chosen flattening by using different unloading rates, which gives differential burn-ups between two concentric zones.

In these conditions, it remains possible to :

- either maintain the maximal channel power and reduce heavy water investment but, in this case, the neutron losses are considerably increased because of the flux form and the core size reduction;

- or reduce the thermal performances of the centre channels and maintain heavy water investment constant. In this case, the neutron losses are increased solely because of the flux form;

- or else choose an intermediate solution between those two.

The thermal performances of the fuel element now under investigation are rather low (maximal specific power in the region of 24 MW/T), which is due to the fact that attemps are being made not to exceed a 1200 to 1300°C carbide maximum temperature. It is a fact that favorable irradiation results might lead us to revise this value. In this case, the flux-flattening ratio would considerably influence the energy cost. Its optimal value is however rather low (in the region of 0,4); the gain obtained as compared to a non-flattened flux reactor is of the order of 7 to 8 %.

This gain and the optimal value of the flattening ratio are however quite dependent on the plant load factor, on the heavy water depreciation, and on the thermal performances of the fuel element; for example, if the plant operation time reaches 8000 hours, this gain would be reduced by half.

Fig. 6 shows the influence of the reactor flattening ratio, which is regarded as optimal to date.

IV.4. Reactor height

The reactor height determines the power extracted from the channel and the temperature rise of the coolant within the reactor. By reducing the reactor height by 6 to 5 m for example, the power extracted from the centre channel is reduced, but the radial losses, which are considerable when the flux is flattened, are reduced; at constant organic coolant flow, the temperature rise is lowered, which has a favorable effect on the thermodynamic efficiency of the cycle. Therefore, the optimal height seems to range between 5 and 5,5 m (*).

IV.5. Lattice pitch as $\frac{\text{moderator volume}}{\text{fuel volume}}$ ratio

When the $\frac{Mv}{Fv}$ ratio changes from 18 to 24, the neutron characteristics of the unirradiated lattice improve; however, those of the irradiated lattice deteriorate.
Moreover, it increases heavy water investment but reduces neutron losses.

Fig. 7 shows the development of energy cost as a function of the $\frac{Mv}{Fv}$ ratio and of the reactor height; the values of the flattening ratio and of the radial reflector thickness have been optimized in each case.

IV.6. Radial reflector thickness

By increasing the radial reflector thickness, one improves the shape factor, resulting in reducing the number of channels but increasing the heavy water investment and the burn-up of the fuel elements. The optimal thickness of the radial reflector depends on the flattening ratio, but its effect on the cost is relatively low (**); its optimal value is in the region of 50 cm.

(*) Organic coolant flow : 8 m/sec.
(**) If d_R oscillates by ± 20 cm around the optimal value, the energy cost varies by ± 0,3 %. Of course, this time only in the case of identical economical environment.

IV.7. Organic coolant outlet temperature

An increase of the organic coolant outlet temperature entails a considerable improvement of the plant efficiency; it is interesting to note that, at a 25°C increase of the outlet temperature, it corresponds to an improvement in efficiency of 0,01. It is therefore expected that this parameter will strongly influence the energy cost.

There is nothing of the kind in the temperature range considered (maximal cladding temperature 440°C - outlet temperature 380-400°C), where two negative effects counteract the influence of efficiency : they are the decrease of channel power because the difference between the cladding temperature and coolant mean temperature is reduced, and the increased organic destruction due to pyrolysis. There is, in these conditions, no advantage in increasing the organic coolant outlet temperature above 400°C. Fig. 8 shows the influence of organic coolant outlet temperature on the energy cost for different organic liquid speed rates and maximal cladding temperatures.

IV.8. Coolant flow

The influence of coolant flow on the energy cost has been investigated at 7,5 - 8 and 8,5 m/sec. No minimum value has been found; the energy cost is lowered as the flow raises. In the field investigated, there is an advantage in increasing the specific power provided it does not result in deteriorating the lattice neutron balance.

IV.9. Effect of rod clearance

By increasing the organic section in the fuel element, it is possible to lower the heating and to increase the channel efficiency. This improvement in thermal characteristics is however coupled with a considerable deterioration of the lattice neutron characteristics. The balance of these diverging effects is negative : an increase of the rod clearance entails an increase of the energy cost (fig. 9).

Resulting technical characteristics of optimized reactor

Gross electrical power	250 MW
Net electrical power	234 MW
Fission power	737 MW
Net electrical efficiency	0,317
Organic outlet temperature	400°C
Heating in the reactor	135°C
Organic coolant flow	8 m/sec
Fission power of centre channel	2,42 MW
Specific power	24 MW/T
Neutron flux	6,5 10^{13}nv
Pinch point	10°C
Vapor temperature at superheater outlet	390°C
Vapor pressure at turbine inlet	60 kg/cm2
Efficiency of plant secondary part	0,3516
Pressure at condenser	44 g/cm2
Reactor core height	5,5 m
Reactor core radius	2,85 m
Lattice pitch	23,7 cm
Number of channels	452
Axial reflector saving	2 x 5 cm
Radial reflector saving	50 cm
Axial reflector thickness	-
Radial reflector thickness	50 cm
Flattened zone radius-extrapolated core radius ratio	0,36
Radial shape factor	0,748
Flux ratio at core periphery/centre flux	0,31
Heavy water tonnage	196 T
Organic tonnage in reactor supposed at 400°C	79 T
Mean combustion rate :	
central zone	8900 MWD/T
external zone	6400 MWD/T
Hourly organic consumption	77 kg/h

IV. 10. Effect of reactor independent variables on energy cost

Fig. 10 shows the penalty on energy cost of a 10 to 20 % divergence on the values of the resulting optimized variables.

CONCLUSION .

This preliminary study of an ORGEL reactor associated to a 250 MWe plant makes it possible to emphasize the relative importance of the different constructive parameters of the installation. It appears desirable to establish a careful design of the channel : this suggests the development of theoretical studies and of extensive experiments from the thermal, neutron, technological and metallurgical viewpoints.

It will then be necessary to carry through thermodynamic studies in order to complete the comparative investigation of the different vapor cycles and to make an appropriate choice between the organic exchangers-vapor water concepts.

Finally, the studies on optimal flux must be conducted jointly with the long-term range study of the neutron characteristics of the reactor nuclei.

This brings us back to the overall ORGEL program as described in the table contained in Part I of this paper. These experimental programs are aimed at answering a great deal of the questions set forth above. And, inversely, they are permanently being oriented in accordance with the results and trends which stem from the optimization work.

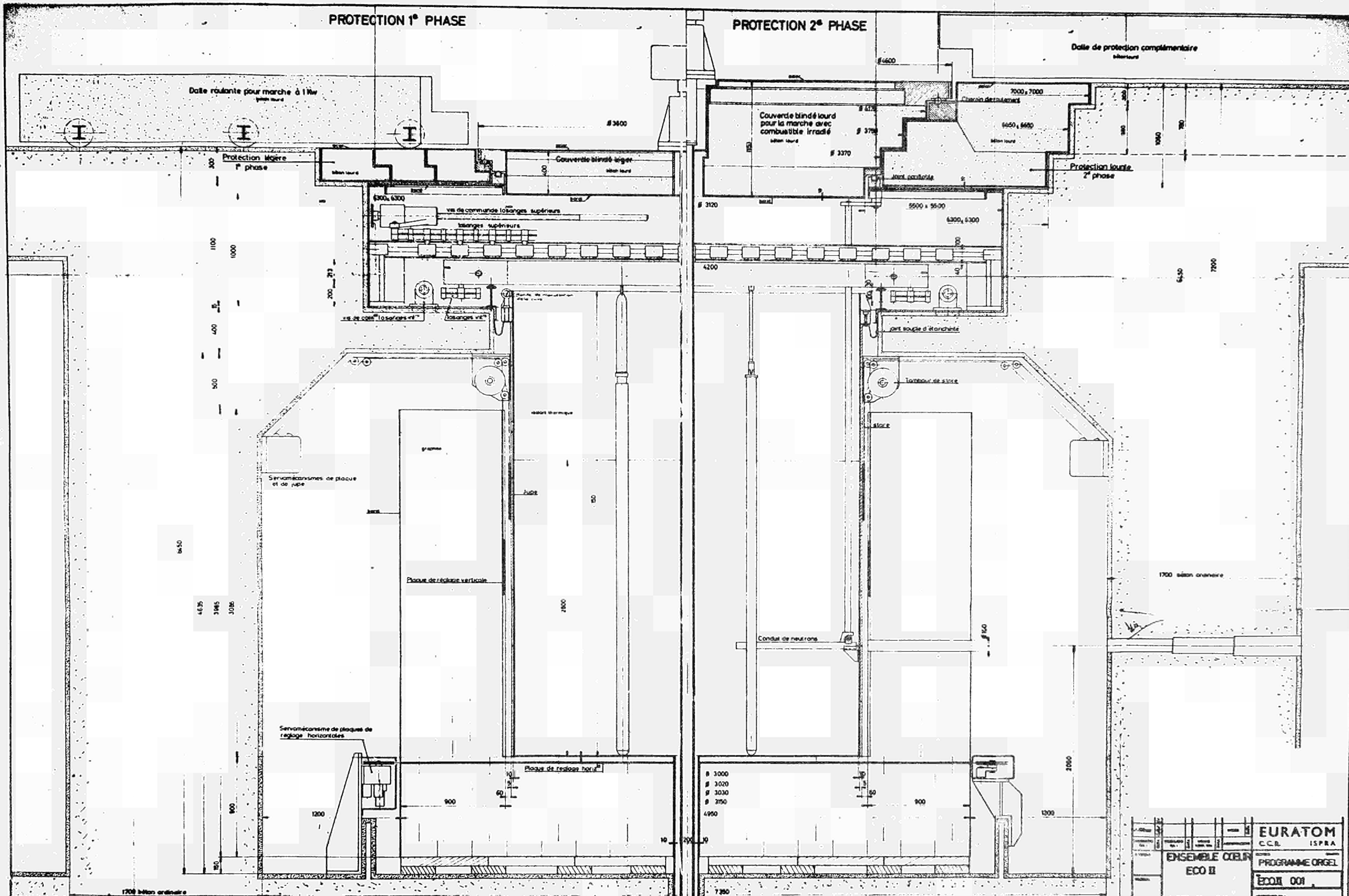


Fig. 1 - ECO core : General view.

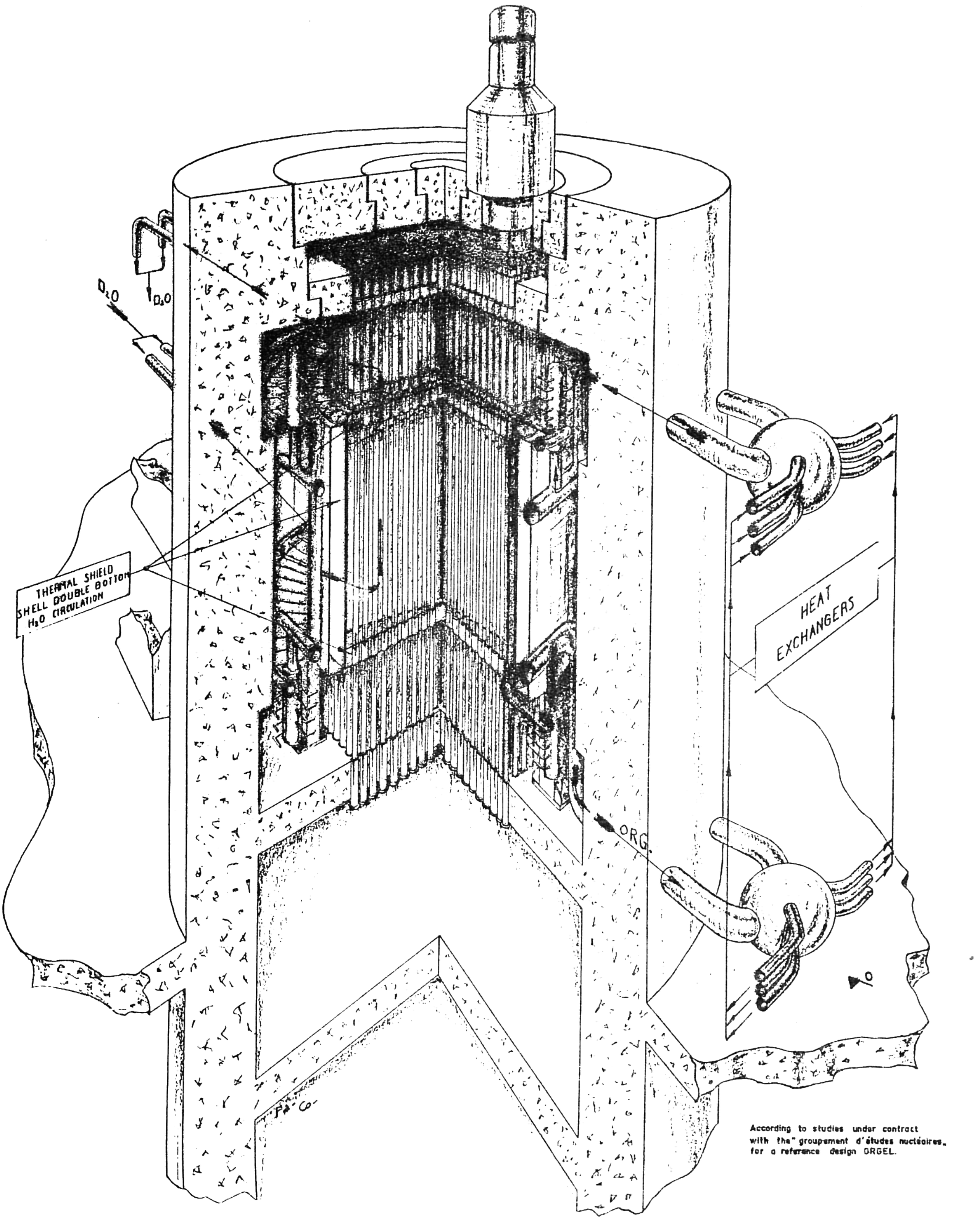
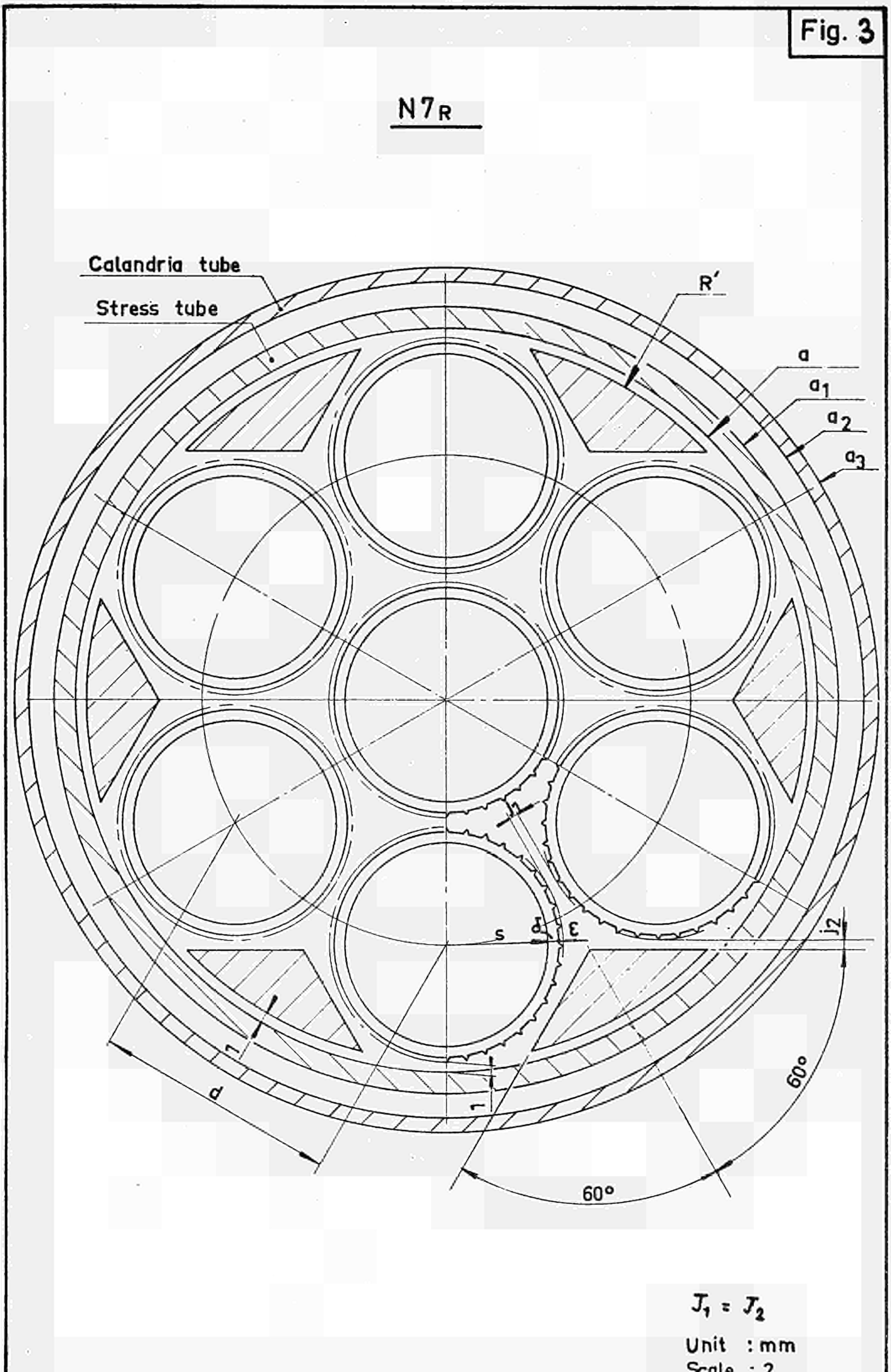


Fig. 2 - ORGEL core : General view.



Fif. 3 - Cross-section of ORGEL fuel bundle.

Fig. 4

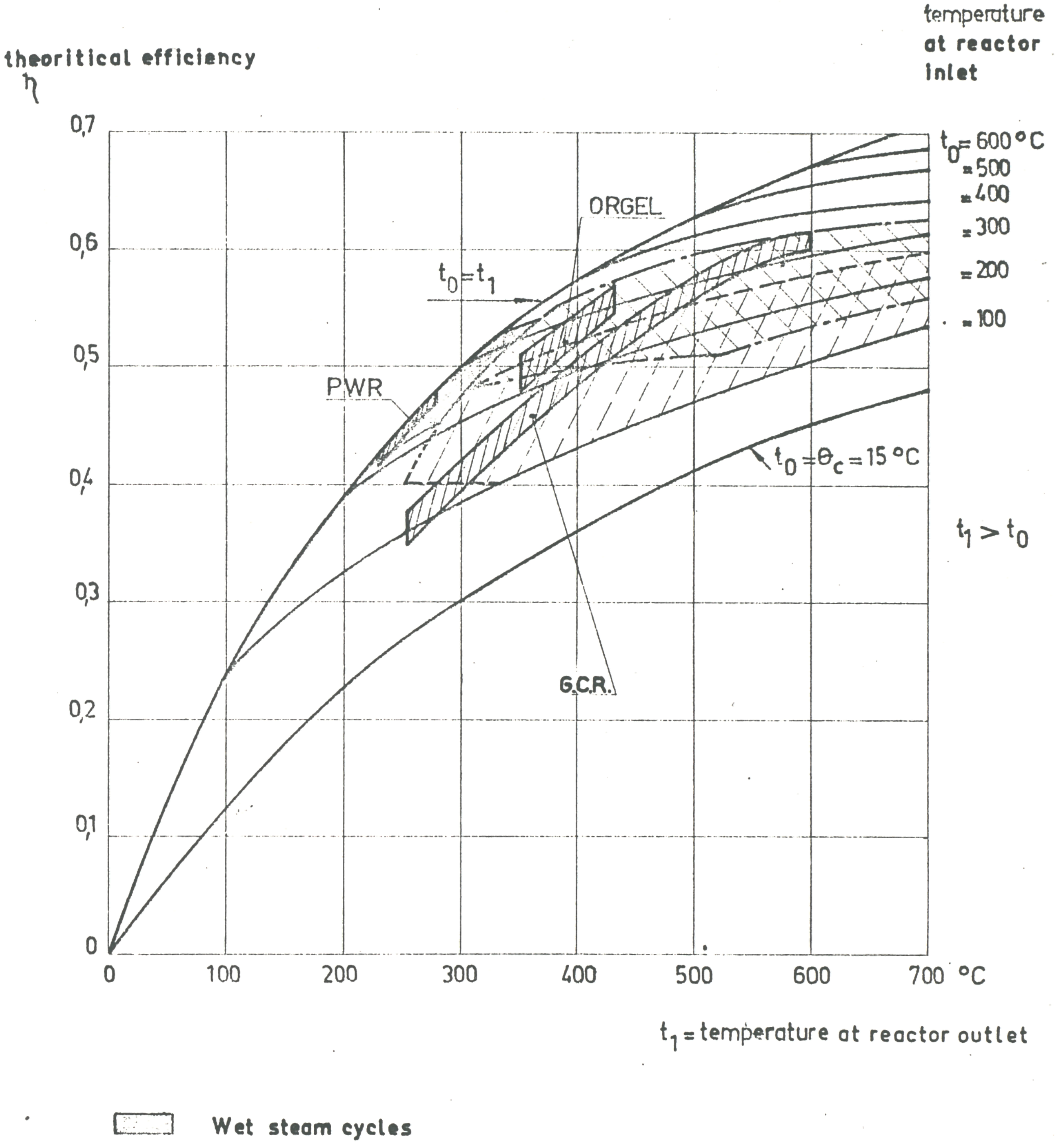


Fig. 4 - Curves relative to theoritical efficiency versus inlet and outlet temperatures.

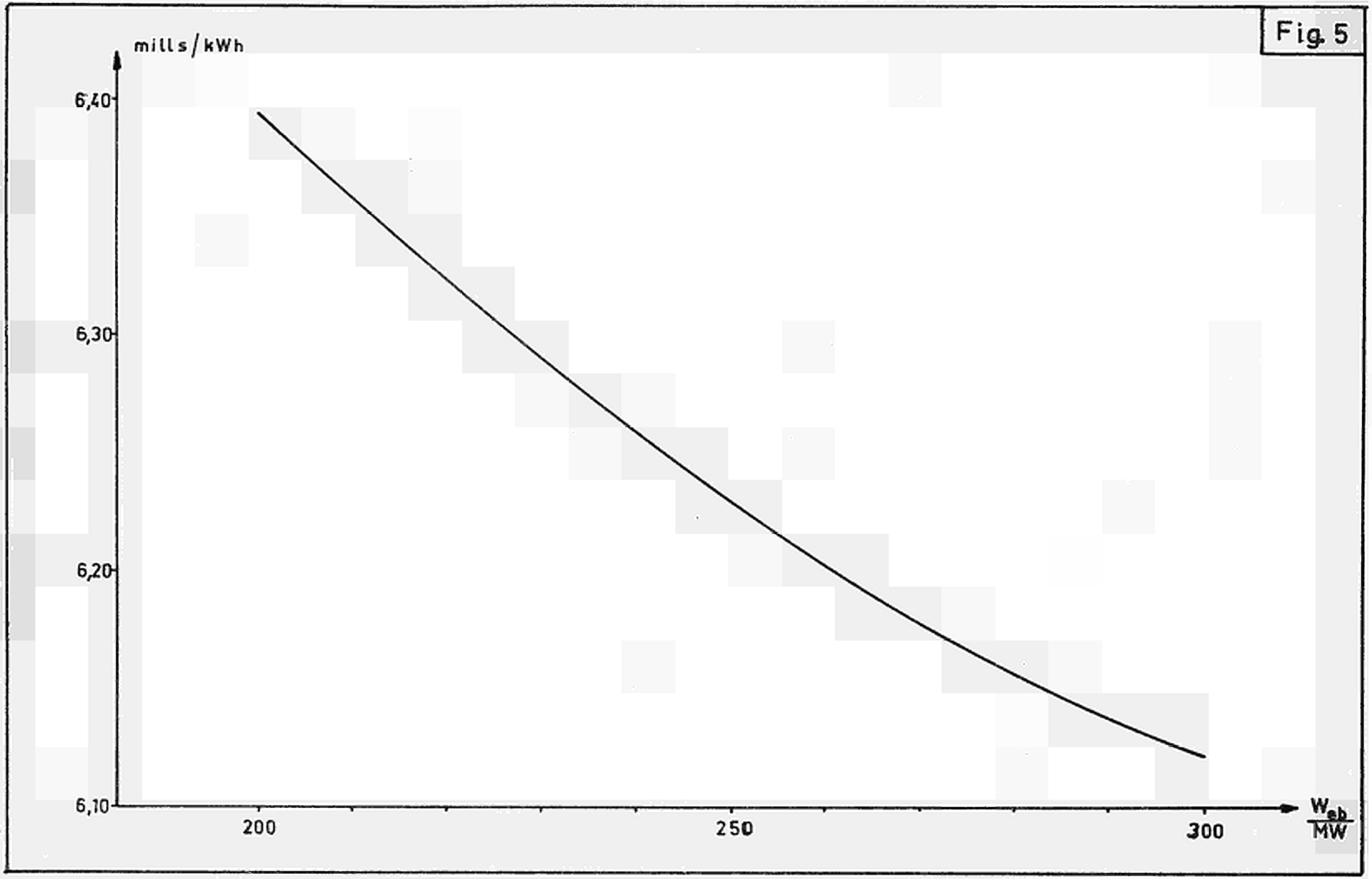


Fig. 5 - Energy cost versus the capacity of an ORGEL power plant.

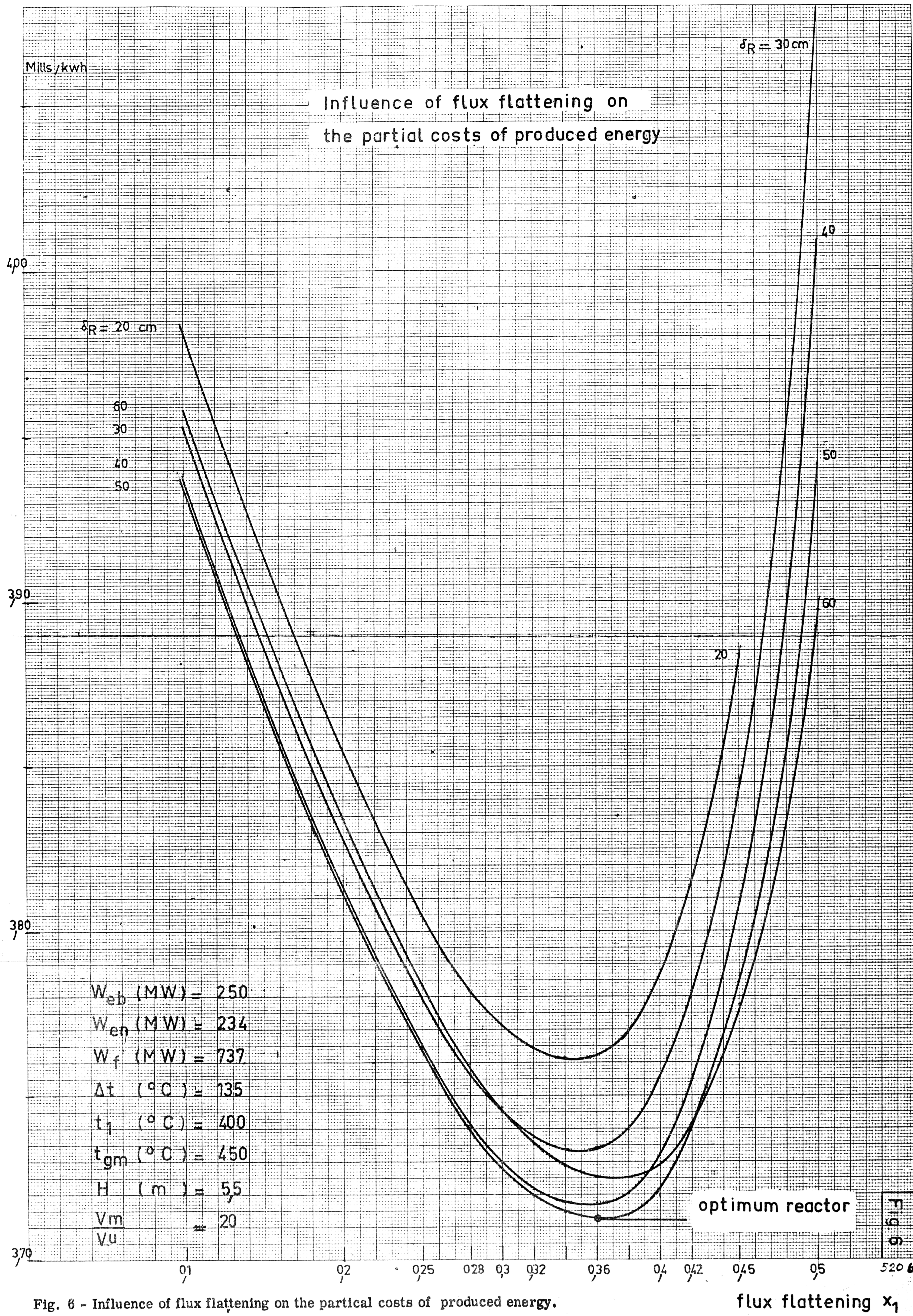


Fig. 6 - Influence of flux flattening on the partical costs of produced energy.

Fig. 7

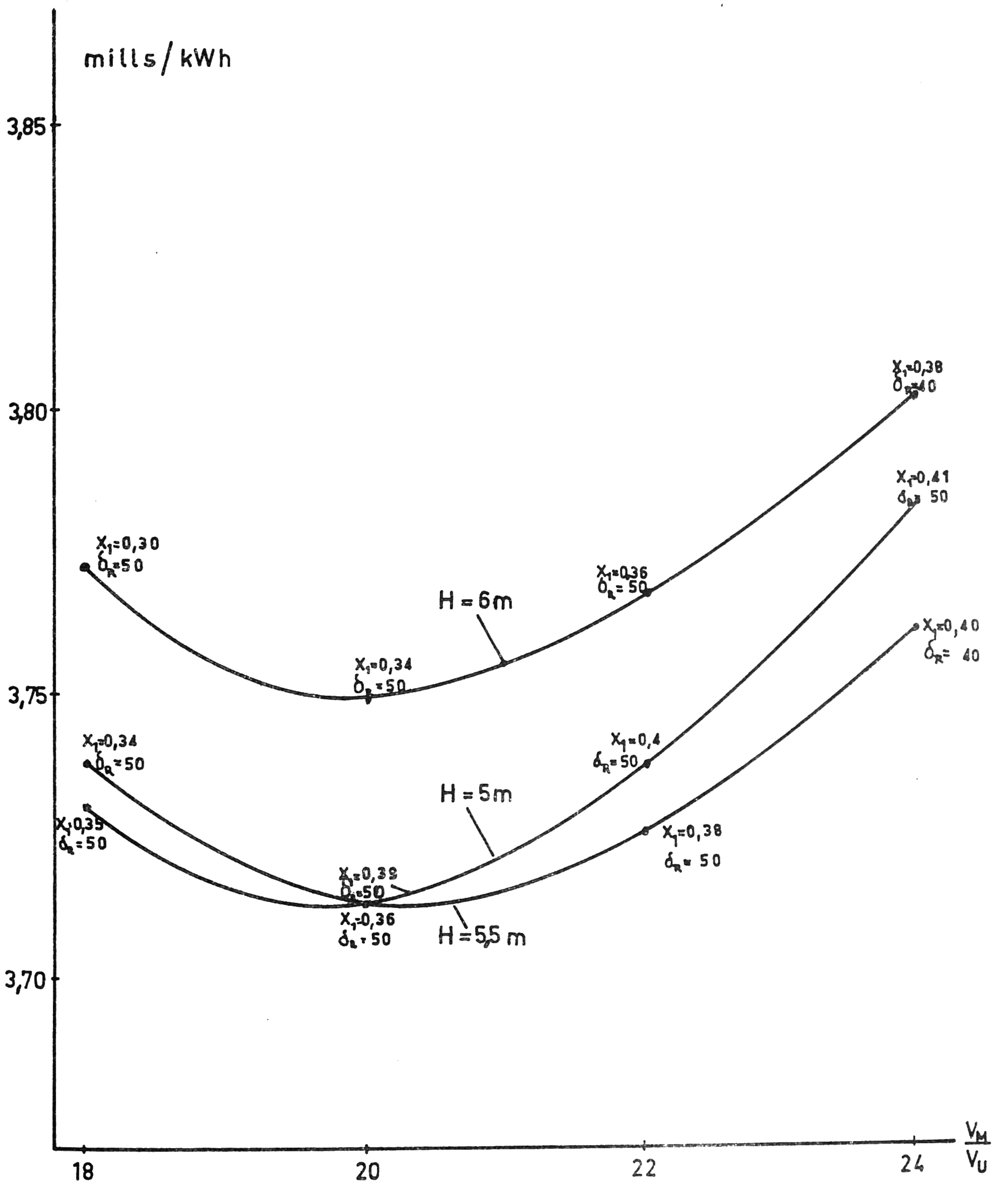


Fig. 7 - Effect of reactor height and moderating ratio on partial energy cost for optimally flattened and reflected reactors.

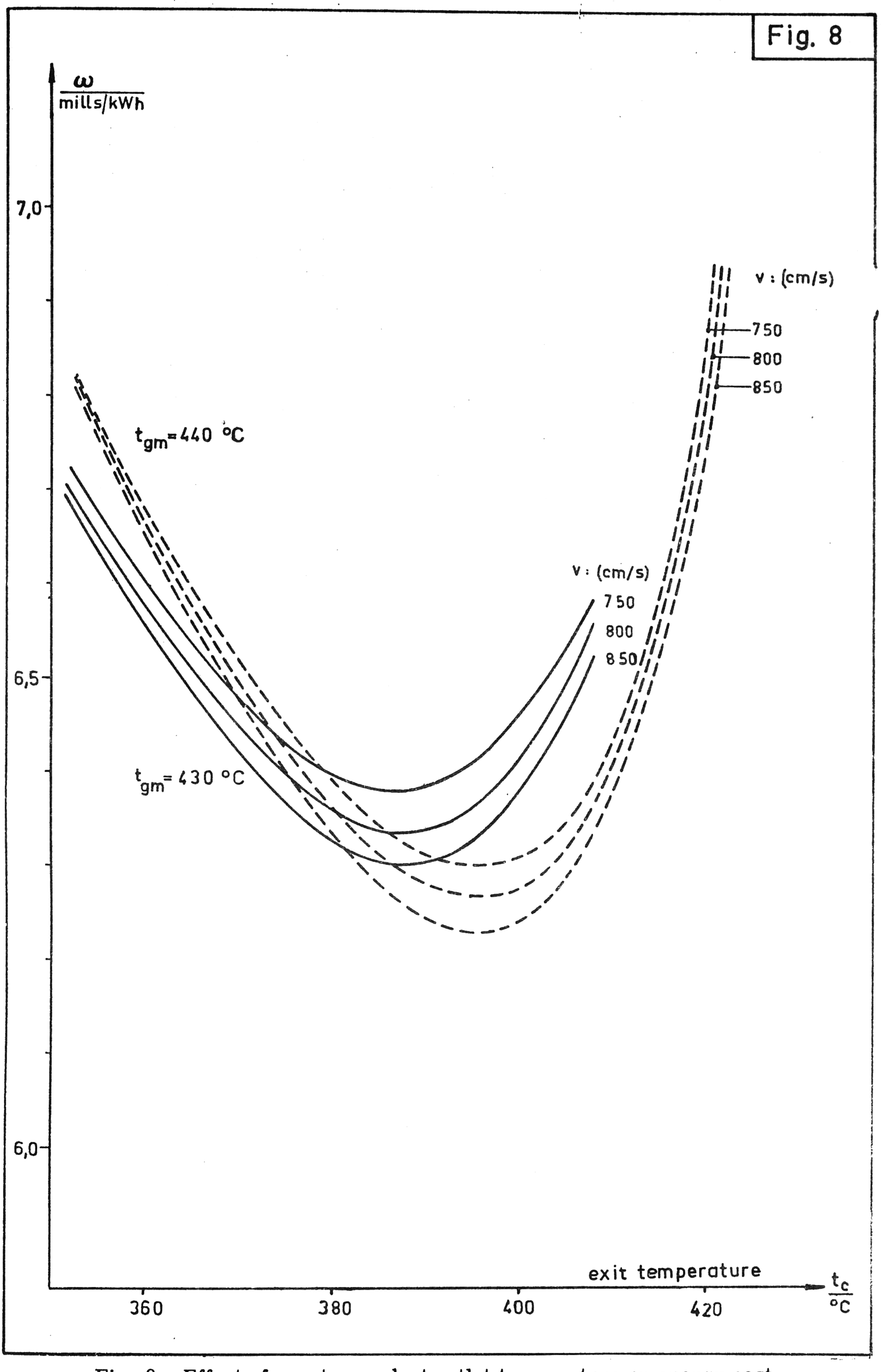


Fig. 8 - Effect of reactor coolant outlet temperature on energy cost.

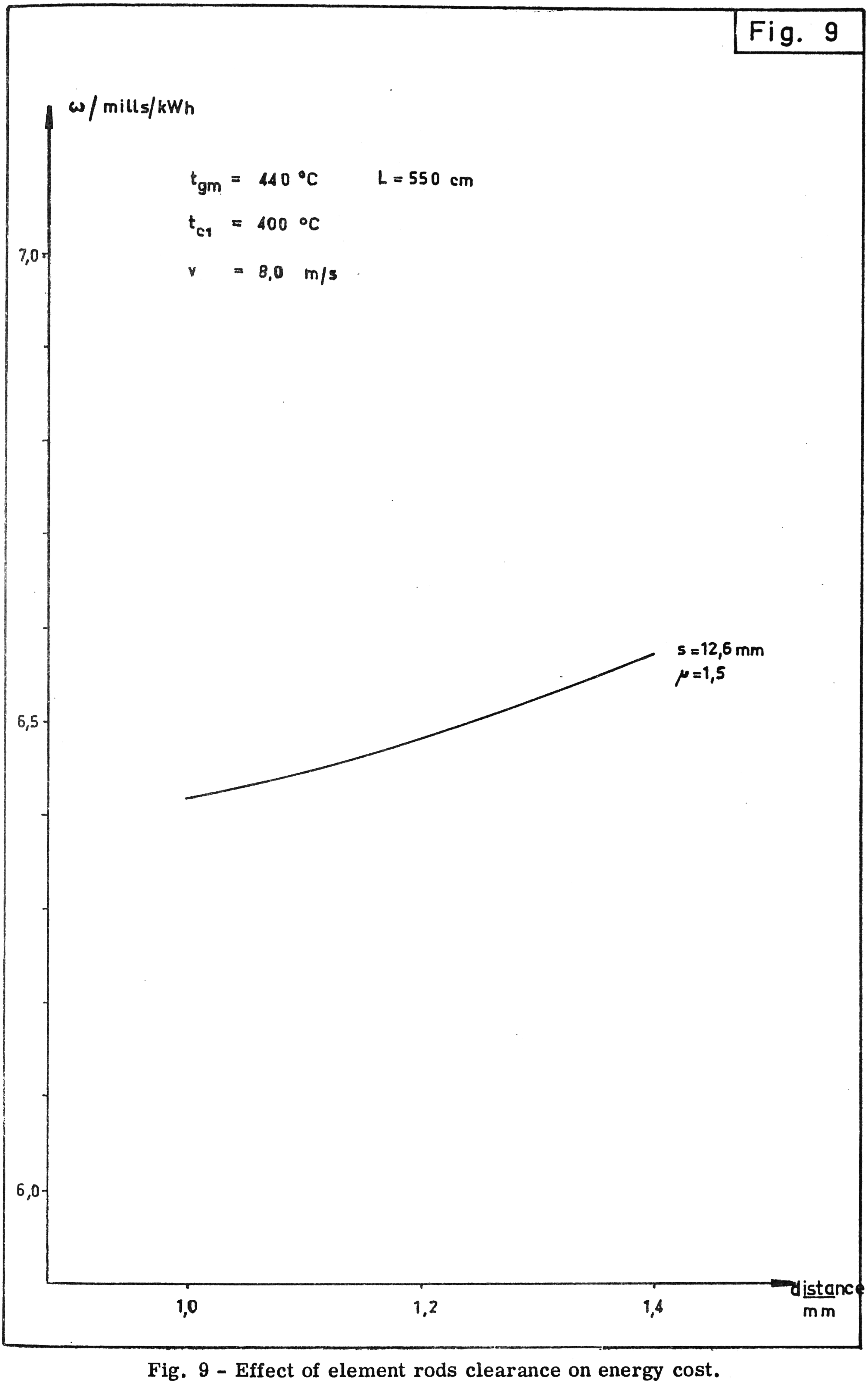


Fig. 9 - Effect of element rods clearance on energy cost.

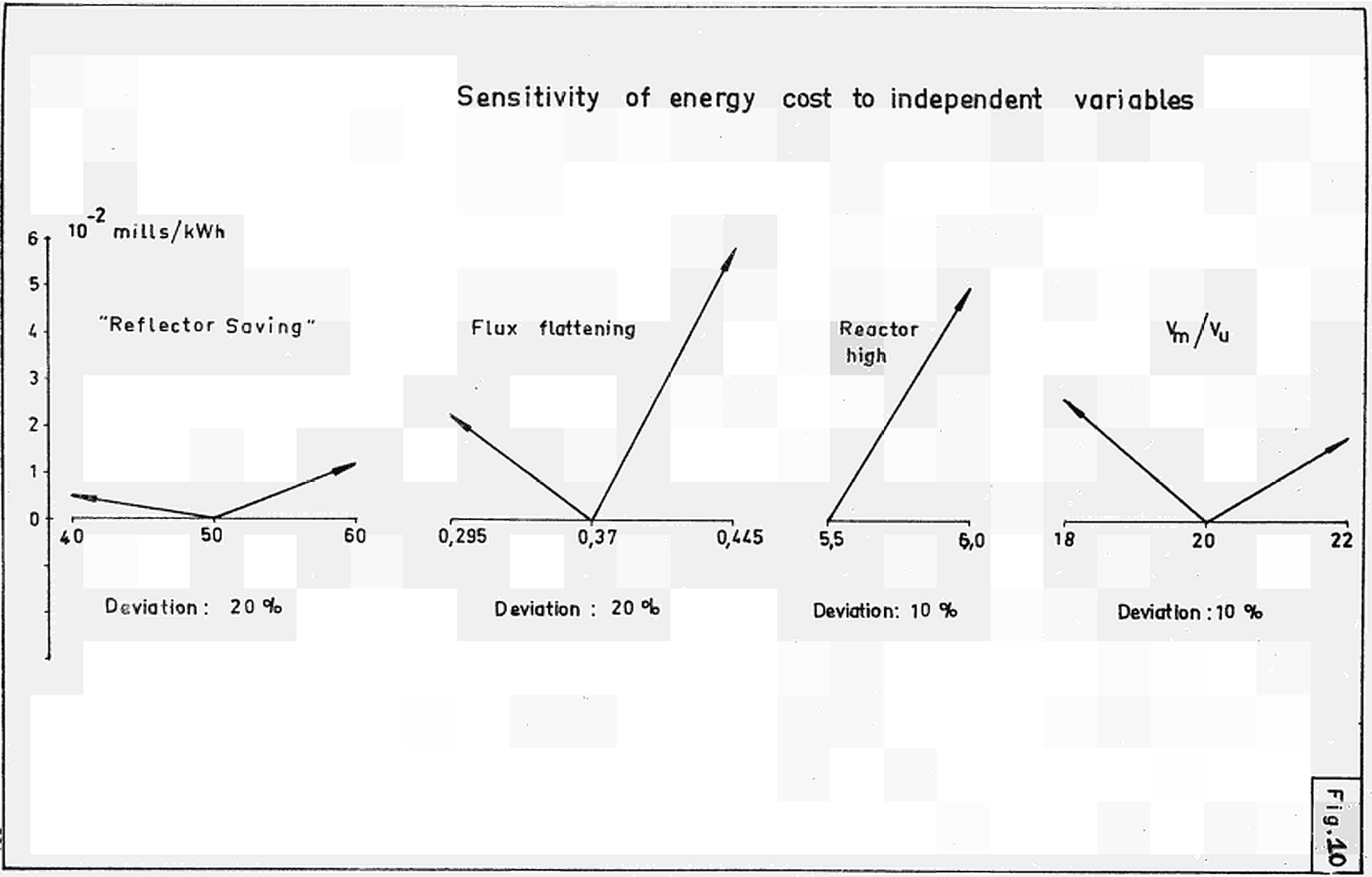


Fig. 10 - Sensitivity of energy cost to independent variables.