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ORIENTATION STUDY ON THE ECONOMIC POTENTIAL OF AN ORGEL POWER PLANT EQUIPPED WITH A G-30 FUEL ELEMENT

by

W. BALZ, B. CHAMBAUD,
GC. REALINI and P. TAUCH

1969

ORGEL Program

Joint Nuclear Research Center
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ORGEL Project

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The aim of this study is to assess the economic potential of such an ORGEL Prototype plant being alternatively equipped with a further subdivided uranium carbide fuel element consisting of bundles of 30 SAP-clad fuel rods. This element

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ABSTRACT

In the frame of the ORGEL Prototype Contest an industrial group formed by "GAAA, INTERATOM, MONTEDISON" studies a power plant of 250 MWe gross output. The organic liquid cooled and heavy water moderated ORGEL type reactor is fuelled with slightly enriched uranium carbide elements consisting of bundles of 18 SAP-clad rods.

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KEYWORDS

ECONOMICS
ORGEL REACTOR
POWER PLANTS
ORGANIC COOLANT
HEAVY-WATER MODERATOR
URANIUM CARBIDES
FUEL RODS
SAP
COATING
PRESSURE TUBES
REACTOR CORE

Table of contents

ORIENTATION STUDY ON THE ECONOMIC POTENTIAL OF AN ORGEL POWER PLANT EQUIPPED WITH A G-30 FUEL ELEMENT**

1. Introduction

In the frame of the ORGEL Prototype Contest an industrial group of the Community formed by "GAAA, INTERATOM, MONTEDISON" studies a power plant of 250 MWe gross output. The organic liquid cooled and heavy water moderated ORGEL type reactor is fuelled by slightly enriched uranium carbide elements consisting of bundles of 18 SAP-clad rods (G-18 type element).

The aim of this study is to assess the economic potential of such an ORGEL prototype being alternatively equipped with a further subdivided uranium carbide fuel element consisting of bundles of 30 SAP-clad fuel rods (G-30 type element). This element is designed to fit into the pressure tubes of the reference plant reactor core and moreover to yield the same mean burn-up as the reference G-18 type element ; necessary modifications of the reactivity potential are effected by appropriate adjustment of the fuel enrichment.

As this report was written, the ORGEL Contest prototype plant was not yet completely defined by the industrial group ; therefore, the supposed reference prototype plant is that described in [1] "Fuel managements for an ORGEL prototype; orientation study", normalized to 250 MWe gross. It will be named Plant A in this study and is characterized by an MR* fuel management, a uranium carbide fuel slightly enriched at 1.9 times natural U-235 content ($\alpha = 1,35$ %) and a radial D_2O reflector tickness of 25 cm. The organic coolant is a mixture of terphenyls industrially known as OM-2 continuously purified by distillation and containing about 5 % high boiling residues.

The characteristics of this reference plant and of the other plants compared in this study are specified more in detail in chapter 2 and in Annex I. The comparison is done for the plants indicated hereunder and having the following features :

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* MR stands for on-power refuelled with radial shuffling of the fuel element string .

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Plant B : Core geometry identical to plant A, maximum linear heat rating of G-30 element the same as that of G-18 element; resulting electricity output 350 MWe gross.

Plant C : Power output increased, e.g. to 532 MWe gross, by increasing the number of channels (larger core radius, same max. heat rating of G-30 fuel element as in plant B.

Plant D : Power output limited to 250 MWe gross as for plant A, max. linear heat rating of G-30 fuel element the same as that of G-18 element, resulting in reduced number of channels (smaller core radius).

Plant E : Power output limited to 250 MWe gross, core dimensions identical to those of plant A ; resulting in 32 % less max. linear heat rating of G-30 fuel element.

Plant F : Core dimensions identical to those of plant A, same power generation costs as plant A ; resulting in 23 % less max. linear heat rating of G-30 fuel element compared to that of G-18 element in plant A ; plant output slightly increased to 280 MWe gross.

Characteristics of the plants

(see also tables in Annex I)

Plant performances

The plant performance data of plant A pertain to the state as calculated before normalization to 250 MWe gross output (see Ref. 1). In the cost comparisons done later on (figures 1 and 2) the electricity generation costs are indicated for both states, before and after normalization.

The steam cycle adopted is a classical one with superheat and reheat by the primary coolant and feedwater heating by extraction steam. The thermodynamic efficiency of such steam cycles has been evaluated under EURATOM contracts, in a range of primary coolant temperatures and steam pressures being typical for an ORGEL power plant. By means of a computer code developed in the frame of the ORGEL Program [3] the thermodynamic efficiency-optimized over the live steam pressure - has been reevaluated for the plants of this study.

The pinch point at evaporator inlet of the steam generator (BENSON type) was fixed to 20 °C based on preliminary optimization studies. Superheater and reheater are arranged in parallel, the pinch points at their outlet being fixed at 10 °C.

2.2 Reactor block

The inner diameter of the fuel channel, the core height, axial and radial reflector thickness and lattice pitch are not changed when the G-18 type element is substituted by a G-30 type one. In the course of this study, the number of channels and the core radius are adjusted according to the power output of the plants and the stipulated maximum linear heat rating of the fuel rods ; hence, the core fuel inventory and the heavy water inventory vary considerably.

2.3 Fuel element

The external dimensions of the fuel element (height, diameter) are the same for G-18 and G-30, but to house an element with 30 rods in the same coolant channel as one with only 18 rods the total cross section of fuel has to be reduced resulting in a higher ratio of moderator to fuel for the G-30 type element. Moreover, the structural material (SAP) cross section increases due to the further subdivised fuel, the coolant cross section remains nearly constant.

The SAP cladding of the fuel rods is fitted with fins in order to increase the heat transfer to the coolant. The height of these fins is adjusted such as to adapt the G-30 fuel elements power output to the envisaged plant (see table 7.3 Annexe I.)

In the frame of this study, assumption is made that the core unit cell material buckling of the different plants be identical in order to have the same average burn-up of fuel. Thus the poorer reactivity potential of the G-30 element asks for a higher fuel enrichment. However, a rather small supplementary enrichment is sufficient because of the higher ratio of moderator to fuel cross section, obtained with the G-30 element bundle compensating partly the negative effect of its smaller fuel section.

The reactor form factor (at withdrawn control rods) is supposed to be constant for all plants considered.

2.4 Fuel and thermal performances

Both fuel elements, G-18 and G-30, are characterized by the same maximum linear heat rating as far as the comparison at equal thermal sollicitation is concerned (Plants B, C, D). In Plant E the fuel element has a much smaller heat rating chosen as to give a plant output of 250 MWe gross without changing the core dimensions of the reference Plant A. The max. linear heat rating of the G-30 element in Plant F is smaller than that of the G-18 element and determined such as to obtain the same power generation costs as for Plant A.

The reactor coolant outlet temperature t_1 and the maximum coolant velocity in the channels are kept constant ; at constant max. linear heat rating the heating of the coolant across the core is higher for the G-30 than for a G-18 element. Under these hypotheses the maximum caldding temperature tgm (without hot spots) is 408 °C for G-30, whereas in the G-18 it reaches a value of 420 °C.

This difference reflects the degree of uncertainty on hot spots for the two fuel elements in so far as the G-30 type element has been studied only theoretically up to now and therefore claims for a greater safety margin.

3. Economical evaluations

The different cost elements of the plant investments have been calculated by the method used in the code ORION II [4]. The electricity generation costs are computed following the principles outlined in [5].

To remind some important data :

Heavy water	20	\$/lb
Indirect construction costs	35	% of direct cost
Annual instalment	10	%
Annual plant load factor	0.8	
Costs of fuel element (UC-SAP clad)	160	\$/kgU (α =1,39%)
(fabrication capacity of 100 t/year)		
Cost of organic coolant	0.30	\$/kg
Heavy water losses per year	0.5	% of inventory

No fuel reprocessing

Operation and maintenance costs include only organic make-up and D_2O losses

4. Results

A comparison between Plants A, B, C illustrates the well know electricity generation cost reduction with increasing plant power.
The maximum linear heat rating of the fuel rods is not changed in substituting the G-18 element of Plant A by a G-30 element in Plant B and C. This substitution increases the electricity output of Plant A to 350 MWe gross (called Plant B) without any change in the dimensions of the core and the reactor block; only the "classical" side of the power plant is concerned by the higher power output. The cost saving is about 0.3 mills/kWh.

It is interesting to get an estimation about a further power increase, e.g. to 500 MWe net (532 MWe gross, Plant C). This may be done by a linear upscaling of the number of channels * resulting in a larger core diameter. The fuel and thermal performances are the same as of Plant B. The cost saving over Plant B is another 0.4 mills/kWh.
If, by using the G-30 element, the electric power output of Plant A has to be conserved at 250 MWe gross, one can reduce the number of fuel channels and thus the core diameter (Plant D). Such a plant is characterized by a smaller reactor block and less heavy water inventory, whereas the "classical" side (except the heat exchanger) of the plant is not touched by the change. The comparison of Plant A and Plant D shows slightly higher costs of the latter, due to increased fabrication costs of the G-30 type fuel element, accompanied by a higher fuel enrichment necessary to balance its poorer reactivity potential. The cost savings effected on plant investment on the other hand are not sufficient as to compensate the higher costs of the fuel.

Fig. 1a shows the variation of electricity generation costs vs. gross electric power output for the 4 plants considered.

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* For reasons of core symmetry the number of channels must be divisable by 4

Under the hypothesis of no change in plant component dimensions (neither on the reactor block nor on the "classical" side) of Plant A one gets a power output of 250 MWe gross, in utilizing a G-30 type fuel element but operating it at a 32 % lower maximum linear heat rating (Plant E.). As can be expected from the discussion on the before mentioned Plant D, the electricity generation costs of Plant E are by about 0.3 mills/kWh higher than for Plant A (increased costs of the G-30 type fuel element) ; see figures 1a and 1b. From an economical point of view such a solution has to be rejected.

However, if for some reasons the thermal sollicitation of the G-30 fuel element (expressed in terms of maximum linear heat rating $q/4\pi$) has to be reduced, one may envisage to put a G-30 type element into Plant A without changing the core dimensions. At equal power generation costs as Plant A such a Plant F would be characterized by an electricity output of 280 MWe gross but about 23 % lower maximum linear heat rating than Plant A (see fig. 2).

From Plants B and E it is possible to show (figure 2) the variation of plant output and power generation costs vs. maximum linear heat rating of the G-30 type fuel element (the calculated intermediate points, being of minor interest, are not mentioned in the tables). Moreover, in figure 1b, the variation of power generation costs and max. linear heat rating is given vs. gross electric power output in the range of 240 to 350 MWe.

5. Conclusions

The substitution of the G-18 fuel element by a G-30 one in an ORGEL prototype plant appears justified from an economical point of view in the following two cases :

1) At constant core dimensions and equal max. linear heat rating $q/4\pi$ of the fuel rods the electric power output can be raised to 350 MWe gross (Plant B), resulting in production cost savings of about 0.3 mills/kWh. The total plant investment (without fuel) is about 15 % higher than for the reference Plant A.

2) With a slightly larger core, but equal max. heat rating of the fuel rods the plant output may be pushed, e.g. to 532 MWe gross (Plant C) ; the production cost savings over Plant B would be another 0.4 mills/kWh. The total plant investment (without fuel) is about 47 % higher than for the plant A delivering only half the power output of plant C.

From a technical point of view a third case seems interesting :

3) At constant core dimensions and slightly higher plant output of 280 MWe gross the max. linear heat rating of the fuel rods can be reduced to about 77 % of the G-18 element's value upon substituting it by a G-30 type element (Plant F.). The electricity generation costs are nevertheless the same as for Plant A.

In the next two cases the substitution is economically not advisable and leads to higher power generation costs :

4) At constant max. linear heat rating of the fuel rods and always 250 MWe gross power output the core dimensions can be reduced (Plant D) ; the production costs are slightly higher than those of Plant A.

5) At constant core dimensions and also constant plant output of 250 MWe gross the max. linear heat rating of the fuel rods can be reduced to about 68 % of the G-18 element's value upon substituting it by a G-30 type element (Plant E). However, this results in higher production costs of about 0.3 mills/kWh over plant A.

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7. Annex I

7.1 Plant performances

Plant		A*	B	C	D	E	F
Gross electric power	MWe	263	350	532	253	250	280
Net electric power	MWe	246	330	500	238	231	261
Net plant efficiency, related to the fission power	-	0.325	0.319	0.319	0.319	0.329	0.328
Reactor fission power	MW	752	1032	1567	746	701	796
Thermal power transmitted to coolant	MW	707	970	1473	701	659	748

* Before normalization to 250 MWe gross

7.2 Reactor block

Plant		A	B	C	D	E	F
Inner diameter of pressure tube	cm	11.1	11.1	11.1	11.1	11.1	11.1
Number of channels	--	216	216	328	156	216	216
Core radius	cm	200	200	248	170	200	200
Core height	cm	400	400	400	400	400	400
Axial reflector thickness	cm	30	30	30	30	30	30
Radial refector thickness	cm	25	25	25	25	25	25
Lattice pitch (square)	cm	24.2	24.2	24.2	24.2	24.2	24.2
Core fuel inventory	10^3kg U	49.5	44.8	68.0	32.4	44.8	44.8
Total D_2O inventory	10^3kg	71.5	71.5	104.8	54.7	71.5	71.5

7.3 Fuel element

Plant		A	B,C,D	E	F
Type		G-18	G-30	G-30	G-30
Number of elements per channel	-	5	5	5	5
Number of fuel rods per element	-	18	30	30	30
Overall length of the element	cm	80	80	80	80
Length of fuel core	cm	75.5	75.5	75.5	75.5
Diameter of the fuel pins	cm	1.83	1.35	1.35	1.35
Carbon content in UC (wt.%)	%	4.9	4.9	4.9	4.9
Cladding material	-	SAP	SAP	SAP	SAP
Cladding thickness (between fins)	cm	0.095	0.071	0.071	0.071
Finning ratio	-	1.75	1.5	1.23	1.34
Fuel cross section	cm^2	47.34	42.94	42.94	42.94
Cladding and other SAP structure cross section	cm^2	16.4	16.4	14.1	15.0
Gas	cm^2	3.5	8.3	8.3	8.3
Coolant cross section	cm^2	29.6	29.1	31.4	30.5
Ratio of coolant to fuel cross section	-	0.625	0.678	0.730	0.708
Fuel enrichment	% U-235	1.35	1.39	1,39	1.39
Ratio of moderator to fuel cross section	-	9.5	10.5	10.5	10.5
Average burn-up	MWd/t U	12,800	12.800	12,800	12.800
Global power form factor	-	0.72	0.64	0.64	0.64
Reactor form factor	-	0.80	0.80	0.80	0.80
Bundle form factor	-	0.90	0.80	0.80	0.80

7.4 Fuel and thermal performances

Plant		A	B	C	D	E	F
Maximum linear heat rating $q/4\pi$	W/cm	53,2	53.2	53,2	53.2	36	41
Average max. coolant coutlet temperature t_1	°C	369	369	369	369	369	369
Average heating of the coolant across the core	°C	66.5	89	89	89	56.5	66
max. cladding temperature tgm	°C	420	408	408	408	408	408
max. coolant velocity V	m/s	10	10	10	10	10	10

Fig. 1

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Power generation costs vs. gross electric power output with G-30 fuel element

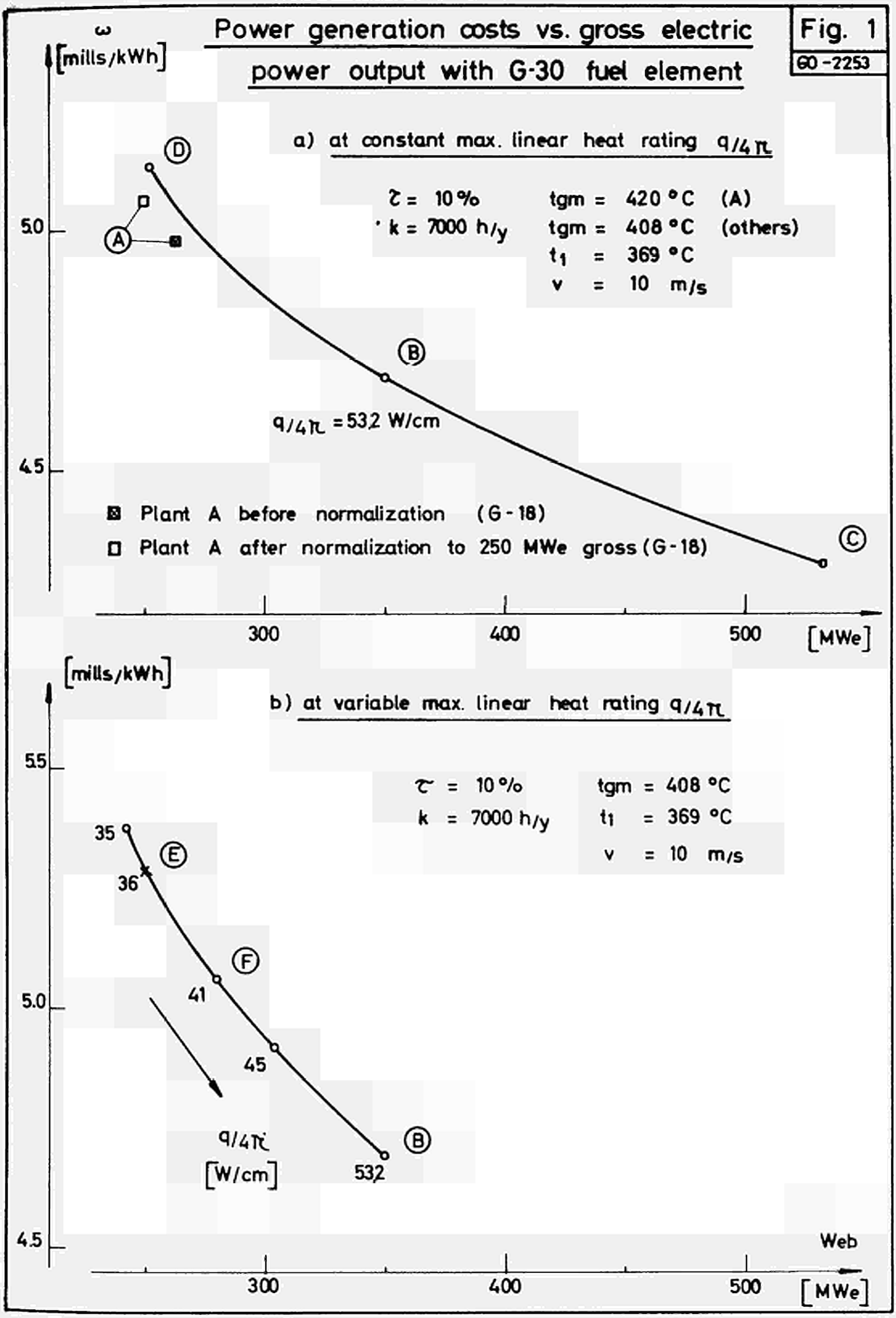
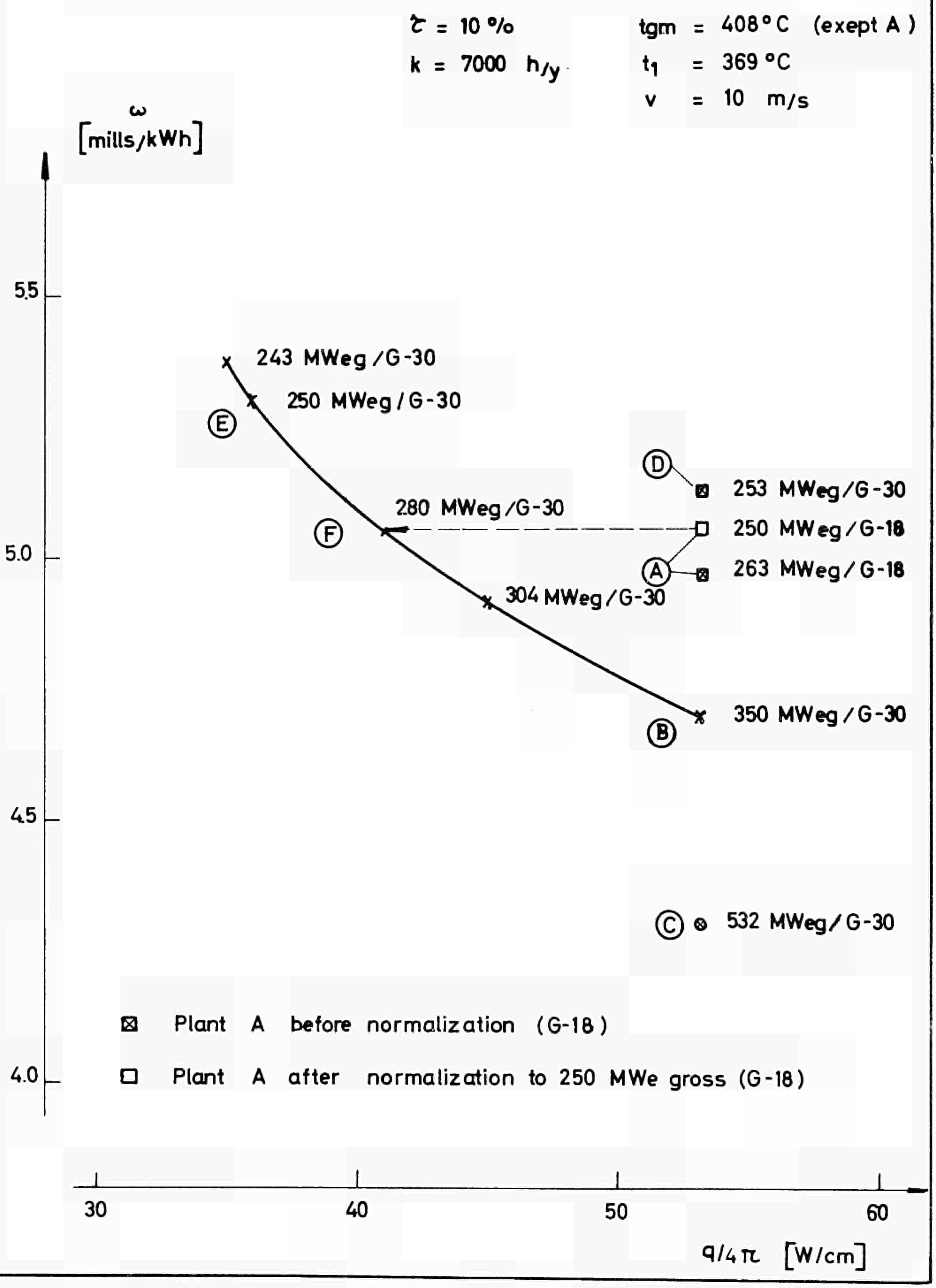


Fig. 2

GO-2254

Power generating costs vs. max. linear heat rating $q/4\pi$ for G-30 and G-18 type fuel element



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