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HIGH POWER DENSITY - HIGH TEMPERATURE REACTOR (HPD - HTR)

by

L. Valette, R. Schulten, B. Markowski and S. Förster

1970

THTR 89

Work performed at the KFA
Kernforschungsanlage Jülich des Landes Nordrhein-Westfalen e. V. - Germany
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The fuel temperature would not exceed 1400° C and the fast neutron dose in fuel and graphite would be slightly increased.

It is recommended, on the basis of this preliminary study, to perform more detailed cost analysis of systems with increased power density.

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ABSTRACT

An assessment of the effect of increasing simultaneously the power density of the core of an HTGR and the pressure of the primary coolant circuit is made.

It is shown that by increasing the power density up to 12 MW/m^3 and the helium pressure to 80 atm, the fuel cycle cost would not be increased and the capital cost of a 600 MWe plant might be decreased by 5 %. The pumping power would be smaller and thus the efficiency increased.

The fuel temperature would not exceed 1400° C and the fast neutron dose in fuel and graphite would be slightly increased.

It is recommended, on the basis of this preliminary study, to perform more detailed cost analysis of systems with increased power density.

KEYWORDS

ANALYSIS
RADIATION EFFECTS
STRESSES
GRAPHITE
MATRICES
FUEL ELEMENTS
CREEP
ANISOTROPY

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I. Introduction *)

The first generation of High Temperature gas-cooled power Reactors are designed with power densities around 6 MW/m^3.
The arguments used for setting an upper limit to the power density were taken from neutron physic and thermodynamic calculation:

- from the thermodynamic point of view
  the pumping power would be increasing to unacceptable values (for the same primary circuit pressure),
  the fuel element temperature would become too high;

- from the neutron physic point of view
  the protactinium, Xe losses and leakage would increase with power density,
  the fast neutron flux would also increase proportionally to power density.

The progress in concrete pressure vessel technology has shown, that the primary circuit pressure of HTR could be increased above the values used in the present HTR design (40 to 50 ata). The use of higher pressure would offset most of the thermodynamic limitations set by the use of higher power density. The decreased neutron economy with higher power densities might also be compensated by a resulting decreasing in capital and first charge cost. A higher power density would yield higher thermal power from the same volume core and a new optimum for total electricity generation cost might be reached.

The objective of this document is

1. to survey how the thermodynamic characteristics of the core are affected by varying the power density and the pressure of the primary circuit.

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*) Manuscript received on 29 July 1969

2. to perform a parametric study of the fuel cycle costs at various power densities;

3. to consider the engineering problems resulting from the use of high power density for the primary circuit components.

The reference case used in the survey is a 600 MWe^{12+} (12 MW/m^3) plant extrapolated from the 300 MWe^{6} THTR pebble bed prototype (6 MW/m^3) using the one type element fuel cycle. A similar survey could be done for an HTR with prismatic fuel elements. The generating power and mass flow are increased proportionally to the power densities, so the inlet and outlet temperature of He is unchanged.

The possible capital cost saving of this 600 MWe^{12} (12 MW/m^3) compared to a 600 MWe^{6} (6 MW/m^3) is also considered.

II. Thermodynamic performance of HPD HTR

In order to study the influence of the power density and gas pressure on the thermodynamic performances of the core, we take as reference case the THTR prototype design. We assume, that the core size and geometry as well as the inlet and outlet gas temperatures are unchanged. This straight forward extrapolation, does not probably correspond to the optimum case, but it is the easiest way to get a feeling of the advantage and problems introduced by selecting a higher power density.

We assume that the power density is increased by a factor a and the primary circuit pressure raised by a factor b.

$$\frac{W}{W_o} = a \qquad (1) \qquad \frac{p}{p_o} = b \qquad (2)$$

W power density

W_o initial power density THTR 6 MW/m^3

p pressure ata

p_o pressure THTR 40 ata

We can use the equations developed by W.Kersting [1] to find the factor affecting the thermodynamic properties of the core

+ The abrevation MWe^{6} or MWe^{12} are used to indicate the electrical generated power and the power density 6 MW/m^3 or 12 MW/m^3 in the core.

1. The total thermal power output:

We have assumed an unchanged core geometry and an increased power density consequently the thermal power output is increased proportionally

$$\frac{N_{th}}{N_{th_o}} = a \qquad (3)$$

2. The mass flow:

We have assumed that the inlet and outlet temperature of the gas are unchanged, consequently the mass flow varies proportionally to the power density.

$$\frac{\dot{m}}{\dot{m}_o} = a \qquad (4)$$

3. The Reynolds number:

$$Re = \frac{\dot{m} \cdot d_k}{F_c \cdot \eta \cdot (1-\varepsilon)} \qquad (5)$$

$\dot{m}$ mass flow

d_k ball diameter

F_c cross section of empty core

ε void fraction of core ($\varepsilon = 0.39$)

η dynamic viscosity of gas

d_k, F_c, ε are geometrical factors and are unchanged

η is only temperature dependent and also unchanged

consequently $\frac{Re}{Re_o} = a$

4. The heat transfer coefficient:

$$\alpha = \frac{0.363 \cdot \lambda_G \cdot (Re)^{0.7}}{d_k} \qquad (6)$$

λ_G thermal conductivity of the gas is only a fonction of temperature and we have seen that the He temperatures are unchanged.

$$\frac{\alpha}{\alpha_o} = (a)^{0.7} \qquad (7)$$

5. The boundary layer temperature gradient between fuel element and gas

$$\Delta T_G = \frac{Q}{\alpha \cdot F_K} \qquad (8)$$

Q power per ball

F_k surface of the sphere

α heat transfer coefficient

ΔT_G temperature drop in the gas boundary layer

$$\frac{\Delta T_G}{\Delta T_{Go}} = \frac{Q}{Q_o} \cdot \frac{\alpha_o}{\alpha} = a \cdot (a)^{-0.7} = a^{0.3} \qquad (9)$$

6. The power per fuel element

The power per fuel element increases proportionally to the power density

$$\frac{Q}{Q_o} = a \qquad (10)$$

The maximum fuel element temperature

$$T_m = T_{gas} + \Delta T_G + \frac{Q}{8\,\pi ri}\left[\frac{1}{\lambda} + \frac{2}{\bar{\lambda}}\left(\frac{ra - ri}{ra}\right)\right] \qquad (11)$$

$$T_m = T_{gas} + \Delta T_G + \Delta T_{fuel}$$

λ thermal conductivity of unfuelled region of the fuel element

$\bar{\lambda}$ thermal conductivity of fuelled region of the fuel element

ra fuel sphere radius

ri fuelled zone radius

ΔT_{fuel} temperature drop in the fuel element

$$T_m = T_{gas} + \Delta T_{Go} \cdot a^{0.3} + \Delta T_{ofuel} \cdot a \qquad (12)$$

7. The pressure drop in the core

$$\Delta p_c = \xi \cdot \frac{\rho \cdot w^2}{2} \cdot c \qquad (13)$$

$$= \xi \cdot \frac{\dot{m}^2}{\rho \cdot F_c^{\,2} \cdot 2} \cdot c \qquad (14)$$

ξ drag coefficient
c body shape factor unchanged
F_c cross section "
ρ gas density "

$$\frac{\Delta p_c}{\Delta p_{co}} = \frac{\dot{m}^2}{\dot{m}_o^{\,2}} \cdot \frac{\rho_o}{\rho} = \frac{a^2}{b} \qquad \text{with } b = \frac{p}{p_o} \qquad (15)$$

8. The pumping power

The required pumping power is proportional to pression drop Δp in the primary circuit, which includes the Δp_c pressure drop in the core.

$$Nel = \frac{\dot{m} \cdot \Delta p}{\rho_s \cdot \eta_p \cdot \eta_m}$$

ρ_s blower inlet gas density
η_p polytropic efficiency
η_m mechanical efficiency

$$\frac{Nel}{Nel_o} = \frac{a}{b} \cdot \frac{\Delta p}{\Delta p_o}$$

Should b = a then $\frac{Nel}{Nel_o} = \frac{\Delta p}{\Delta p_o}$ which means that if the pressure is increased proportionally to the power density then the required pumping power varies proportionally to Δp. The pressure drop Δp is subdived in Δp_c pressure drop in the core and pressure drop in the rest of the circuit. If the geometry of the primary circuit

is unchanged

then $\frac{\Delta p}{\Delta p_o} = \frac{\Delta p_c}{\Delta p_{co}} = \frac{a^2}{b}$ see equation (15)

then $\frac{Nel}{Nel_o} = \frac{a}{b} \cdot \frac{\Delta p}{\Delta p_o} = \frac{a^3}{b^2}$ and as we have assumed b = a

then $\frac{Nel}{Nel_o} = a$. In this case the total thermal output and pumping power are increased in the same proportion.

III. Fuel cycle and fast neutron in HPD HTR

a) Mr. Markowski [2] has calculated the optimum fuel cycle for the U/Th cycle at different power density from 6 to 18 MW/m^3. He has used the following assumptions and limitations:

- the volume of the core is unchanged
- the heat transfer coefficient α is increasing with power density
- the thermal conductivity λ and $\bar{\lambda}$ of unfuelled and fuelled part of the fuel element are constant
- the coated particles size are
  - 800 μ diameter
  - 150 μ coating thickness
- the fuelled region diameter is 5 cm.

The results are summarized in the attached figure 1 and table 1.

It can be seen that the total fuel cycle cost has a very flat optimum near 12 MW/m^3 corresponding to a total power of 600 MWe^{12} per reactor. The adverse neutron losses by leakage, Xe and Pa losses are compensated by the reduction in the fixed costs. At this optimum corresponds a maximum fuel temperature of 1400 °C.

The maximum design temperature of 1400 °C with possible random peak temperature as high as 1600 °C should be considered as technically feasible in the near future.

We will take this 600 MWe[12] plant with a power density of 12 MW/m^3 as a typical example for investigating the influence of higher power density. We can compare the technical data of this HPD HTR 600 MWe[12] to the data of a 300 MWe[6] using lower power density [3] (see Table 2).

b) Fast Dose: The fast flux in the 600 MWe[12] is ~factor 2 higher than in 300 MWe[6]. For the fuel element the residence time is shorter and consequently the accumulated dose marginally greater than in the reference case. For example

$$\text{Dose} = \phi_f \cdot t$$

ϕ_f fast flux

t residence time

$$\frac{\text{Dose}}{\text{Dose}_o} = \frac{\phi_f}{\phi_{fl}} \cdot \frac{t}{t_o} = 2 \cdot \frac{2.15}{3.49} = 1.23$$

The structural graphite would of course be subjected during its life time to a higher dose. Recent evaluation of the damage dose in the reflector of the 300 MWe[6] THTR with control rods in the reflector indicates, that the expected dose would be $\sim 1.7 \cdot 10^{22}$ Dido Ni eq. Should this dose be increased by a factor 2, one would exceed any available data on graphite irradiation. Testing of graphite to these high doses and temperatures would have to be performed or another solution using removable reflector blocks should be used.

IV. Technical and engineering problems of the primary circuit of 600 MWe[12] (12 MW/m^3)

We have seen in the previous paragraphs that 1500 MWth equivalent heat of 600 MWe[12] could be produced and removed from a core volume not greater than the one used in the 300 MWe[6] prototype plant. We have assumed a He mass flow of 591 kg/s and a pressure of 80 ata twice as high as for the prototype. The He inlet 262 °C and outlet temperatures 750 °C of the core are unchanged. In this chapter we consider the components of the plant, which are mainly affected by the increase of performance.

1. The fuel elements

The core consists of 675,000 fuel elements. The fabrication method of the fuel elements is based on the actual technology used for the reference elements for the 300 MWe^6 prototype, the pressed fuel elements.
The fabrication methods and costs should be the same, because the heavy metal content per fuel element is very conservative. The heavy metal content per ball is increased from 10.47 g to 10.99 g.

The coated particle design 800μ in diameter with a 150μ coating is conservative. If need be, smaller size coated particles could be used because the loading factor 0.078 selected, is far below the maximum admissible value of 0.25 for the pebble bed fuel elements.
The operating conditions of the fuel elements are more severe than for the prototype although not too futuristic.

The burn-up is 15.9 % fima instead of 13.5 % fima. The fast dose is a factor 1.23 greater than for the prototype; although the fast flux is increased by a factor of 2 the residence time in the core is shorter, 2.15 years instead of 3.49 years.

The maximum design temperature of 1400 °C would probably lead to occasional random peak temperatures as high as 1600 °C. Coated particles, which could operate under these conditions should be considered as technically feasible for several reasons:

a) tests in the Dragon reactor have shown that fuel element maintained at 1600 °C for more than 80 days and 2 % fima behaved well.

b) In a pebble bed reactor the maximum design temperature and more so the random peak temperature will only occur in the fuel element for short period. Only a small fraction of the core is at the maximum design temperature and the residence time of the fuel in this zone corresponds to a small percentage of its life in the core. The random peak temperature would be due to statistical accumulation of conditions leading to a hot spot in the core. By nature,

these statistical accumulation would be destroyed rapidly by the movement of the balls.

2. The graphite components

The temperature distribution in the reflector would be similar to the temperature distribution in the 300 MWe^6, but the fast dose would be twice as high, and one would then reach a peak dose of $3.5\ 10^{22}$ Dido Ni eq. in the 700 °C region of the reflector. This dose is beyond the dose reached by any tested graphite. A development programme would be necessary to guarantee the life time behaviour of the reflector. Alternatively design with replaceable reflector graphite could be used.

3. Boilers:

The firm Buckau R. Wolf [4] had kindly looked in different ways of adapting boilers to the new conditions e.g. double pressure, mass flow and power density in the core. From the different alternative proposals we present the versions which do not require a change in the He inlet and outlet temperature. It should be pointed out, that in all cases the gas pressure (80 ata) is higher than the pressure of the medium pressure steam (50 ata). This might lead to the decision of performing the reheat in an external heat exchanger if one wishes to preserve, for safety reason (contamination of the turbine), the principle of keeping the steam pressure always higher than the gas pressure. It is however possible to keep the reheater in the pressure vessel by using fast closing valves, which would in case of tube rupture, avoid a large flow of gas to the turbine.

Version I: In this case 6 boilers are used with the same cross section for the gas, and the same gas speed as for the 300 MWe^6. From the heat transport and energy balance equations it can be seen that in this case the required surface for transferring the energy of the 600 MWe^{12} in 80 ata He should be 1.54 greater than the surface required for 300 MWe^6 in 40 ata.
In the boilers with spiral tubes the

$\frac{\alpha}{\alpha_o} = (b)^{0.63}$ relation is used instead of equation (7).

This greater heat transfer surface is obtained by a double pass He stream in the boilers. The outer diameter of the boiler would be 3 m. The pressure drop in the boilers would be 1.54 greater than the pressure drop of the 300 MWe^{6} boilers e.g. 0.71 ata instead of 0.45 ata.

The heat transferred from the gas side to the steam side by unit surface is increased. The problem of thermal stresses in the tube material would become more acute and one should probably select more expensive materials for the super-heater and reheater. The costs of this version is estimated to be 60 % more expensive than for the 300 MWe^{6}.

Version II: Use is made of 12 boilers identical to those used for the 300 MWe^{6} plant. The heat transfer rate is not changed in this case, because the Re is not affected, the increase in pressure being compensated by the reduction of gas velocity in the boilers. The pressure drop (0.225 ata) in the 600 MWe^{12} boilers would be half the pressure drop (0.45 ata) of the 300 MWe^{6} boilers.

This version has the advantage of keeping the simple design of the single pass He flow and keeps the heat transfer rate in the limits where cheap material could be used.

The diameter of each boiler is 2 m. It is quite clear, that in this case the costs of the 12 boilers of the 600 MWe^{12} would be twice as high as for the boiler costs of 6 units for the 300 MWe^{6}.

With increasing number of boilers the costs of valves, metallic structures will also increase.

4. The pressure vessel

The pressure vessel of 600 MWe^{12} should be designed in order to compensate the drawbacks of the higher pressure by making use of the small size of the core.

Some preliminary investigations made by Fried.Krupp GmbH [5] indicate that the pressure vessel layout used for the 300 MWe^6 plant is not appropriate to take advantage of the reduced size of the core. As a matter of fact by the radial disposition of the boiler, the inner size of the pressure vessel is dictated by the size and the space required for the boilers. The table 3 gives a comparison of the 300 MWe^6 pressure vessel and the 600 MWe^{12} pressure vessels with 6 or 12 boilers. In the same table the data for a 600 MWe^6 pressure vessel with 12 boilers are also indicated. It is clear that the high pressure results in larger and more expensive pressure vessel.

TABLE 3

Version	Number of boilers	Pressure ata	I.D. m	O.D. m	I.H. m	Ø penetration m	Cost DM (indicative)
300 MWe^6	6	40	15.9	24.8	15.3	2.25	$\sim 25 \cdot 10^6$
600 MWe^{12}	6	80	17.4	35.	15.3	3.10	$\sim 44 \cdot 10^6$
600 MWe^{12}	12	80	18.	37.	15.3	2,25	$\sim 51 \cdot 10^6$
600 MWe^{12} pod boiler	12	80	9.3	24.	15.3	2.25	$\sim 40 \cdot 10^6$
600 MWe^6	12	40	18.3	30.	17.	2.25	$\sim 33 \cdot 10^6$

The "pod boiler" type pressure vessel developed by the Dragon Project seems to be a better proposal for the higher power density. Another alternative pressure vessel for HPD HTR could be similar to the one used by GGA in Fort St. Vrain Reactor [6] . Some more detailed investigations are needed to confirm these points.

5. Blowers

The required pumping power is given by equation (16). It can be seen, that when pressure and mass flow are increased in the same proportion then the pumping is proportional to the pressure drop. Thus

$$\frac{Nel\ (600\ MWe^{12})}{Nel\ (300\ MWe^{6})} = \frac{\Delta p\ (600\ MWe^{12})}{\Delta p\ (300\ MWe^{6})}$$

The pressure drop in the He circuit depends on the boiler arrangement used

$$\Delta p = \Delta p \text{ core} + \Delta p \text{ boiler.}$$

The pressure drop in the 600 MWe[12] core is twice as high as for the 300 MWe[6] core. The pressure drop in the boilers depends on the arrangement selected

Version I: 6 higher rated boilers

$\Delta p = 0.59 \times 2 + 0.71 = 1.89$ ata.

$$\text{Nel (600 MWe}^{12}\text{)} = 10.7 \times \frac{1.89}{1.04} = 19.4 \text{ MWe,}$$

which represents 3.25 % of total power produced.

Version II: 12 boilers

$\Delta p = 1.305$ ata

$$\text{Nel (600 MWe}^{12}\text{)} = 10.7 \times \frac{1.305}{1.04} = 14 \text{ MWe,}$$

which represents 2.35 % of total power produced.

It may be assumed as a first approximation, that the version with "pod boiler" would give similar results as version II.

Both versions give a reasonable ratio between blowers power and power produced. This ratio for the 300 MWe[6] is 3.5 %.

The second version is in this case more attractive and results in an increase of ~0.5 % in net plant efficiency.

6. The control rods

The calculation of the control rod worth is a difficult task and we will merely assume, that the 42 core rods and the 36 reflector rods would have an anti-reactivity of 28.1 Nile as in the 300 MWe[6].

On the other hand the reactivity to compensate is higher in the 600 MWe[12], because of the increased Xe and Pa poisoning due to the higher thermal and epithermal flux. The Xe poisoning would

not be significantly increased, because the thermal flux in the 300 MWe[6] is already very high and the Xe poisoning saturates. A 20 % increase in the required ΔK would be a good guess on the Xe effect [7].

The protactinium build up also saturates with flux, but in this case we are far from the saturation point and we pessimistically assume that the Pa yield is increased by a factor two.

Although the fuel temperature is higher one may consider, that the average reflector temperature is unchanged and as a first approximation the temperature effect on reactivity should be kept unchanged. We may figure out the reactivity requirement for controlling the reactor between 100 % and 40 % power as:

	300 MWe[6]	600 MWe[12]
Temperature ΔK (T)	2.4 Nile	2.4 Nile
Xenon ΔK Xe	3.5 Nile	4.2 Nile
Protactinium ΔK Pa	3.5 Nile	7. Nile
Excess reactivity	1.65 Nile	1.65 Nile
Minimum reserve	0.5 Nile	0.5 Nile
Reserve	1.85 Nile	1.85 Nile
	13.4 Nile	17.6 Nile

The control rod arrangement of the 600 MWe[12] would be then sufficient.

7. The charge machine

The charge machine design is essentially the same in the 600 MWe[12] as in the 300 MWe[6]. The size of the fuel element is unchanged, the rate of circulation of the balls should be increased to take into account the shorter residence time of the fuel element in the core 2.3 years instead of 3.5 years. The existing machine designed for a maximum speed of 500 balls/h could do the job, because the nominal rate of circulation in the 300 MWe[6] is only 154 balls/h.

The machine should be only redesigned to take into account the higher pressure. A more detailed analysis is required to predict the effect of using stronger tubes, for 80 ata on the precision of measurement in the burn-up analysis equipment.

8. The purification plant and He storage

The size of the chemical purification plant is determined by the required purification mass flow. This mass flow is in its turn determined by the averaged and maximum surface temperature of the graphite components of the core. We have seen that the surface temperature of the fuel elements and of the reflector are unchanged, consequently the same mass flow would be used for the 600 MWe^{12} as for the 300 MWe^{6}.plant. The volumetric flow would be reduced due to the increase of pressure. The pipings should be redesigned to take advantage of the reduced volumetric flow.

The size of the active plant is determined by the time required to transfer the He from the primary circuit to the He storage. The volume of the primary circuit being unchanged the same volumetric flow (double mass flow) would be required for this part of plant. The size of the He storage would have in any case be increased by a factor of two [8] .

	300 MWe^{6}	600 MWe^{12}
Purification flow in the chemical plant	5,000 Nm^3/h	5,000 Nm^3/h
Purification in the active plant	2,000 Nm^3/h	4,000 Nm^3/h
Storage operation	50,000 Nm^3/h + reserve	1000,000 Nm^3/h + reserve

V. Conclusion

We have seen that it is technically feasable to increase the power density in HTR to 12 MW/m^3 if the coolant pressure is also increased to 80 ata. We list hereunder as a kind of con-

clusion the technical advantages and drawbacks, that this increased power density introduces.

Drawbacks

1. Increased fuel temperature: the claimed temperature of 1400 ^{o}C is not excessively futuristic.
2. Increased fast neutron flux would require better graphites or removable graphite structures.
3. Increased pressure: influence adversely the size of the pressure vessel but this drawback could be overcome by adopting the "pod boiler type pressure vessel".

Technical advantages of HPD HTR

1. Smaller core, this advantage should be used to optimise the pressure vessel design.
2. Smaller relative pumping power with corresponding higher plant efficiency.
3. For a pebble bed reactor the actual reflector control rod solution used for the prototype could be used for a 600 MWe[12].
4. Reduced capital costs.

The determining argument for or against the use of higher power densities would be the balance between the economy of the system and the risk introduced by higher performances. A detailed comparison of the costs of a 600 MWe[6] and a 600 MWe[12] plant should be performed. In table 4 we give a summary of the plant parts, which we feel are affected by the selection of one system or the other. The 600 MWe[12] tends to be cheaper than the 600 MWe[6]. The extent of capital cost saving could reach 5 %.

VI. References

1 Kersting, W., KFA-Report Jül-519-RG, Feb., 1968

2 Markowski, B., -private communication-

3 THTR reference design; Technischer Bericht BBK

4 Buckau R. Wolf AG, -private communication-

5 Fried. Krupp GmbH, -private communication-

6 Walker, R.F., IAEA-Symposium 21.-25. Oct.
paper SM-111/75

7 Massimo - BBK -, -private communication-

8 Werner - BBK -, -private communication-

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TABLE 1 Fuel cycles for different power densities

Input data

plant efficiency	40 %	C-sigma absorption mb(2.200m/s)	4.5
power range	1 to 0.4	moderator temperature (K^o)	900
height/diameter core	0.9100	fuel temperature (K^o)	950
ratio of dummy balls	0	coated particle diameter/u	800
fuelled zone diameter cm	5.	coating thickness/u	150
C-atom density 10^{24} at/cm^3	0.0530		

Results of burn-up calculation:

Power density MW/m^3	6	9	12	15	18
Reactor power MWe	300	450	600	750	900
Moderation ratio	8,954	8,194	7,201	7,551	7,557
Residence time y.	3.49	2.55	2.15	1.71	1.48
Burn-up MWd/t	135,386	147,977	158,896	173,484	190,889
Specific power MW(Th)/kg HM	0.11684	0.17702	0.22774	0.31792	0.41100
Specific power MW(Th)/kg FM	2.606	3.576	4.189	5.490	6.591
Fifa	1.388	1.315	1.266	1.216	1.176
Conversion factor core	0.524	0.483	0.457	0.417	0.384
Conversion factor tot.	0.539	0.503	0.479	0.442	0.410
Fuel content per ball (HM)g	10.469	10.493	10.988	9.995	9.451
Coated particle loading factor	0.074	0.074	0.078	0.071	0.067
Loading parameters					
Th-232/ U-238 (%)	88.948/0.618	87.253/0.713	85.783/0.795	83.837/0.904	81.619/1027
U-233 / Pu-239	0.0/0.0	0.0/0.0	0.0/0.0	0.0/0.0	0.0/0.0
U-234+U-236/ Pu-240+Pu-242	0.139/0.0	0.161/0.0	0.179/0.0	0.204/0.0	0.232/0.0
U-235 / Pu-241	10.295/0.0	11.874/0.0	13.244/0.0	15.056/0.0	17.122/0.0
Discharge parameters					
Th-232/U-238 (%)	93.929/0.552	93.210/0.634	92.532/0.699	91.842/0.808	91.055/0.929
U-233/Pu-239	4.483/0.009	4.549/0.011	4.674/0.013	4.562/0.015	4.503/0.018
U-234+U-236/Pu-240+Pu-242	2.581/0.017	2.997/0.020	3.373/0.024	3.850/0.028	4.396/0.033
U-235/Pu-242	0.377/0.004	0.440/0.005	0.518/0.006	0.533/0.007	0.556/0.008
First core cost Dpf/kWh	0.274	0.203	0.173	0.141	0.124
Total cost Dpf/kWh	0.627	0.614	0.611	0.614	0.619

TABLE 1 (page 2)

Maximum power pe ball kW		4.1	6.35	8.9	7.82	10.13
Maximum fuel temperature	°C	1130	1260	1400	1600	1800

Input economical data

amortisation period	17 years	Th-price	100 DM/kg
load factor	0.7	graphite price	35 DM /kg
rate of interest	7.0 % year	fabrication cost	300 DM/kg HM
taxes	2.7 % year	fabrication time	0.5 year
U_3O_8	8. $/lb	reserve	1.03

TABLE 2

Comparison of 300 MWe[6] and 600 MWe[12] plants

	300 MWe[6]	600 MWe[12]
moderation ratio	8.954	7.200
fuel element residence time	3.49 y	2.18 y
average fissible material in core	287 kg	358 kg
initial $N = \frac{Th}{U\text{-}225}$	8.61	6.35
burn-up fima %	13.5	15.8
max. fuel temperature	1130 °C	1400 °C
max. power per ball kW	4.1	8.9
He mass flow	295.5 kg/s	591 kg/s
pressure	40 ata	80 ata
core inlet temperature	262 °C	262 °C
core outlet temperature	750 °C	750 °C
power density	6 MW/m^3	12 MW/m^3
Δp boilers	0.45 ata	
version 1 (6 units)		0.71 ata
version 2 (12 units		0.225 ata
Δp total	1.1 ata	
version 1 (6 boilers)		1.89 ata
version 2 (12 boilers		1.305 ata
Blowers six units	10.7 MW	
version 1 (6 boilers)		19.4 MW
version 2 (12 boilers)		14. MW

TABLE 4

Qualitative Comparison of cost of a 600 MWe^{6} and 600 MWe^{12}

Item		Remarks
Building at the exclusion of reactor hall	o	
Reactor hall	-	depends on size of pressure vessel
Reactor pressure vessel	+	optimum design must be found
Graphite structure	-	
Steel components	-	
Control rods	-	
Charge machine	-	
Helium system	o	
Auxiliary cooling plant	?	
Blowers	-	
Boilers	o	
Fuel storage and decontamination	o	
All other components	o	
Secondary circuit	o	
First charge	-	
Total fuel cycle cost	o	

o = no costs change

+ = increased costs for 600 MWe^{12}

- = decreased costs for 600 MWe^{12}

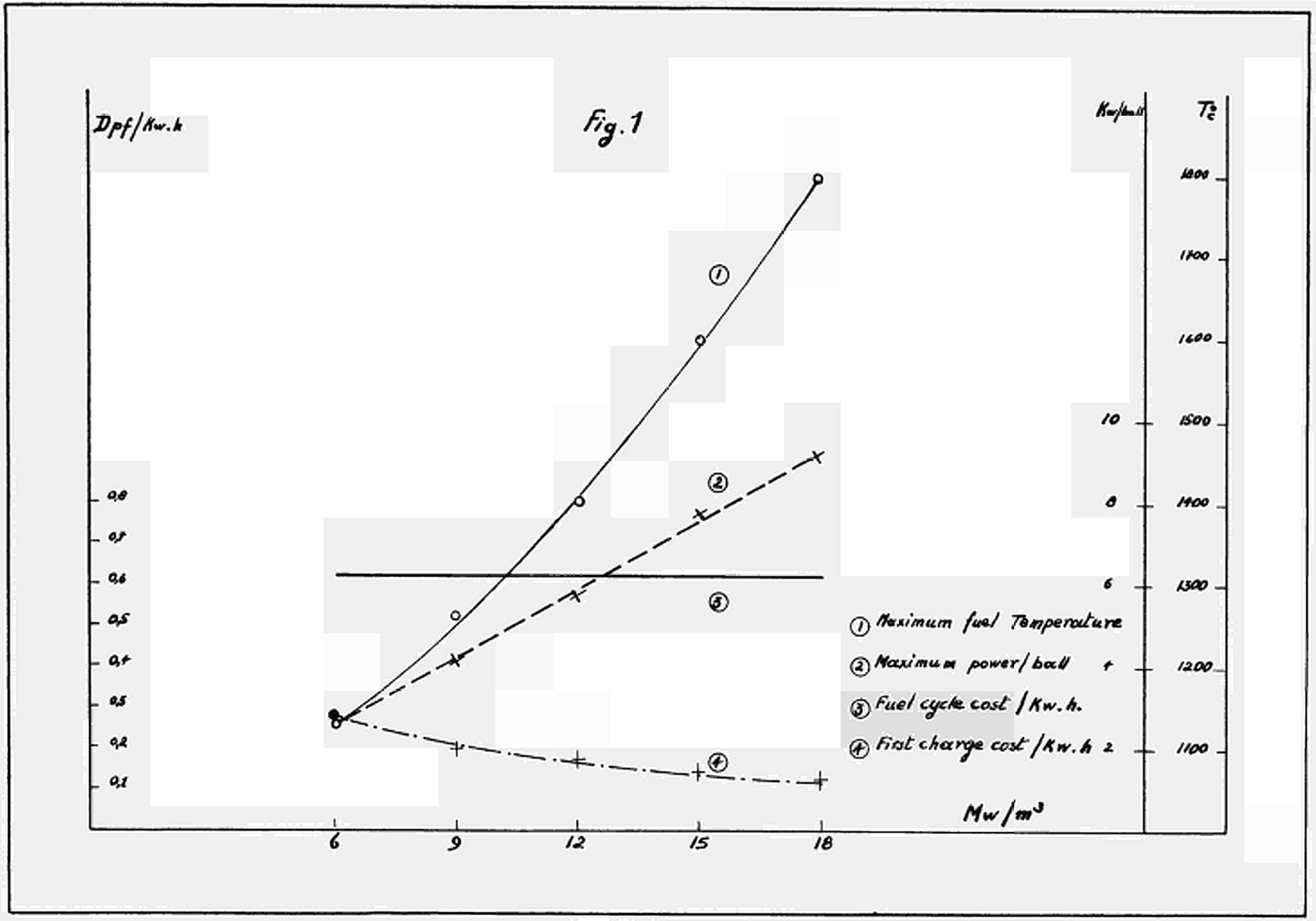
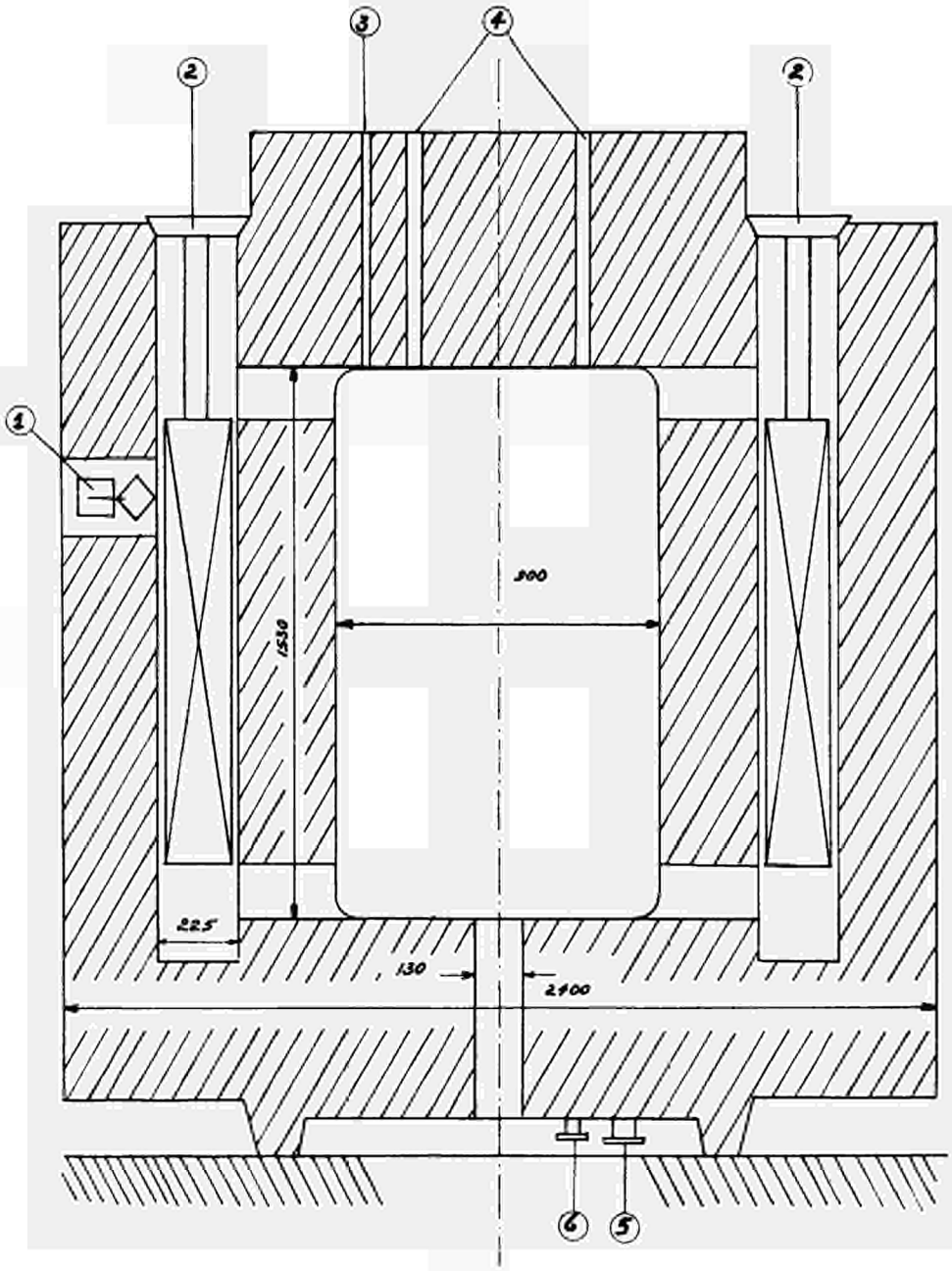


Fig. 1
Dpf/Kw.h
Kw/litre
Tc°
1800
1700
1600
10
1500
8
1400
6
1300
4
1200
2
1100
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
6
9
12
15
18
Mw/m³
① Maximum fuel Temperature
② Maximum power/ball
③ Fuel cycle cost /Kw.h.
④ First charge cost /Kw.h

Fig. 2

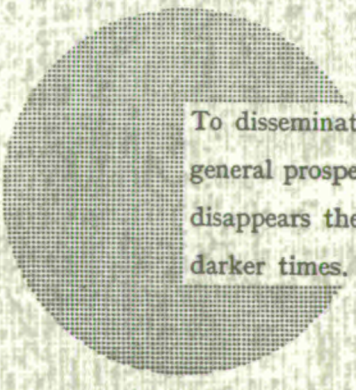
Pod boiler - Pressure vessel for 600 Mwe H.P.D.H.T.R.



1. 6 blowers penetration ϕ 215 cm
2. 12 boilers penetration ϕ 225 cm
3. 3 neutron instrumentation penetration ϕ 20 cm
4. 55 control rods penetration ϕ 40 cm
5. Loading machine 10 penetrations ϕ 52 cm
6. Purification plant 4 penetrations ϕ 30 cm

- For the size and location of the penetration, refer to the 300 Mwe THTR vessel

- The boilers are the same as for the 300 Mwe THTR 12 instead of 6



To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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