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Preliminary Design of a Borax Internal Core-Catcher for a Gas Cooled Fast Reactor

Abstract

Preliminary thermal calculations show that a core-catcher appears to be feasible, which is able to cope with the complete meltdown of the core and blankets of a 1ooo MWe GCFR. This core-catcher is based on borax ($Na_2B_4O_7$) as dissolving material of the oxide fuel and of the fission products occuring in oxide form. The borax is contained in steel boxes forming a 2.1 meter thick slab on the base of the reactor cavity inside the Prestressed Concrete Reactor Vessel, just underneath the reactor core. The fission products are dispersed in the pool formed by the liquid borax. The heat power density in the pool is conveniently reduced and the resulting heat fluxes at the borders of the pool can be safely carried away through the PCRV liner and its water cooling system.

Vorläufiger Entwurf eines internen Core-Catchers mit Borax für einen gasgekühlten Schnellen Brüter

Zusammenfassung

Die vorläufigen Wärmeberechnungen zeigen, daß es möglich ist, einen Core-Catcher zu konzipieren, der die gesamte Schmelze des Cores und des Blankets eines 1000 MWe-GSB aufnehmen kann. Dieser Core-Catcher basiert auf Borax ($Na_2B_4O_7$) als Auffang- bzw. Lösemittel für den oxidischen Brennstoff und die Spaltprodukte, die in oxidischer Form vorliegen werden. Der Borax wird auf dem Boden der mit Spannbeton umfaßten Reaktorkaverne direkt unterhalb des Kerns gelagert. Die Schichthöhe beträgt 2,1 m. Die Spaltprodukte werden in der Auffangwanne in dem flüssigwerdenden Borax gelöst und verdünnt. Dadurch wird die Wärmedichte in der Auffangwanne entsprechend verringert und die resultierenden Wärmeflüsse an die Begrenzungswände über den wassergekühlten Liner des Spannbetonbehälters sicher abgeführt werden.

1. Introduction

The meltdown of a reactor core is such an improbable event in a gas breeder that it has not considered as a design basis accident [1] . However, to cover the residual risk inherent in such a hypothetical accident, catching and cooling of the molten core in a core retention device, in short "core-catcher", has been nevertheless investigated for the Gas Cooled Fast Reactor (GCFR), as well as for other reactor types.

In a GCFR the absence of large reactivity excursions and the downward direction of the cooling flow ensures that the core melt is falling on the base of the reactor cavern. The fact of knowing the position of the core melt after the accident makes the containment of the melt less difficult. The problem becomes one of cooling the decay heat in the core melt from below, for istance by means of water flowing in coils placed underneath the steel liner of the Prestressed Concrete Reactor Vessel (PCRV). For this reason we investigated the temperature and the heat flux distribution in a slab of molten GCFR core and blanket material [2,3]. The calculations were based on the experiments of Fiedler and Wille [4] and showed that the major part of the heat is radiated in the upward direction in the reactor cavern. Recent experiments of Fieg [5], although predicting rather higher temperatures in the melt confirm this result. The heat radiated from the melt has as a consequence that in two to three days all the internals of the reactor cavern, up to the directly cooled liner, fall or melt down. One has therefore to control not only the mass of about 200 tonnes formed by core and blanket material, but also the 1000 tonnes of the other internals, mainly the neutron shields. A core-catcher capable to trap the melt and avoid the upward radiation of heat was designed [1]. This consits essentially of many narrow containers cooled by water coils on their vertical walls and on the base, the containers being twice as high as the molten material contained and placed

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on the base of the reactor cavern. This solution has many draw-backs: it is expensive, requires a large number of liner penetrations for the water cooling coils in the region of the reactor cavern base, and relies on the not yet proven assumption that the major portion of the molten mass enters the containers before a considerable part of the reactor cavern internals is molten.

Other solutions have been therefore investigated. These include various emergency coolants, whose objective is not only to protect the internals of the reactor cavern but also to disperse the core melt and therefore decrease the volumetric heat production due to the fission products in the bath and the heat flux to the liner wall. The last point is the most important, because the liner, with its water cooling, constitutes the barrier to the core melt, and obviously when the heat flux increases above a certain limit the liner fails, as we shall see in more detail later in the paper. These various types of possible core-catcher are discussed in reference [6].The main solutions are:

a) The use of salt with a relatively low melting and evaporation temperature, like for instance $ZnCl_2$. The heat would be transported to the liner walls of the reactor cavern by evaporation and condensation of $ZnCl_2$. $ZnCl_2$ is compatible with the components of the melt and the other materials contained in the reactor cavern. High pressures and explosive reactions with the hot debris are avoided [7].

b) A lead slab, two meters deep, placed on the base of the reactor cavern. If we assume that, due to the high turbulence caused by the decay heat and to the small difference in density of the molten lead and of fuel pellets, the fuel is dispersed in the lead bath, then calculations show that the heat at the liner walls is always safely lower than the maximum allowable and the limitation below $\approx 1200^{\circ}C$ of maximum temperatures in the lead bath ensures that the bulk of the neutron shields inside the reactor cavern is protected against excessive temperatures [8].

c) Injection of water, either alone or in connection with lead (solution b)) or with another substance (for istance H_3BO_3, see reference [6]), appears to be a possibility. Water could be present anyway due to possible failure of the heat exchangers. It has been shown that formation of explosive oxyhydrogen gas, given by reaction of H_2, coming from water in contact with hot steel and the oxygen of the air in the reactor containment, is not possible due to the presence of helium and steam which act as dilution media [7].

With all these coolants there are still open questions and problems. For instance it is difficult to ensure that a sufficient amount of condensed $ZnCl_2$ returns on the base of the reactor cavern, thus the cooling process by evaporation and condensation may be interrupted for lack of $ZnCl_2$ in the core-catcher. With the lead bath, it is not sure that the fuel is really dispersed in the lead, furthermore steel containing some or all metallic fission products, due to its lower density, may lay on top of the lead bath radiating its heat to the neutron shields and producing dangerous local heat fluxes at the liner walls in the regions where the steel is still molten. Finally, with water injection, pressure pulses could be produced in the reactor cavern due to steam formation from contact of water with hot debris.

For these reasons we thought to use an alternative material for the core-catcher, which would be able of reliably dispersing the fuel and at the same time allow the steel containing the metallic fission products to fall on the bottom of the core-catcher in direct contact of the liner, so that it could be safely cooled and mantained in a solidified state. A reliable way of dispersing the fuel pellets would be the use of a material capable of dissolving them at relatively low temperatures and at the same time not so chemically active to attack the other materials present in the reactor cavern. Originally we thought to use B_2O_3, but experiments in our laboratory showed that the time required to dissolve UO_2 at reasonable temperatures would have been too long, so we opted for a more active material namely $Na_2B_4O_7$ usually called borax. This is a well known substance in the glass industry. It has convenient melting and boiling points (741°C and 1575°C respectively) and can dissolve large quantities of UO_2 and probably PuO_2 and the fission products in oxide form, in a relatively short time ($\simeq$ 1 hour) in the temperature range 1100-1400°C [6]. On the other hand borax is compatible with the other materials contained in the reactor cavern and it contains a strong neutron-absorbing element like boron, thus making absolutly sure that the core melt remains subcritical. Another advantage of borax is that it is soluble in water, thus making much easier the eventual removal of the dissolved core debris [6].

In the present paper we will illustrate preliminary simplified thermal calculations to try to show that a core-catcher based on borax can control the complete melt down of core and blanket of a large GCFR. As a basis for our calculations the KWU design of a 1000 MWe GCFR was used [9].

All this of course refers to an internal core-catcher, i.e. a core-catcher contained in the PCRV. Besides the internal core-catcher a GCFR with its massive concrete vessel offers the possibility of having a second line of defense. Here one would make use of the 8.7 meter thick concrete slab forming the base of the concrete pressure vessel. Recent experiment performed in Karlsruhe show that the reaction velocity of molten UO_2 and steel with concrete is relatively low (300 mm/ hour) and the melt in entrapped by the resolidified concrete which forms a glass cover over it [10]. Parallel to these, investigations are being carried out at KWU as well. Other investigations performed by Jansen and Stepnewski [11] show that the use of sacrificial materials similar to concrete, like basalts, in which the fuel is soluble, reduces the temperatures by diluting fission product decay heat generators and increasing heat transfer surface. A molten pool formed by the reactor fuel debris reaches a manageable limiting size rather than penetrating to an indefinite distance in an uncontrolled manner. Jansen and Stepnewski show that the molten pool formed by the fuel inventory of a 1000 MWe fast reactor and by the sacrificial material reaches a maximum penetration of 8.5 meter after 230 days. Jansen and Stepnewski assume a semispherical geometry for the pool, in reality Jahn and Reineke [12] show that in presence of a spherical geometry the radial heat flux on the upper edges of the semisphere is five times higher than the heat flux in the downwards direction. Accordingly the pool should, during the expansion, assume the form of an ellipsoid of revolution, which has been experimentally observed [13] and the maximum penetration in the downwards' direction should be considerably less than 8.5 meter. However, although the penetration of the molten pool is limited to a maximum, the outer layers of concrete would be subjected, as time progresses, to large temperature and temperature gradients, which would crumble the concrete. To use the concrete pressure vessel as an external core-catcher, it would then be necessary to cool the outer surface of the lower part of the concrete pressure vessel, in order to mantain intact a sufficiently thick layer of concrete. This could be done either by filling with water the lower space between concrete pressure vessel and reactor containment, or providing the outer surface of the lower part of the concrete pressure vessel with water cooling coils. In case of accident involving a gross core melt failure, plenty of time, probably many days, would be available to provide ad hoc these cooling systems.

2. Description of the Core-Catcher

Figure 1 shows the reactor cavity in the Prestressed Concrete Reactor Vessel of the 1000 MWe GCFR KWU-design. The core is hanging from the top and the helium flow through the core is in the downward direction. The core-catcher is placed underneath the core with nothing in between. In case of a melt-down accident gravity and helium flow direction both force the fuel elements to fall onto the core-catcher. In the core-catcher region no neutron shields for the liner are required, the material of the core-catcher acting itself as a neutron shield. The core-catcher is formed by seven layers of steel cubes of 30 cm side length. Each cube is filled with borax. Also the three charge pipes are filled with borax boxes during reactor operation. The boxes in the charge pipes have to be removed during the yearly fuel element charge and discharge operations. The borax boxes are separated from the liner by a layer of graphite bricks, 30 cm thick near the vertical walls of the liner and 5 cm thick near the base of the reactor cavity. The liner is made up of a 2 cm thick steel plate. If thermal calculations would show that a liner thermal insulation is required, a sufficiently thick layer of silica (SiO_2) would be placed between the graphite and the borax. During the melt-down accident, SiO_2 would be dissolved as soon as it would come into contact with the molten borax. As usual the liner is directly cooled with water coils of square cross section. In the core-catcher region, however, the cooling coils are much nearer to each other due to the large heat fluxes present at the liner wall in case of core melt down. In the figure, tentatively, a coil pitch is shown only twice the coil side.

3. Calculation of the Maximum Admissible Heat Flux in the Liner

We assume that the liner is made by steel having the following properties:

s = thickness of the liner wall = 2 cm
k = thermal conductivity = 0.23 w/cm ^{o}C
α = coefficient of linear thermal expansion = 11×10^{-6} ^{o}C^{-1}
E = Young modulus = 2.1×10^{6} kg/cm^{2}
$\sigma_{0.2}$ = yield strength = 5000 kg/cm^{2}
ν = Poisson's ratio = 0.33

The maximum admissible heat flux in the liner is limited by the thermal stress given by the temperature gradient in the liner thickness, caused by the heat flux itself. Due to stress relaxation phenomena, maximum thermal stresses equal to twice the yield strength are usually accepted, especially when, as in the present case, the stresses are not acting for a long time, or they are not at high temperatures or cyclic. The maximum admissible strain ε_{max} in the liner is therefore:

$$\varepsilon_{max} = \frac{1-\nu}{E} 2\sigma_{0.2} \tag{1}$$

On the other hand the maximum strain given by the temperature gradient ΔT across the liner wall is:

$$\varepsilon_{max} = \alpha \Delta T \tag{2}$$

while the heat flux across the liner wall is given by:

$$q = \frac{k\Delta T}{s} \tag{3}$$

From equations (1), (2) and (3) one has:

$$q = \frac{k}{s}\,\frac{1-\nu}{\alpha E}\,2\sigma_{0.2} \tag{4}$$

and using the numerical values given above

$$q = \frac{0.23}{2}\;\frac{1-0.33}{11\times10^{6}\times2.1\times10^{6}}\;2\times5000=33.4\ \text{w/cm}^2=334\ \text{KW/m}^2$$

We will see in the section 6 that the maximum heat flux through the liner wall is about 180 KW/m^2, that is safely below the above calculated admissible maximum. The heat flux of 180 KW/m^2 corresponds approximatively to a maximum thermal stress in the liner equal to the yield strength.

4. Calculation of the Liner Cooling in the Core-Catcher Region

Figures 1 shows the disposition of the cooling coils along the wall of the liner. The coils have a square cross section with outer side of 3.1 cm and a pitch of 6.2 cm. The inner side of the square cross section is 2.5 cm, and the hydraulic diameter of square duct is also 2.5 cm. Assuming that each 4 coils are connected to the headers, then the length of a single coil is:

$$l = 4\times\pi\times823 = 1.03\times10^{4}\ \text{cm}$$

With a heat flux of for instance 170 KW/m^2 = 17 w/cm^2 and a coil pitch of 6.2 cm the heat quantity to be carried away from each coil is:

$$Q = 17\times1.03\times10^4\times6.2 = 1.086\times10^6 \text{ w} = 0.259\times10^6 \text{ cal/sec}$$

Assuming a water temperature difference between outlet and inlet of the coil of 80°C = 100-20°C (remember that is necessary only in case of core gross melt-down) the water flow is:

$$M = \frac{0.259\times10^6}{80} = 3240 \text{ gr/sec} = 3240 \text{ cm}^3\text{/sec}$$

and the water velocity is:

$$v = \frac{3240}{2.5^2} = 519 \text{ cm/sec}$$

The kinematic viscosity,the thermal conductivity and the Prandtl number of water at 60°C are:

$$\nu = 0.46\times10^{-6} \text{ m}^2\text{/sec} = 0.48\times10^{-2} \text{ cm}^2\text{/sec}$$

$$\lambda = 0.575 \text{ Kcal/mh}^{\circ}\text{C} = 6.69\times10^{-3} \text{ w/cm }^{\circ}\text{C}$$

$$Pr = 2.7$$

Thus the Reynolds number in the cooling duct is given by:

$$Re = \frac{v \times D_h}{\nu} = \frac{519 \times 2.5}{0.48 \times 10^{-2}} = 2.70 \times 10^5,$$

the resulting Nusselt number:

$$Nu = 0.023\ Re^{0.8} Pr^{0.4} = 0.023(2.7 \times 10^5)^{0.8} 2.7^{0.4} = 757$$

and the heat transfer coefficient between cooling coil wall and water:

$$h = Nu \frac{\lambda}{D_h} = 757\ \frac{6.69 \times 10^{-3}}{2.5} = 2.03\ w/cm^2\ {}^oC$$

Thus the temperature difference between wall of the coil and water is:

$$\Delta T_w = \frac{2 \times 17}{2.03} = 16.7\ {}^oC$$

The friction factor for the flow of the water in the coil is:

$$f = 0.046\ Re^{-0.2} = \frac{0.046}{(2.7 \times 10^5)^{0.2}} = 3.77 \times 10^{-3}$$

Thus the friction pressure drop in the coil is:

$$\Delta p = \frac{4l}{D_h} f \frac{\rho v^2}{2} = \frac{4\times1.03\times10^4}{2.5} 3.77\times10^{-3} \frac{1\times519^2}{2} = 8.37\times10^6 \text{ dyne/cm}^2 =$$

$$= 8.26 \text{ Atms}$$

Assuming a total heat to be carried away of 20 MWth (see section 5 and 6), the total required cooling water flow is:

$$M_t = \frac{20\times10^6}{4.186\times80} = 59720 \text{ gr/sec} = 59720 \text{ cm}^3\text{/sec}$$

(this means 59720:3240≈18 coils in parallel) and the required water pumping power is:

$$P_t = \frac{M_t \Delta p}{\eta} \simeq \frac{5.97\times10^4\times8.37\times10^6}{0.7} = 7.1\times10^{12} \text{ erg/sec} = 71 \text{ KW}$$

where $\eta = 0.7$ is the efficiency of the pump.

All the above calculated values appear to be reasonable and the cooling of the liner for a heat flux of 170 KW/m^2 appears to be feasible.

5. Transient Thermal Calculations for the Initial Phase After Core Melt-Down

For the preliminary thermal design of the core-catcher we will make the following simplifying assumptions:

a) The whole core and the lower axial blanket fall coherently onto the core-catcher and spread uniformly over a circle of 4 meters in diameter (diameter of the core = 3 meters)

b) After about ten minutes the upper axial blanket and the radial blanket fall onto the core-catcher over a diameter of 4.6 meters (diameter of the core + radial blankets = 4.2 meters)

c) The decay heat of the fission products contained in the fuel and in the steel is generated in the first row of borax boxes corresponding to a cylinder of 4 meters in diameter, and it is used to heat up and melt the borax. Heat losses by radiation in the reactor cavity and by conduction to the adjacent boxes as well as the heat capacity of the steel walls of the boxes are neglected.

d) When the temperature of the considered cylinder has reached the melting point of steel ($1700^{o}K=1427^{o}C$) the steel walls of the boxes fail and the melt comes into contact with the borax of the adjacent boxes both in the sideward and downward direction (we will see in the section 6.2 that this assumption appears to be legitimate).

The initial average temperature of the borax bed will be the average between helium core inlet temperature ($320^{o}C$ [9]) and the outer temperature of the graphite liner, assumed to be $40^{o}C$, i.e. $180^{o}C$. The melting point of borax is $741^{o}C$ [6]; the heat of fusion is:

$$19.4 \text{ Kcal/Mol} = \frac{19400}{201.22} \text{ cal/gr} = 96.4 \text{ cal/gr} = 403.5 \text{ wsec/gr}$$ [14]

while the specific heat between 180°C and 741°C is:

$$0.4163 \text{ cal/gr } ^{\circ}\text{C} = 1.743 \text{ wsec/gr}^{\circ}\text{C}$$ [15]

and the specific heat of liquid borax is:

$$\frac{106.33}{201.22} = 0.5284 \text{ cal/gr}^{\circ}\text{C} = 2.212 \text{ wsec/gr}^{\circ}\text{C}$$ [15]

Thus the heat necessary to bring 1 gr of borax from 180°C to 1427°C is:

$$1.743(741-180)+403.5+2.212(1427-741) = 2899 \text{ wsec/gr}$$

The density of liquid borax is 2.04 gr/cm^3 [14], therefore the amount of heat required to bring the first cylinder of 4 meter diameter and 30 cm deep (30 cm is the height of a box) to the melting point of steel is:

$$2899\times\frac{\pi}{4}\, 400^2\times30\times2.04 = 2.23\times10^{10} \text{ wsec}$$

The core contains 14.5 t of steel and 29.8 t of oxide fuel, the lower axial blanket 5.8 t of steel and 13.0 t of oxide [9]; the average temperatures at the time of melt-down are estimated to be:

steel core = 800°C
fuel core = 1700°C
lower blanket steel = 1000°C
lower blanket oxide = 1200°C

and the heat required to bring these masses to the melting point of stainless steel is:

$$10^6[29.8(1427-1700)+13(1427-1200)]\,0.31+10^6[14.5(1427-800)+ +5.8(1427-1000)]\,0.5=0.42\times 10^{10}\text{ wsec}$$

where the specific heat of UO_2 and steel have been taken as 0.31 and 0.5 wsec/gr°C respectively.

In total the heat required is then:

$$(2.23+0.42)\times 10^{10} = 2.65\times 10^{10}\text{ wsec}$$

The total thermal output of the reactor is 2700 MWth = 2.7×10^9w [9]. Assuming with reference [16] that 80% of the decay heat is given by the fission products contained in the fuel and in the steel, then the ratio of the integrated fission product power to the time t_1, at which the first borax cylinder has reached the steel melting point, to the total reactor thermal power is:

$$\frac{\int_0^{t_1} P dt}{P_o} = \frac{2.65\times 10^{10}}{0.8\times 2.7\times 10^9} = 12.3\ \frac{\text{wsec}}{\text{w}}$$

This corresponds to a time t_1 of 620 sec after reactor shutdown for a fuel which has been subjected to one year irradiation [17].

During the melting of the second layer of boxes we assume that the upper axial blanket and the radial blanket fall onto the core-catcher. The masses are [9] :

	rad. blanket	upper ax.blanket
oxide	98.6 t	13.0 t
steel	27.5 t	5.8 t

and the average temperatures: oxide $\simeq 1000^{\circ}C$, steel $\approx 800^{\circ}C$.

The heat required to bring those masses to the melting point of steel is therefore:

$$111.6\times10^{6}\times0.31(1427-1000)+32.8\times10^{6}\times0.5(1427-800)=2.51\times10^{10}\ \text{wsec}$$

and the heat required by the borax boxes of the second layer is:

$$2899\times2.04\times\frac{\pi}{4}\left[460^{2}\times60-400^{2}\times30\right]=3.68\times10^{10}\ \text{wsec}$$

In total the heat required to bring the core, the blankets and the first two layers of borax boxes to the melting point of steel is:

$$(3.68+2.51+2.65)10^{10}=8.84\times10^{10}\ \text{wsec}$$

And the ratio integrated fission product power to total reactor power becomes:

$$\frac{\int_{o}^{t_2} Pdt}{P_o} = \frac{8.84\times10^{10}}{0.8\times2.7\times10^{9}} = 40.9\ \frac{wsec}{w}$$

With reference [17] this corresponds to a time t_2 after reactor shut-down of 2900 sec. The calculation can be repeated for each layer of boxes. Figure 2 shows the various layers and the time necessary for each layer to reach the melting point of steel. After t_7 = 36000 sec, i.e. ten hours, all the borax boxes have reached this melting point. In reality, this time will be considerably greater because a large amount of heat gets lost by conduction through the liner walls and by radiation from the catcher surface. At the time t_7=36000 sec the power produced by the fission products is 0.96 % of the nominal reactor power [17] i.e.:

$$2700\times0.8\times0.0096 = 20.7\ MW.$$

At this point it should be noticed that the use of steel boxes has been not only chosen for construction purposes, but mainly to provide high melting point barriers to the downward movement of the fuel. To dissolve UO_2 in a reasonable time, borax requires temperatures above 1000°C [6], while the melting point of borax is 741°C only. Therefore these barriers are required to allow UO_2 and borax to remain in contact for a sufficient time at sufficiently high temperatures. A temperature of 1427°C is not necessary, at 1300°C the process of dissolution of UO_2 in borax is fast and complete [6], so stainless steel could be replaced by a lower melting point material (for instance cast iron: melting point ≃1300°C), especially if at this temperature the evaporation of borax would be excessive (the evaporation point of borax is 1575°C [6]).

6. Steady State Thermal Calculations at the Time When the Melt Reaches the Graphite Layer.

Experimental information on heat transfer correlations for natural convection with volumetric heat production in a finite cylinder is presently not available to us. We decided therefore to perform the calculations in two steps. First we calculate the heat transfer to the vertical walls of the graphite layer protecting the liner with the usual correlation valid for natural convection to vertical walls, but without volumetric heat production. Then we calculate the heat flux to the upper and lower surfaces of the bath with the heat transfer correlation valid for natural convection with volumetric heat production in an infinite slab. This procedure requires an initial arbitrary splitting of the heat produced between vertical and horizontal walls. The calculation must be repeated until the bulk temperature of the bath calculated from both sides is the same. In the paper we will show only the last iteration of the calculation.

6.1. Heat Transfer to the Lateral Vertical Walls of the Bath

The temperature of the bulk of the borax bath at the time of the calculation (t=36000 sec after melt-down) is the melting point of steel: $T_B=1427^oC$. The last iteration of the calculation results in a temperature at the interphase bath/vertical graphite wall of 1320^oC, and the film temperature of the borax bath is:

$$T_{\text{borax film}} = \frac{1427+1320}{2} = 1373.5\ ^oC$$

The heat transfer coefficient to the vertical walls is given by:

$$Nu_V = 0.15\ Ra_V^{1/3}\ [18] \tag{5}$$

where:

$$Nu_V = \frac{hL}{\lambda}$$

$$Ra_V = \frac{g\beta\rho^2 c}{\mu\lambda} L^3 (T_B - T_W) \tag{6}$$

and

h = heat transfer coefficient between bath and wall [$w/cm^2\ ^oC$]

L = height of the bath = 210 cm

g = acceleration of gravity = 981 cm/sec^2

T_W = temperature of the wall of the bath = 1320^{o}C

T_B = temperature of the bulk of the bath = 1427^{o}C

$\rho(1373.5^oC)$ = bath density = 2.04 gr/cm^3 [14]

$c(1373.5^oC)$ = bath specific heat = 2.212 wsec/gr ^{o}C [15]

$\lambda(1373.5^oC)$ = bath thermal conductivity = 0.084 w/cm ^{o}C (see fig.3, Ref. [20])

$\mu(1373.5^oC)$ = bath dynamic viscosity = 1.73 gr/cm sec (see fig.4, Ref. [21])

$\beta(1427^oC)$ = coefficient of volumetric thermal expansion of the bath = $1.96\times10^{-4}\ {}^oK^{-1}$ (see fig.5, Ref. [22])

where the bath physical properties have been taken as the properties of liquid borax at the film temperature, with the exception of the coefficient of volumetric thermal expansion which has been evaluated at the bulk temperature of the bath.

From equations (5) and (6) one has:

$$h = 0.15\,\frac{\lambda}{L}\left[\frac{g\beta\rho^2 c}{\mu\lambda}\,L^3\,(T_B-T_W)\right]^{1/3} =$$

$$= 0.15\,\frac{0.084}{210}\left[\frac{981\times1.96\times10^{-4}\times2.04^2\times2.212\times210^3\times107}{1.73\times0.084}\right]^{1/3} =$$

$$= 6\times10^{-5}\times\left[1.207\times10^{10}\right]^{1/3} = 0.138\ \mathrm{w/cm^2\ {}^oC}$$

and the heat flux at the wall is:

$$q = h(T_B-T_W) = 0.138(1427-1320) = 14.7\ \mathrm{w/cm^2} = 147\ \mathrm{KW/m^2}$$

The inner diameter of the liner in the reactor cavity is 820 cm [9]. Assuming a graphite layer thickness of 30 cm (see calculation below) the surface of the vertical walls of the bath is given by

$$2.1\times\pi\times(8.20-0.60) = 50.1\ \mathrm{m^2}$$

and the total heat flux to the vertical walls is:

$$Q_V = 50.1\times147 = 7370\ \mathrm{KW} = 7.37\ \mathrm{MW}$$

With a heat flux of 14.7 w/cm^2 the outer temperature of the steel liner is:

$$T_1 = 120 + \frac{14.7\times 2}{0.23} = 248\ ^{o}C$$

and the thickness of the graphite protective layer required to have 1320 ^{o}C at the interface graphite/bath is:

$$s = \frac{(1320-248)0.416}{14.7} = 30\ cm$$

where k_g=0.416 w/cm ^{o}C is the thermal conductivity of the graphite used (EYX60 graphite, the value given is an average between the values of thermal conductivity for the direction parallel and perpendicular to the extrusion direction [19]).

6.2. Heat Transfer to the Horizontal Walls of the Bath

In section 5 we have shown that the heat to be carried away from the bath at the time t=36000 sec, when the bath is supposed to have reached the graphite layer, is 20.7 MW. Of this heat, according to reference [16] $\frac{0.5}{0.8}20.7 = 12.93$ MW are produced in the fuel and 20.7-12.93 = 7.77 MW in the steel. In the previous section 6.1 we have calculated that the vertical walls of the bath take 7.37 MW, thus the horizontal walls of the bath must take the rest = 12.93-7.37 = 5.56 MW.

For the internal and external Rayleigh numbers of the bath with volumetric heat production under consideration Fieg shows that for an infinite slab 85% of the heat produced goes to the upper horizontal surface and 15% to the lower [23]. The upper surface of the bath must therefore radiate away: 0.85×5.56 = 4.73 MW of heat. Figure 6 shows the heat radiated from the pool surface Q_r as a function the surface temperature T_1. Q_r has been calculated with the grey body radiation equation, assuming that the radiating surface has an emissivity of 0.9 (value of UO_2 at higher temperatures, borax is transparent) and that the heat receiving surface is at a temperature $T_2=1000^oK$. The heat receiving surface is taken equal to the rest of the pressure vessel reactor cavity and with an emissivity coefficient typical of steel ($\varepsilon_2=0.4$). For $Q_r=4.73$ MW, the resulting pool surface temperature is $1320^oK = 1047^oC$. The pool bulk temperature is again 1427^oC, thus the film temperature is:

$$T_{film} = \frac{1427+1047}{2} = 1237^oC$$

and the relevant properties of the bath are:

$\rho(1237^oC) = 2.04$ gr/cm^3 [14]
$c(1237^oC) = 2.212$ wsec/gr^oC [15]
$\lambda(1237^oC) = 0.074$ w/cm ^oC (fig.3, Ref.[20])
$\mu(1237^oC) = 4.0$ gr/cm ^oC (fig.4, Ref.[21])
$\beta(1427^oC) = 1.96\times10^{-4}$ K^{-1} (fig.5, Ref. [22])

For natural convection in an infinite slab with volumetric heat production the data of Fieg [5] can be correlated by the following relationship:

$$M = \frac{\frac{q_vL^2}{8\lambda}}{T_B-T_W} = 0.285\ Ra_{int.}^{0.18} = 0.285 \left[\frac{g\beta\rho^2cL^3}{8\mu\lambda}\ \frac{q_vL^2}{8\lambda}\right]^{0.18} \qquad (7)$$

in the range $6\times10^5 \leq Ra_{int.} \leq 3\times10^8$

where

q_v = volumetric heat production in the bath [w/cm^3]
M = ratio of the hypothetical temperature difference which one would obtain by heat conduction only to the temperature difference by convection
$Ra_{int.}$ = internal Rayleigh number based on the volumetric heat production

With the above data and with $q_v = \frac{12.93\times10^6}{\frac{\pi}{4}760^2\times210}$=0.136 w/cm^3(the total heat 12.93 MW is considered, because in the central portion of the pool the whole heat is going away in vertical direction) one has:

$$\frac{q_v L^2}{8\lambda} = \frac{0.136\times210^2}{8\times0.074} = 10131\ ^oC$$

$$Ra_{int.} = \frac{981\times1.96\times10^{-4}\times2.04^2\times2.212\times210^3}{8\times4\times0.074}1013=7.01\times10^{10}$$

and

$$T_B-T_W = \frac{10131}{0.235\times(7.01\times10^{10})^{0.18}} = 397\ ^oC$$

This temperature difference agrees approximately with the temperature difference assumed at the beginning of this calculation (1427-1047=380^{o}C) and the iteration calculation can be considered sucessfully terminated.

At the time t=36000 sec, the steel is supposed to lay on the bottom of the pool in direct contact with the graphite protective layer. As mentioned in section 5 the total amount of steel from the core and blankets is 53.7 tonnes [9]. The density of solid steel is 7.9 t/cm^3, thus the volume of the steel layer is:

$$V_s = \frac{53.7}{7.9} = 6.80\ m^3$$

the free surface of the bottom of the catcher is $\frac{\pi\times7.60^2}{4}$=45.4 m^2, and the thickness of steel layer is:

$$s_s = \frac{680}{45.4} = 0.15\ m = 15\ cm$$

The heat produced by the fission products dissolved in the steel is given by 20.7-12.93 = 7.77 MW. Furthermore 15% of the heat produced in the fuel dissolved in the borax pool, which is transported away from the pool in the vertical direction, goes downwards through the steel layer: 0.15×5.56=0.834 MW. The resulting temperature drop in the steel layer is:

$$\Delta T_s = \frac{7.77\times10^6}{6.8\times10^6}\,\frac{15^2}{2\times0.233} + \frac{0.834\times10^6}{6.8\times10^6}\,\frac{15^2}{0.233} = 552+118 = 670^\circ C$$

And the total heat flux to the catcher bottom is:

$$q_b = \frac{(7.77+0.834)\,10^6}{45.4\times10^4} = 19.0\ \mathrm{w/cm}^2$$

The outer temperature of the steel liner is then:

$$T_1 = 120 + \frac{19\times2}{0.23} = 285^\circ C$$

and assuming a 5 cm thick graphite liner, the temperature on the lower side of the steel layer is:

$$T_g = 285 + \frac{19\times5}{0.416} = 513^\circ C$$

while the maximum temperature in the steel is 513+670=1183°C (The steel is solid as it was assumed). 1183°C is also the temperature of the lower side of the borax pool. We calculated above that the temperature of the upper surface of the pool is according to the definition of reference [23]:

$$Ra_{ext.} = \frac{g\beta\rho^2 cL^3}{\mu\lambda}\,\Delta T = \frac{981\times1.96\times10^{-4}\times2.04^2\times2.212\times210^3}{4\times0.074}(1183-1047) =$$

$$= 7.53\times10^9$$

with a $Ra_{int.} = 7.01\times10^{10}$, i.e. an order of magnitude greater, the assumption that the heat going upward is 85% of the total is justified [23].

The heat flux to the bottom of the pool (19 w/cm^2) is not very different from that calculated for the vertical walls of the pool (15 w/cm^2), and if one assumes that this occurs in the single boxes as well, then the assumption d) of section 5 appears to be legitimate.

7. Conclusions and Future Work

The preliminary thermal calculations shown in the paper indicate that a core-catcher, capable to cope with the complete melt-down of the core and blankets of a 1000 MWe GCFR and based on borax as dissolving material of the fuel and oxide fission products, appears to be feasible. The borax slab is placed on the base of the reactor cavity inside the Prestressed Concrete Reactor Vessel, and thus constitutes an internal core-catcher. The 8.7 meter thick lower slab of the PCRV could be used as a second line of defense in case of gross reactor melt down and thus give the possibility of having an external core-catcher as well, providing that some sort of cooling for the lower outside surface of the PCRV is provided.

There are however still some open questions and problems before a core-catcher based on borax can be deemed to operate reliably. In particular the following points should be clarified by further work:

a) How the relevant physical properties of liquid borax, and in particular the viscosity are affected by UO_2, PuO_2 and the oxides of the fission products dissolved.

b) If sufficient time and sufficient contact surfaces are available to the oxides in the borax boxes to be dissolved in the liquid borax.

c) If an unduly high amount of borax evaporates away at $1427^{\circ}C$. In this case one could use cast iron (melting point $\approx 1300^{\circ}C$) as material for the box walls.

d) Better heat transfer correlations should be made available, valid for cylinder geometries with internal heat production.

e) The cooling of the borax core-catcher during normal operation conditions with helium at core inlet temperature should be designed (In principle this should be the same design as for the presently foreseen lower neutron shields)

f) It should be clarified if the borax slab can act effectively as neutron shield for the liner in place of the usual graphite-steel neutron shields (In the mean time information from General Atomic is available, which shows that the borax slab is even better a neutron shield than the normal shields foreseen now).

g) It should be clarified if a thermal insulation formed by a SiO_2 slab on the inner side of the graphite layer is required to reduce the heat losses during normal operation. The SiO_2 would be quite effectively dissolved as soon as it comes in contact with liquid borax.

h) The compatibility of borax with materials which would possibly be available inside the reactor cavity should be further investigated.

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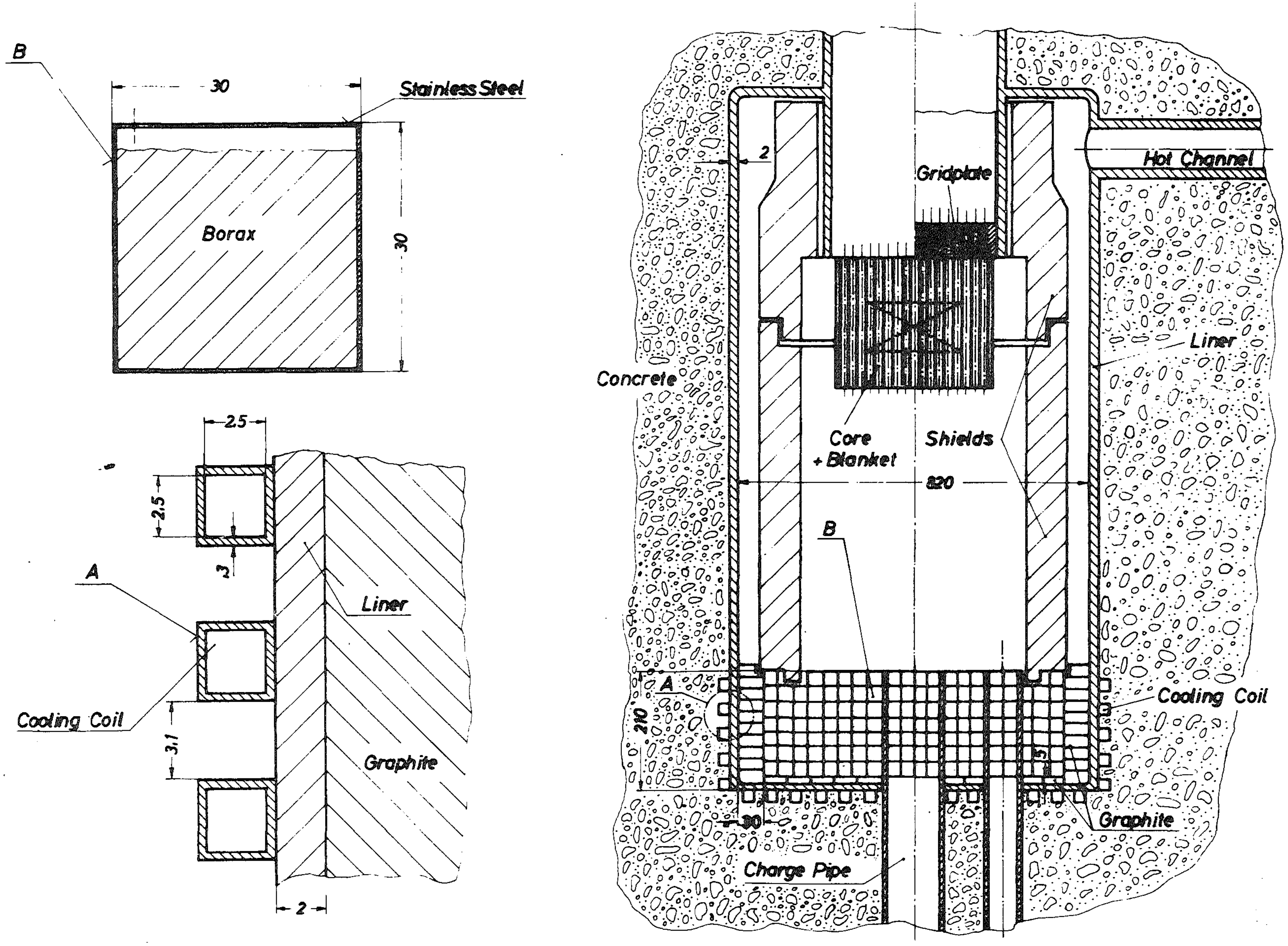

Dimensions in Centimeters

Dimensions in Centimeters

Fig.1: Core-catcher lay-out inside the reactor cavity of the Prestressed Concrete Reactor Vessel.

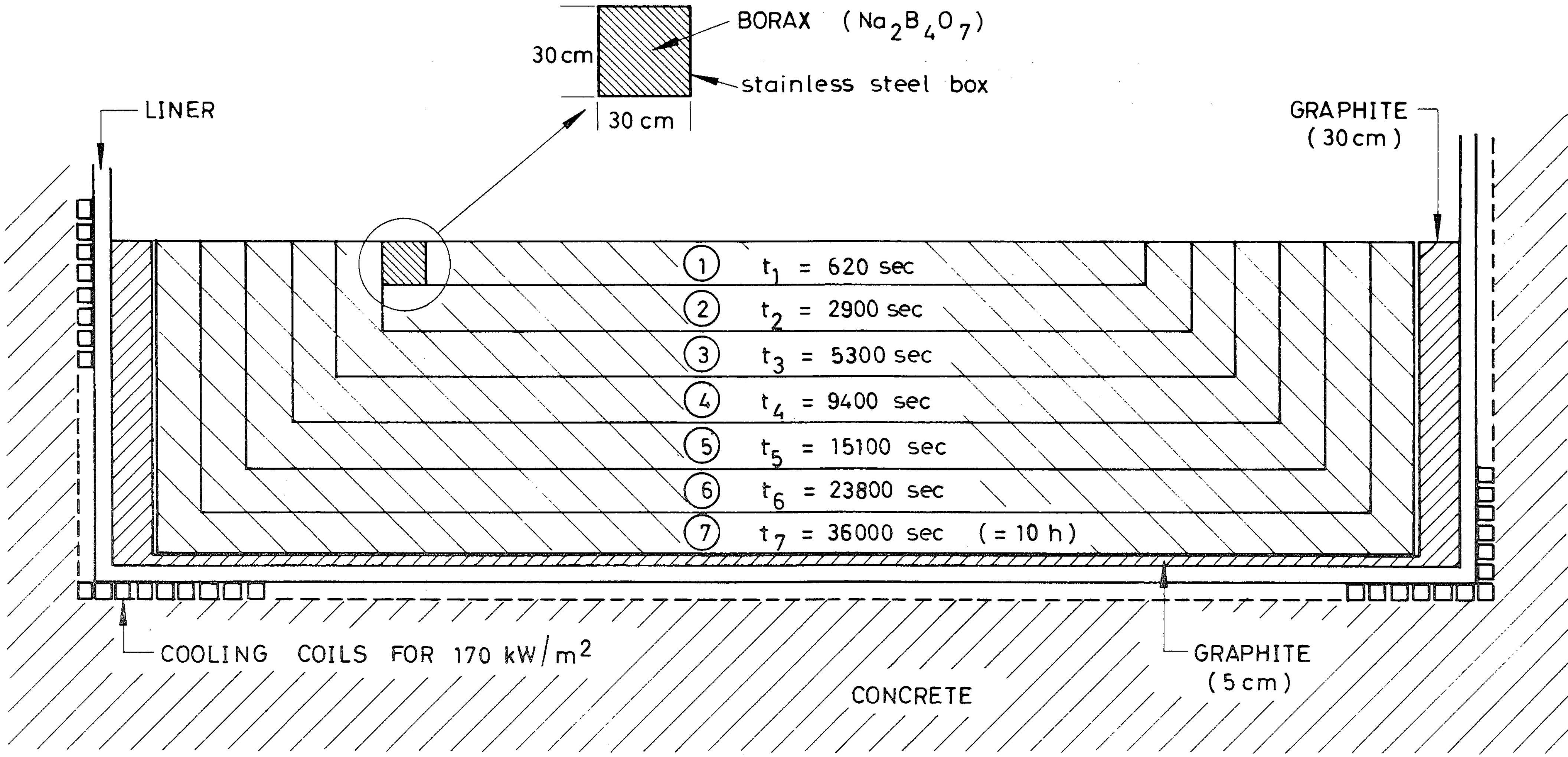

Fig.2: Core-catcher. Melting time of the various rows of borax boxes.

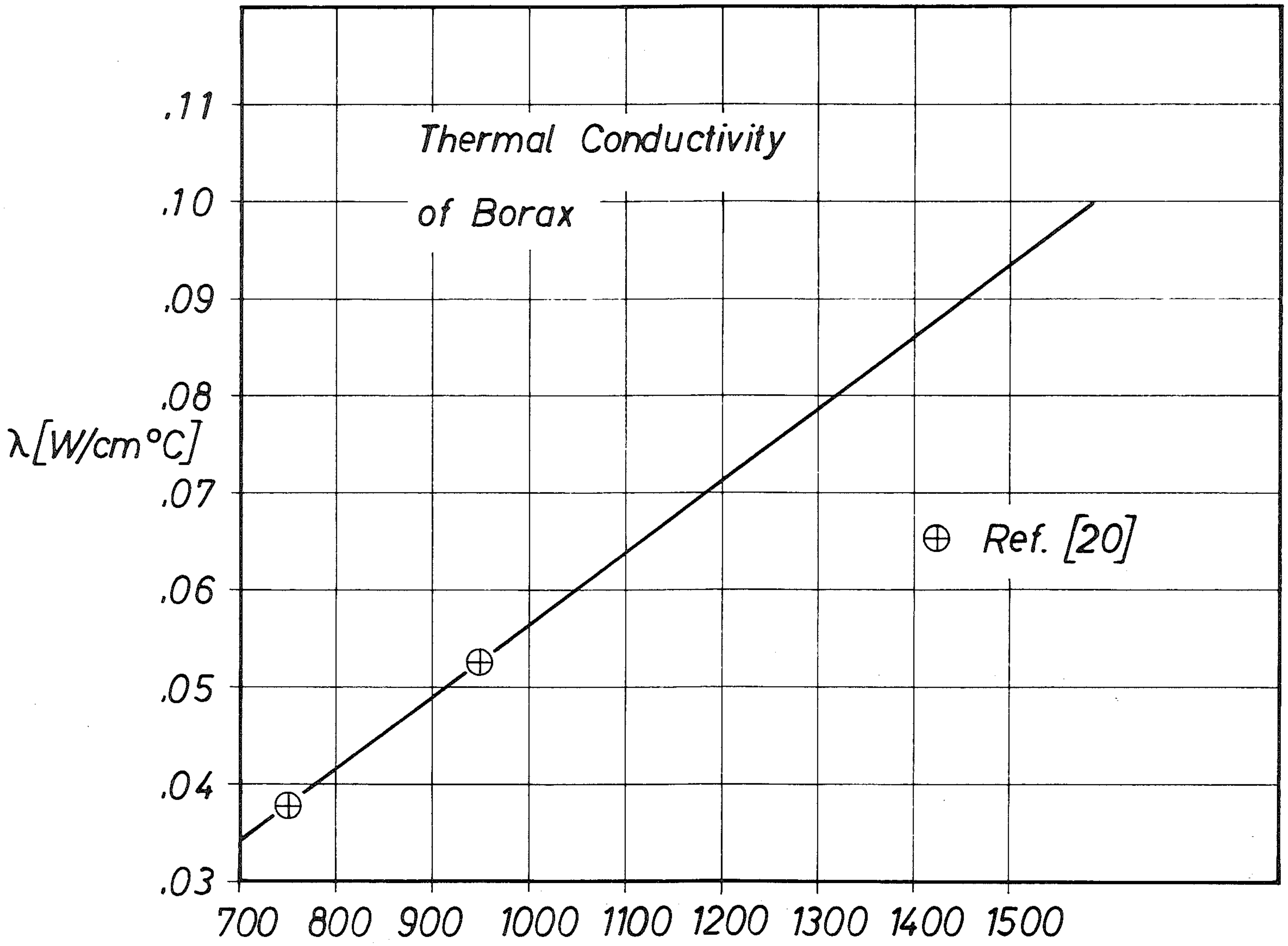
Thermal Conductivity
of Borax
⊕ Ref. [20]
λ[W/cm°C]
.11
.10
.09
.08
.07
.06
.05
.04
.03
700
800
900
1000
1100
1200
1300
1400
1500
T(°C)

Fig. 3

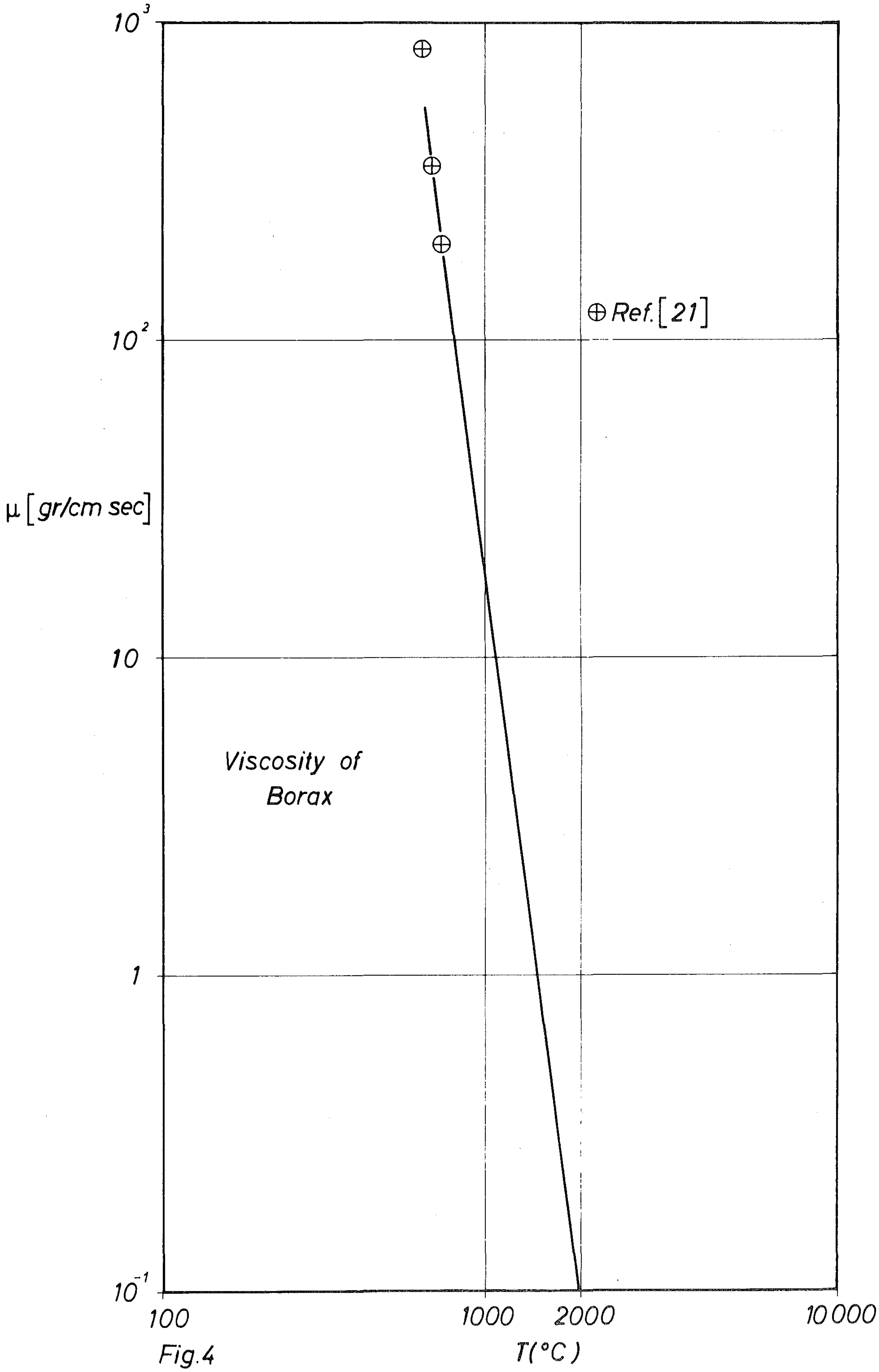
10^3
10^2
10
1
10^{-1}
μ [gr/cm sec]
⊕ Ref. [21]
Viscosity of Borax
100
1000
2000
10000
T(°C)

Fig.4

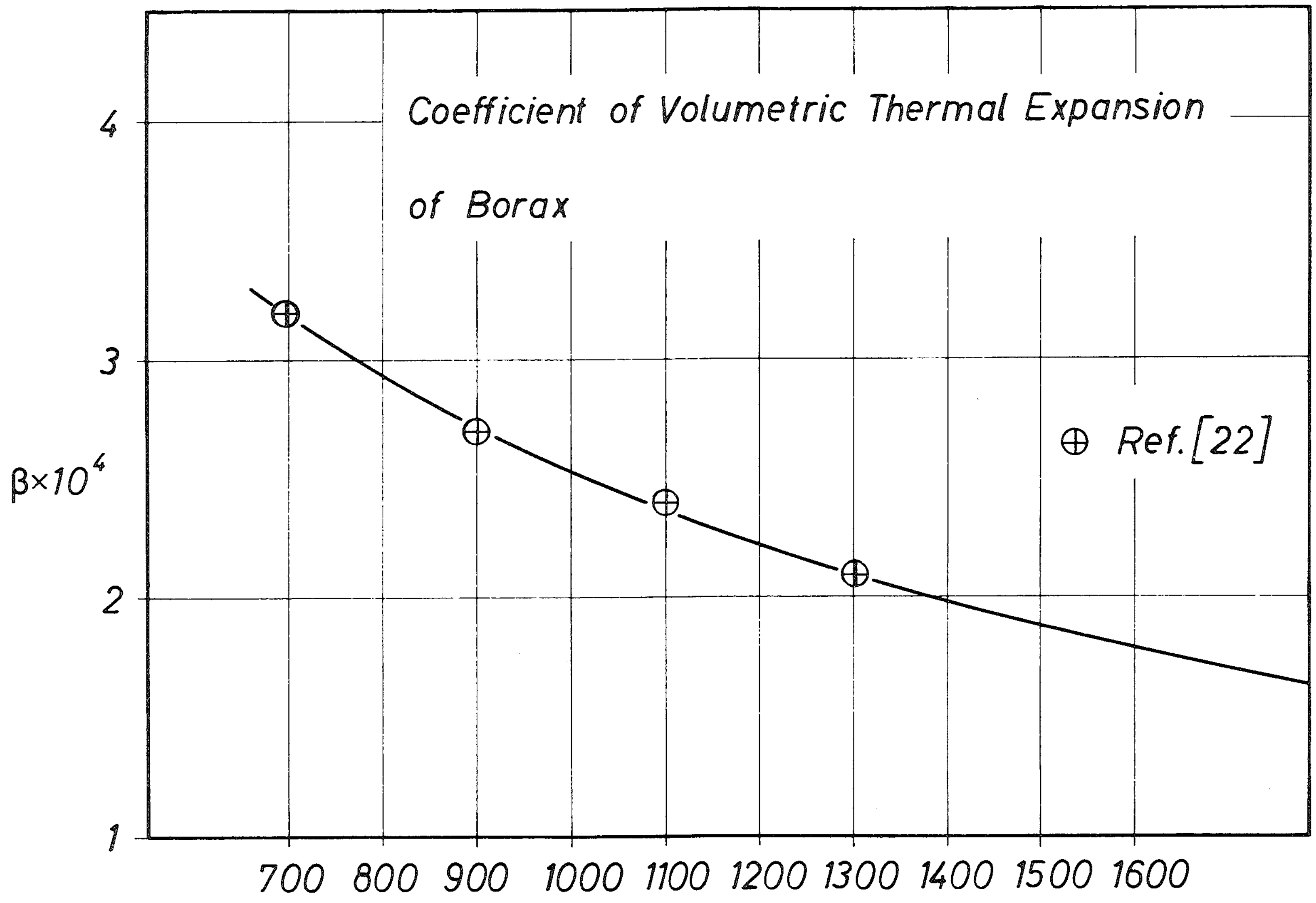
Coefficient of Volumetric Thermal Expansion
of Borax
⊕ Ref.[22]
$\beta \times 10^4$
4
3
2
1
700
800
900
1000
1100
1200
1300
1400
1500
1600
T(°C)

Fig.5

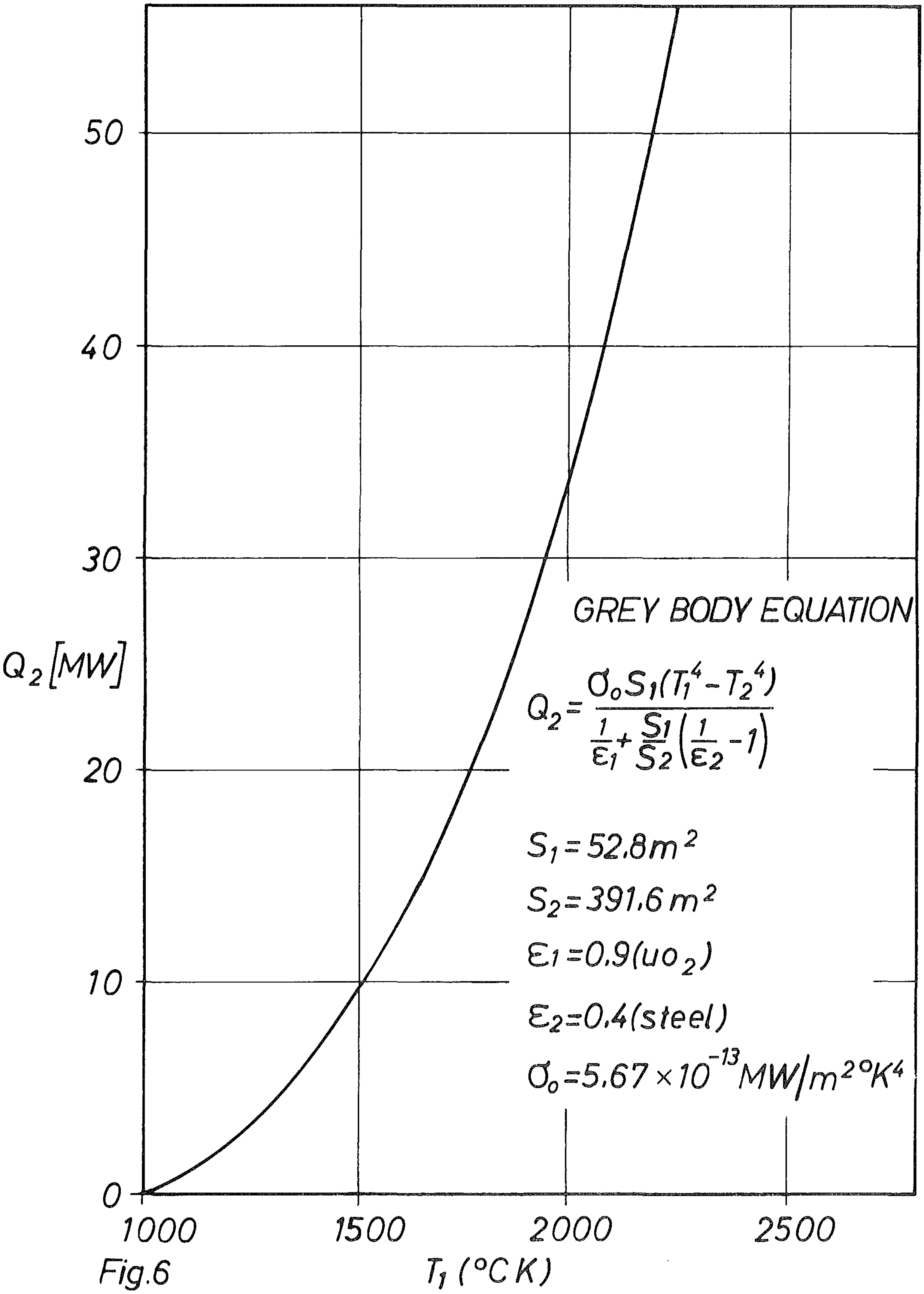
50
40
30
20
10
0
Q_2 [MW]
1000
1500
2000
2500
T_1 (°C K)
GREY BODY EQUATION
$Q_2 = \frac{\sigma_0 S_1 (T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{S_1}{S_2}\left(\frac{1}{\varepsilon_2} - 1\right)}$
$S_1 = 52.8 m^2$
$S_2 = 391.6 m^2$
$\varepsilon_1 = 0.9 (uo_2)$
$\varepsilon_2 = 0.4 (steel)$
$\sigma_0 = 5.67 \times 10^{-13} MW/m^2 °K^4$

Fig.6