THERMAL INSULATION OF THE HIGH-TEMPERATURE HELIUM-COOLED REACTORS

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I. INTRODUCTION

Nowdays the high-temperature helium reactors (HTGR) seem to be the most efficient sources for a complex production of electric and high-temperature heat /1/. Such industries as metallurgy, chemical technology, hydrogen production and others require reactors with a coolant temperature of 800-1000°C and higher. So high temperatures approach and even exceed the boundary of normal operation of many materials. Therefore it is necessary to provide relevant thermal insulation of hot surfaces of reinforced concrete vessels, steel pipes reactor auxiliary equipment an in some cases the core to ensure operability of the structures and reduce heat losses. This allows to prevent the structure materials subject to high pressures from being affected by high temperatures and thus ensures their reliable and long-term operation. In its turn, reduction of heat losses results rising the efficiency of the entire unit and provides the possibility of supplying high-temperature heat to consumers.

Unlike the well-known thermal insulation methods, development of HTGRs rises quite new problems. To understand these problems, let us consider behaviour of thermal insulation inside the helium circuit of HTGR and requirements imposed on it.

2. GENERAL REQUIREMENTS

One of the important indices of heat insulation efficiency is thermal conductivity of the material or structure used for this purpose. In a number of cases this parameter is decisive but far from being the only one. For practical aims choice of the heat-insulating material or structure is connected with a complex of requirements imposed depending on the operation conditions and specific character of the object to be insulated.

We shall confine ourselves with mentioning of the traditional requirements: low thermal conductivity; technological effectiveness in production, assembling and disassembling; convenient transportation, low volume density; non-combustibility; resistance to corrosion; low hydroscopicity, low permeability to water, non-toxicity, commercial production, low cost.

Of special interest are the HTGR thermal insulation life which may be 30 years and helium medium inside the HTGR gas circuit.

Helium is one of the high thermal conductivity gases. With the exotic insulation versions, such as vacuum or gas-filled blankets not taken into account, the thermal conductivity of stagnant helium quite sufficient for heat insulation purposes should be a limit which must be aimed at when developing the thermal insulation for HTGRs.

Possibility to approach the thermal conductivity of stagnant helium is confirmed experimentally. Thus, the thermal conductivities stainless steel foils (stalfol, screen thickness 0,1, gap 1mm)/2/ or quartz cloth packet (thickness 0,4 mm, density $340 g/m^2$, fibre diameter 6-8 μ) are only 10-30% higher (Fig.1, curves 1 and 2), It is far more difficult to obtain such a low thermal conductivity for foam materials. Even zirconium dioxide with the cerium dioxide fillers, in the case of directed channel porosity, (E=65%, pore diameter 500 μ) has a thermal conductivity 3-4 times higher than that of stagnant helium (Fig.1, curves 3).

Unlike the vacuum for screen insulation (stalfol), in the helium medium somewhat unusual regularities can be also observed. A positive effect with increasing the number of screens is observed only until the natural convection of the gas is stopped (Fig.2, section a-b). Further addition of the number of screens on a fixed thickness of the insulation layer results in a monotonous increase in the effective thermal conductivity (section b-c). This is due to the circumstance that in the helium medium the contribution from the radiative component is relatively small up to 1000°C (the case of thermal insulation inside a 200 mm diam. pipe with a radial flux of 5 KW/m, screen thickness 200 μ has been considered). In addition, with an increase in the screen number, the gas volume is substituted by the metal having a higher heat conductivity (by about two orders of magnitude).

It is evident that for a real construction the effective thermal conductivity can only rise due to heat escape by the fitting and spacing grid.

3. GAS DYNAMICAL REQUIREMENTS

The main feature of the HTGRs is application of helium coolant at high pressures (Table I). The dynamical change in the helium pressure from the operating to atmospheric one and back can reach 10^2 and 10^3 cycles for the lifetimes of 3 and 30 years, respectively.

Reactor	AVR (FRG)	Dragon (Great Britain)	UHTREX (USA)	Fort Saint Vrain (USA)	ВГ-400 project (USSR)	ВГР-[illegible] project (USSR)
Coolant pressure kg/cm^2	10	20	35	49	50	160

In the case of emergency loss of sealing in the helium circuit the maximum rates of change in the gas pressure may be 1-3 (average over the volume) and up to 10-30 kg/cm^2/sec (local).

Helium high pressure, variations of helium pressure under various operating conditions or emergency situations as well as periodic pressure fluctuations and associating noises resulting from change in the hydraulic resistance of the channels, should not cause rupture of the thermal insulation or its displacement because of pressure gradients produced.

Foils in the stalfol packet type thermal insulation can be crumpled, broken and taken away. This can be avoided by choice of an appropriate foil thickness, more reliable fittings and provision of special clear openings. It is necessary not to permit a significant increase in the thermal conductivity of the insulating layer because of heat escape by the metal and arising of convective gas flows. To calculate theoretically the convection contribution is simple only for the elementary geometry, but for actual complicated constructions this problem is far from being trivial.

A disadvantage of fibrous materials is dust and its possible formation. The initial amount of dust is removed sufficiently rapidly by fluctuations of the gas pressure (Fig.3, curve 1). But with increasing gas pulsation level, vibrations and noises, the amount of newly formed dust which penetrates into the gas circuit may rise (curves 2,3) and at the worst cause a complete distruction of thermal insulation (curve 4).

Shrinkage of the fibrous material is also possible. Strain behaviour in applying compression load through a solid surface is well studied. The process of shrinkage of the fibrous material is most intense of the first moment (Fig.4). A similar dependence with a characteristic saturation is also observed in the increase of the compression load (Fig.5). Shrinkage will be then the less the higher is the initial density γ_o of the fibrous material (for Figs.4 and 5 γ_o =65 kg/m^3).

The temperature rise, as a rule, affects the strain, increasing it. For example, shrinkage of a silica fibre plate (initial density 65 kg/m^3), with the compression load of $2\ 10^4$ N/m^2, changes almost linearly with a temperature rise (at 20°C $\Delta\ell/\ell \approx 40\%$, at 1000°C - 60%.

Shrinkage behaviour for cyclic variations of the gas pressure inside the fibrous material itself is to be investigated.

For the foam materials the dynamical variations of the pressure result in some additional inner stresses because of equalization of the gas pressure inside and outside the specimen. Possibility of breaking the specimen to smaller parts (Fig.6 curve 2), even to powder, (cur.3) is not excluded. Invariability of the geometry is characterized by equality of the initial, L_o , and final, L_K sizes of the specimen (cur.1) and can be ensured either choosing sufficiently strong materials or preliminary cutting the specimen to smaller parts

In the calculation of the dependence $L_K/L_o = f\,(dP/d\tau)$ the values of the material gas permeability are used. According to the estimations equalization of the pressure in the foam materials with open porosity takes about 1-1 10^{-3} sec; and for that with closed porosity about 10^2-10^4 hour. In the latter case the pressure drop proceeds practically stationarily.

Taking into account the gas dynamical pressure fluctuations, application of thermal insulation of all types requires taking special measures for their local rotention. Possible effect of periodic pulsations of helium pressure on the thermal conductivity of the thermal insulation is to be studied.

4. THERMOPHYSICAL REQUIREMENTS

The maximum working temperatures of the helium coolant both in the operating devises and those to be developed are shown in Table 2.

Table 2.

Reactor	БГР-300	Dragon	Fort Saint Vrain	AVR	ВГ-400	UHTREX
Helium temperature at the outlet, °C	650	750	785	950	950	1320

The cyclic variation of the temperature from the maximum to room and back may reach up to 10^2 and 10^3 cycles for the lifetime of about 3 and 30 years, respectively. The working temperature variation rates are lower than 1-3°C/sec; emergency ones - up to 10-30°C/sec. The stationary temperature drops on the thermal insulation layer are close to the maximum coolant temperatures. Under such operation conditions the thermal insulation should withstand stationary temperature gradients and cyclic heat fluctuations and to keep its thermal stability.

During the first hundreds and even thousands of hours of operation at the nominal temperature level, a noticeable gas release will be observed in the thermal insulation materials and metal structures. This will result in establishing conditions in part of gas composition, different from the main helium circuit having a gas cleaning system. With establishment of the equilibrium pressure of other gases, the thermal conductivity of the gas medium decreases and improves the heat insulation efficiency for some time (Fig.7).

Simultaneously the factors negative from the point of view of the insulation thermal conductivity can be observed. These are loss of elasticity of the material in the cyclic temperature variations, creep, shrinkage and sintering of the material exposed to high temperatures for a long time. The latter is especially important for fibrous and loose system whose thermal insulation properties deteriorate drastically in sintering.

High temperature gradients can cause mass transfer in the pores and cracks in the material, which also can encourage increase of the effective thermal conductivity of the insulation.

5. PHYSICOCHEMICAL REQUIREMENTS

In the HTGR designs under development the oxygen concentration i helium is limited (less than 10^{-4}-10^{-6} Wt%), which is characteristic for nuclear technology. Keeping the helium highly pure from chemically active gases., imposes the requirement of low gas release in heating up to the working temperatures and low sorption capacity relative to the gases contained in the air. In the process of manufacturing, transportation and assembling the thermal insulation absorbs a big amount of gases, which cannot be completely removed before the reactor startup.

The worst materials from the point of view of gas release are highly porous fine-dispersed systems. The foam material can also contain a large amount of water.

There are not much data available on gas release of the graphite materials. For some of them the gas release of the graphite in outgassing may be about $10^5 m^3N/m^2kg$. Therefore many devices are provided with a cleaning system for the primary circuit gas.

From the gas release viewpoint stalfol and metallic fibrous insulation (metallic gauze) are better than ceramic and graphite ones. For example, gas release from the stainless steel at up to 1000°C amounts to about 0.4 m^3N/m^2kg. Physically sorbed gases are desorbed from the surface even at 400°C, i.e. at temperatures lower than the operating ones. The gases can be removed from the volume of the metal beforehand, and the process of removal proceeds rapidly due to small thickness of the screens.

However it is possible that some types of steel can not be used in an oxygen-free medium (in the helium with an oxygen concentration of about 10^{-6}Wt%).

In some cases the operability of the steel-based thermal insulation can be violated because of graphite upset on its surface i.e. when steel foils and fibres are subject to embrittlement and loss of strength properties.

A requirement of complete exclusion or limitation of phase transitions, recrystallization, chemical transformations, gas release, mass-transfer etc. are also imposed on the HTGR thermal insulation.

6. PHYSICOMECHANICAL REQUIREMENTS

To perform the strength tests of the thermal insulation elements for full lifetime of the reactor operation (30 years) is just difficult. Therefore the problems of prediction of long-term strength, elasticity and shrinkage of the materials become very urgent. Grounds are required for more severe conditions of the tests and for much shorter times.

If the coefficients of linear expansion of the thermal insulation material and adjacent structure are close to each other, then problems of temperature compensation do not seem essential. Otherwise a special test of the structure is required.

The dimensions of all metal parts are determined taking into account heat expansion and manufactured, if necessary, with assembling tolerances which are chosen in heating up to the operating temperature. Different joints should move without oiling with a minimum friction, without violation of the surfaces. Change in the form and destruction of the initial thermal insulation material in the process of operation are ~~in~~ not admissible.

Connection between the high velocity of the gas coolant and possibility of changing the thermophysical properties of the thermal insulation have not been studied yet. Appearance of secondary effects causing an additional convection of the gas and rise of the heat transfer through the thermal insulation layer is not excluded.

7. NEUTRON PHYSICAL REQUIREMENTS

The thermal insulation, as a rule, is outside the core, which enables to attain a fluence (E > 0,1 MeV) not exceeding 10^{18}-10^{20} n/cm^2 for all the reactor lifetime. A maximum γ -ray level is about 10^{12} MeV/cm^{2}sec.

Under such conditions no direct effect of the reactor radiation on the thermal conductivity of the heat insulation can be observed. In the case of stalfol and fibrous materials this is due to the circumstance that their effective thermal conductivity, particularly in the helium medium, weakly depends on the thermal conductivity of the solid frame. Preliminary investigations of the fibrous materials, when irradiated on the MR-reactor, showed their good radiation resistivity. The heat conduction of the silica fibre and graphitized cloth (at 950°C and 1000-1500°C to fluences 5 10^{19} and 10^{18} n/cm^2, respectively) remained constant under irradiation. No outer changes of the fibrous materials were observed after irradiation /3/.

Irradiation of the foam materials can result in structure chemical changes and accumulation of defects, which, as a rule, reduces the effective thermal conductivity of the composition. Exception is materials such as pyrographite, for which violation of the directed structure of the material results in an increase in the minimum thermal conductivity (along axis C).

Much more significantly the reactor radiation may affect the insulation thermal conductivity indirectly through recrystallization, sintering, embrittlement, shrinkage and crumbling of the material. Occurance of the above factors is equivalent to replacement of the initial material by another, less effective or to removal of a part of the thermal insulating material from the construction.

Boron and other neutron-absorbing impurities must be excluded from the thermal insulation material or their concentration limited to avoid their penetration to the core via the helium coolant in the process of operation.

To reduce accumulation of radioactive decay products in the thermal insulation and facilitate repair operations in the primary circuit, the materials used must have poor sorption ability relative to other fission products escaping from the fuel assemblies and scattered by the helium coolant.

8. CHOICE OF THE MATERIALS AND DESIGN OF THE THERMAL INSULATION

Difficulty of proper choice of the materials for the thermal insulation is that all complex of the requirements must be taken into account. Some requirements, and hence investigations, could be excluded if the thermal insulation was only constructed of the materials used for the reactor itself. For the HTGR type reactors these are first of graphite and steel.

Using consistently the principle of limiting the amount of materials rises a desire to use helium instead of water as cooling agent in the thermal insulation constructions, which in addition, increases operation safety of the whole apparatus. Taking into account the cost of the materials and their operability, it does not always seem optimal to use similar constructions of the thermal insulation. In a number of cases various versions of the constructions containing two or three different heat insulating materials are possible with allowance made for the temperature level over the layers and use of the bypass helium flux between the layers.

During the construction it is reasonable to use the principle of dispersed effects of various factors. For example, in the construction of a coaxial piping with the hot coolant in the central pipe the effect of the limiting value of the main parameters (in this case these are temperature and pressure) can be brought to one (pressure on the outer pipe) or entirely excluded (on the inner pipe with inner location of the thermal insulation).

Development of the principles of constructing the thermal insulation depends on the "specific weight" of the problem of heat-insulating in a wide range of works on creation of the HTGR. One thing is clear that the importance of this problem will increase continuously as powerful complex industry productions, uniting various consumers of the high-temperature heat, will be developed.

At present various versions of the thermal insulation are used for the HTGRs, which is illustrated by some examples in Table 3.

Table 3.

Thermal insulation	Stalfol	Ceramic blocks	Fibrous materials	Graphite and carbon blocks and crumb
Reactor	Dragon, Peach-Bottom, Fort-Saint-Wrein	Fort-Saint-Wrein, Fulton	Fort-Saint-Wrein, Fulton	AVR, PR-500 (project), Uhtrex

In the project of the installation with the ВГР -50 reactor (coolant temperature 800°C) a stalfol insulation of the hot piping, steam generator and other components is suggested. Difficulty of solving the problems of HTGR thermal insulation is in a direct dependence on the temperature. For the reactors with the temperature of the helium coolant of about 1000°C (ВГ-400) and higher, ceramic material and graphite should be also considered as the thermal insulation material. In this connection it seems interesting to consider the experimental results obtained from measurements of the thermal conductivity of the graphitized fibrous material.

9. THERMAL CONDUCTIVITY OF THE GRAPHITIZED CLOTH

The measurement were performed using a stationary method of radial heat flux with inner electric heating. The ratio of the total height of the vertical cylindric assembly to the outer diameter was 300/34. A 8 mm diam. tungsten rod surrounded with a ceramic tube was used as an inner heater. The cloth layers were arranged between the ceramic tube and outer thin-walled metal cylinder. At a temperature higher than 1000°C an additional outer cylinder heater was used. The temperature was measured by the thermocouples Ir -Ir Rh(60%Rh), ВР 5/20 and X/A, and was monitored pyrometrically. The thermal conductivity coefficient was determined by the formula of the infinite hollow cylinder where the radial temperature difference on the cloth layers investigated was averaged over the azimuthal angle. The experimental values of the thermal conductivity coefficient were referred to the arithmetical mean temperature. The maximum relative error of the measurements was less than 15%.

In the experiments the carbon cloth preliminary graphitized at about 2000°C was used. The thickness of one cloth layer was 0.45 mm, density 330 g/m^2. The calculation volume porosity of the cloth was about 82%. The diameter of individual fibres was 5 ± 2 μ /3/.

The results obtained from the measurements of the heat conductivity of the graphitized carbon cloth packet in vacuum (at a pressure lower than 1 10^{-2} torr), argon and helium (at atmospheric pressure) are shown as points in Fig.8. In this figure the solid lines show dependences $\lambda = f(t)$ obtained from processing the experimental results by the method of the least-squared deviations using the standard program 19-I on БЭСМ-6. For helium, argon and vacuum these dependences are written analytically as:

$$\lambda = 0{,}265 + 1.21\ 10^{-4}t + 9{,}30\ 10^{-8}t^2$$
$$\lambda = 0{,}098 + 1.38\ 10^{-4}t + 3.51\ 10^{-8}t^2$$
$$\lambda = 0{,}052 + 0.275\ 10^{-4}t + 4.14\ 10^{-8}t^2$$

where λ W/m °C, t°C. The standard deviations of the experimental points from the approximating parabolas are 0.011, 0,015 and 0.005W/m °C, repsectively.

Within the temperature range 200-1200°C the slopes of the $\lambda = f(t)$ dependences for graphitized cloth packet in helium and for stagnant helium fit well, and the absolute values of the thermal conductivity for the cloth is higher than for helium by about 25%. This means that within this temperature range a portion of the heat transferred by the graphitized cloth packet in the contact points and by heat radiation is relatively small and for the give composition in the helium medium does not exceed 25% of the heat flux escaping through the insulation. The similar conclusion can be made from comparison of the dependences of the cloth thermal conductivity in helium and in the vacuum, since in the latter case the heat is transferred only through the contacts and by the radiation.

A small contribution to the total thermal conductivity by means of contacting individual fibres to each other can be due to significant porosity of the cloth packet and high heat resistance of the contact points. A weak rise of the contribution from the radiant component with increasing the temperature is connected with the effect of multiple screening of the radiation. The packet of parallel cloth layers has a triple structure: layers, threads, fibres. All fibres are arranged practically normally to the direction of the heat flux spread (Fig.9). With an average diameter and fibre concentrations respectively $\varphi=5\mu$ and $C=\pi\varphi^2/4S^2 \simeq 20\%$ the distance between the fibre centres for an ordered structure is $S=10\mu$ and, hence, in our case the density of the conventional screens along the way of the heat radiation H will be $K=H/2S$ =500 screen/cm. Such a high screen density weakens substantially the contribution from the heat radiation to about 1500°C even at high values of radiation ability of the graphitized carbon fibres.

The experiments under the reactor conditions were performed using the relative method /4/. Taking into account that at a constant reactor power (and at a constant heat removal) the heat conductivity coefficient $\lambda = A/\Delta T$, where A is the constant, the change in the thermal conductivity was estimated from the change in the temperature difference ΔT on a fixed insulation level. The results of the reactor investigations of the graphitized cloth are shown in Section 7.

10. CONCLUSIONS

For solution of the thermal insulation problems of ВГР-50, ВГ - 400, БГР - 300 and other high-temperature apparatuses an extensive program of calculation, technological, designing and experimental investigations are to be carried out, and not always the theoretical investigations of individual processes and experimental tests using small specimens will give a complete solution of the problem. In many cases it is necessary to study the thermophysical and other characteristics of the actual thermal insulating constructions and full-scale elements under test conditions close to actual ones.

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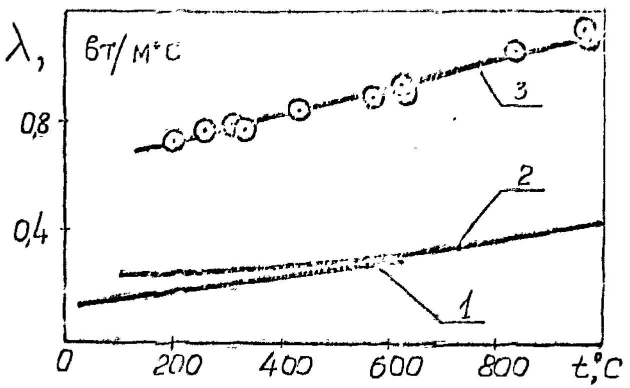

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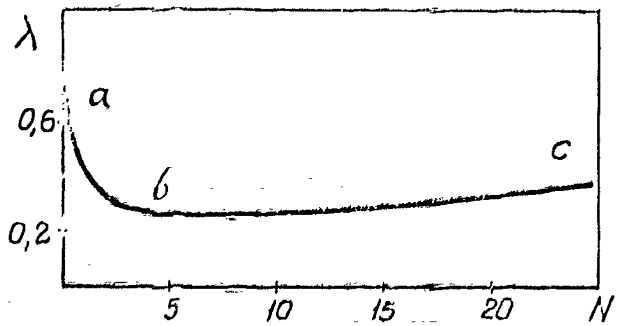

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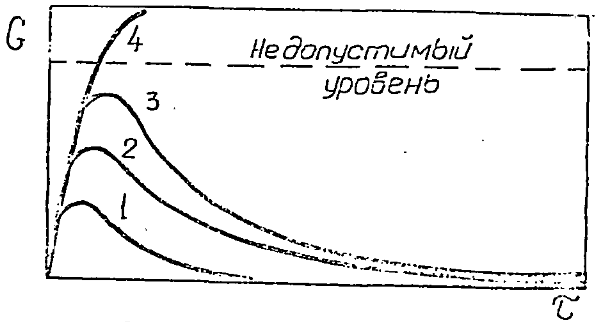

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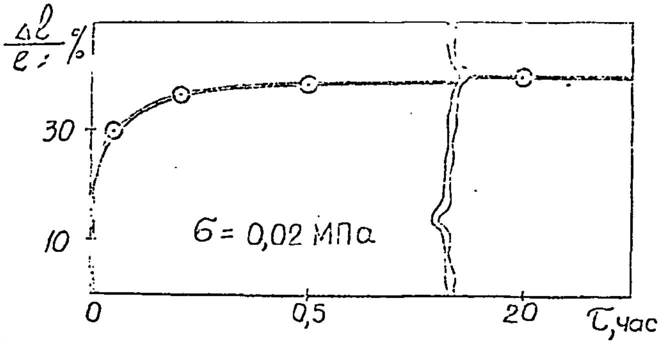

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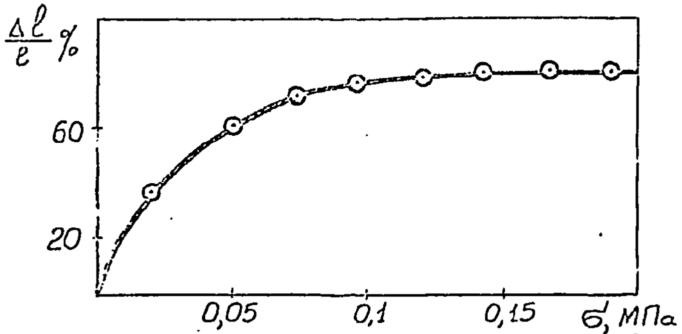

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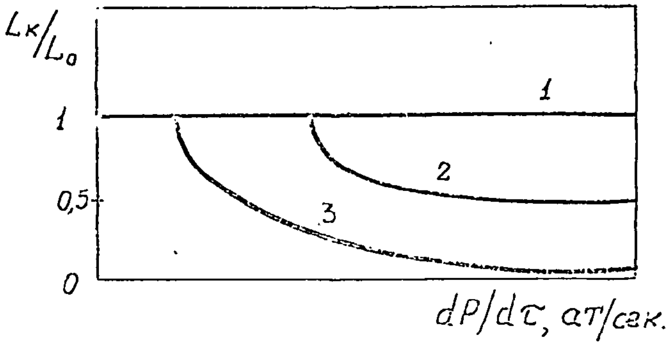

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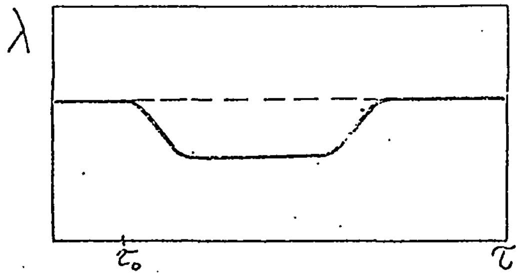

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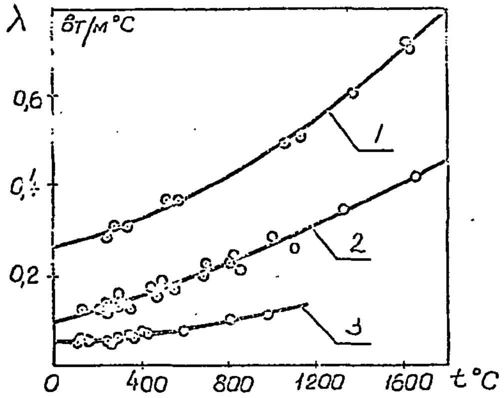

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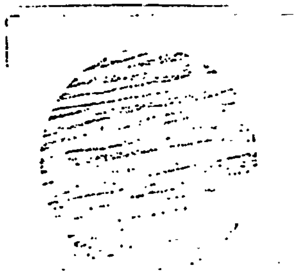

Рис. 9. Микроструктура графитированной ткани X 120

BEHAVIOUR OF PERFORATED CONCRETE SLAB UNDER THERMAL LOADS

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Summary

In 1966, the first commercial nuclear power plant was built in Japan by the JAPAN ATOMIC POWER CO., Ltd. (JAPC). Since then, various observations such as measurements of transformation of reactor structures or internal thermal changes of them have been carried out as a part of the In-Service Inspection (ISI).

This report is to show some data obtained by the above, which possibly predict the relationship between thermal distribution changes and transformation of the perforated concrete slab over the Primary Shield Walls. As these datas shown here are obtained from the Colder Hall type Gas Cooled Reactor, they can substantially be used for the assumption of the effective Young's Modulus of the top perforated concrete slab of PCRV. In this sense, I believe these data are very precious.