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(Final Report)

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Abstract

The second HEBLO experiment with a mixed pebble bed corresponding to the forerunner concept of the helium cooled breeding blanket for DEMO has been completed successfully. The experiment was conducted to simulate a DEMO-related cyclic load of the pebble bed. The pebble bed survived the entire series of experiments totaling 1915 cycles under a variety of different loads without suffering any major damage. The result of subsequent examination was in good agreement with the qualitative evaluation of the temperatures measured and the pressure losses measured in the purge gas.

Recalculations of the experiment performed in accordance with the DEMO design principles showed good agreement of the transient temperatures with the measured levels.

Temperaturzyklische Tests auf einer gemischten Be/Li_4SiO_4 Kugelschüttung in der HEBLO-Anlage

Zusammenfassung

Das zweite HEBLO-Experiment mit gemischter Kugel-Schüttung entsprechend dem Vorläuferkonzept des heliumgekühlten Brutblankets für DEMO wurde erfolgreich beendet. Ziel des Experimentes war, eine demorelevante zyklische Belastung auf die Kugelschüttung zu simulieren. Die Kugelschüttung überstand die gesamte Versuchsreihe mit insgesamt 1915 Zyklen und unter unterschiedlichen Belastungen ohne nennenswerte Schäden. Das Ergebnis der Nachuntersuchung stimmte gut überein mit der qualitativen Auswertung der gemessenen Temperaturen und der gemessenen Druckverluste im Spülgas.

Die nach den DEMO-Auslegungsansätzen durchgeführten Nachberechnungen für das Experiment zeigten eine gute Übereinstimmung der transienten Temperaturen mit den Meßwerten.

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1 Introduction

Within the framework of European blanket development for the demonstration reactor (DEMO) (Fig. 1) numerous conceptual blanket design studies based on the solid blanket and the liquid metal blanket were conducted at the Karlsruhe Research Center (FZK) up to the date of EU blanket selection (BCSE) in late 1995, when two European blanket concepts were selected for further development. There were two advanced forerunner concepts especially in the development of the solid blanket concept which was successful in the BCSE. In the first forerunner concept [1], a Li_4SiO_4 pebble bed was used as a blanket material and beryllium plates served as a multiplier. Heat was removed by means of the tube coils soldered into the beryllium plates and permeated by helium gas. The entire blanket was subdivided into small canister units. In the second forerunner concept [2], i.e. the tube coil concept with a mixed pebble bed, Li_4SiO_4 and beryllium were used together as a mixed pebble bed in order to avoid the problem of beryllium swelling. There is no need for any canister units in this design. Cooling was provided by passing helium through the cooling tube coils installed in the pebble bed. In today's reference concept [3], the HCPB concept, separate pebble beds of Li_4SiO_4 and beryllium are used. This minimizes problems of compatibility of the materials. Cooling is by helium flow through horizontal cooling plates which separate the pebble beds.

The development of the above blanket concepts requires not only calculations and theoretical design work, but also experimental activities to develop manufacturing and inspection techniques and simulate the loads and stresses acting on materials in experiments. For this purpose, HEBLO (**He**lium **B**lanket Test **Lo**op) was built at the IMF III and commissioned in 1992. Numerous successful experiments with the forerunner concepts listed above have since been conducted. They included cyclic temperature transient tests of soldered connections (canister concept) and of the mixed pebble bed under boundary conditions close to those prevailing in DEMO. The results of the first HEBLO experiment on the canister concept were documented in [4].

This report constitutes a summary of the experimental results of the second HEBLO experiment with a mixed pebble bed.

2 Description of the HEBLO Facility

The Helium Blanket Test Loop, HEBLO [5], for experiments with small components of a helium cooled solid blanket was planned and built up in Forschungszentrum Karlsruhe, IMF III between 1990 and 1992. The facility was commissioned in late 1992 after preliminary experiments.

The HEBLO facility (Figure 2) consists of a main loop and a test loop connected by an intermediate heat exchanger. Two different types of experiments can be run:

(A) In the main loop: thermomechanical tests with isothermal coolant gas feed flow, cyclically variable heating power in the test specimen, and/or cyclically variable coolant gas flow.

(B) In the temperature transient test loop: thermomechanical tests with cyclic temperature transients of the coolant gas feed flow, cyclically variable heating power in the test specimen, and/or cyclically variable coolant gas flow.

The key components of the main loop are the helium recirculation compressor with gas bearings, the helium cooler, connections for test rigs of various sizes, with isothermal cooling, and a bypass section for controlling constant flow at the compressor. Additional installations are the helium inlet/outlet system with the pressurizer. The heat sink is a closed water loop with dry cooling towers. These are the operating conditions of the main loop:

- Helium pressure		8	MPa
- helium flow	max.	330	g/s
		100	m^3/h (50 °C)
- helium temperature	max.	250	°C
- cooling capacity		115	kW
- helium differential pressure		0.15	MPa.

The temperature transient test loop is designed according to the loadings expected in DEMO. It serves to generate up to 30 K/s temperature transients in the test specimen without giving rise to inadmissible loads in the cooling system. This is achieved by raising the temperature level of the coolant gas in the intermediate heat exchanger from 30°C to about 260°C. The helium flow is then separated into two split flows: one split flow (I) is heated to approx. 430°C in a heating section and then returned to the intermediate heat exchanger either through the cooling tubes of the test specimen or in the bypass, and then cooled again, while the other split flow (II), without substantial changing its temperature level, returns to the intermediate heat exchanger either through the cooling tubes of the test specimen or in the bypass. Before entering the intermediate heat exchanger, the helium passes through a temperature equalizing section which ensures greater uniformity of the helium temperatures. Cyclic switching of the gas flows is achieved by a group of pneumatically actuated valves. The volumes of the split flows are set manually by control valves.

These are the levels set in the test loop for the experiments conducted:

- Operating pressure	8	MPa
- helium flow	2 x 65	g/s
- lower temperature level	260	°C
- upper temperature level	430	°C
- temperature transient	170	K
- temperature gradient	30	K/s
- heating power, split flow I	60	kW (for transient heating up)
- heating power, split flow II	20	kW (for temperature level control).

Process management and control is achieved by means of an automation system and an operation and monitoring system. This system also allows all measured data to be collected and stored.

3 Conceptual Design of the Helium Cooled Blanket with a Mixed Pebble Bed

3.1 General Structure of the Blanket Segment

The blanket geometry is designed by means of CAD. Figure 3 shows an isometric view of an outboard blanket segment. A total of 48 outboard segments are arranged around the outer torus circumference (see Fig. 1). The inner torus circumference carries 32, mostly vertical, inboard segments. The outboard segments are considered for thermomechanical design because the thermal load is higher in the outboard than in the inboard sections.

In the poloidal direction, the outboard segment is composed of several sections of 1 m height each, producing a curved banana shape with an upper neck for extension. The blanket segment has a radial toroidal dimension of approx. 1 m x 1 m. The total height of the segment is approx. 13 m.

The entire blanket structure is made of martensitic 1.4914 steel (MANET in EU designation). The diffusion welded first wall bent into a U shape constitutes a rigid segment box together with the support and shielding structures. Parallel cooling channels are arranged in the radial toroidal plane of the first wall. Cooling gas from two cooling systems of 8 MPa flows through them in alternating directions. The alternating direction of flow in the cooling channels of the first wall makes for a more uniform temperature in the outer structure and, consequently, minimizes temperature induced stresses. The separate supply systems, 1 and 2, also ensure emergency cooling in case of failure of one cooling system.

The entire blanket within the segment box with a radial depth of 500 mm is subdivided into two parts for neutron physics and thermal reasons, as is evident from the detail in Fig. 3. The front zone with a radial depth of 330 mm, which experiences more heat, contains a mixed bed of Li_4SiO_4 pebbles (dia. 0.1 – 0.2 mm) and beryllium pebbles of high thermal conductivity (dia. 2 mm as the basic pebble bed and dia. 0.08 – 0.18 mm as a filler bed) (Fig. 16). This composition results in an effective packing factor of 88%. The volumetric ratio of beryllium to Li_4SiO_4 is 8:1. This mixed pebble bed was under study also in the second HEBLO experiment. The rear blanket with moderate blanket temperatures contains no fine beryllium filling bed (dia. 0.08 – 0.18 mm), which makes the overall packing factor in this zone only 63.3%. Accordingly, the volumetric ratio of beryllium to Li_4SiO_4 is 3.6:1.

The blanket is cooled by the cooling tube coils extending horizontally through the pebble bed (dia. 14 x 1) and arranged at regular poloidal distances in a hairpin shaped manner. The coolant gas is helium at a pressure of 8 MPa.

The helium coolant gas enters the blanket segment from the top at 250°C, passes first downward through the rear main supply channels and is heated only slightly in the process. After deflection at the bottom end of the blanket, the helium gas from both systems is gradually fed into the parallel first-wall cooling channels, which are horizontally arranged. It is then passed through the cooling tube coils by means of a header/distributor system. The cooling coils are connected to the header/distributor system in such a way that the flow passes through them in alternating directions for upper and lower tube coils. In this way, a homogeneous temperature distribution is achieved in the blanket. The temperature of the helium leaving the blanket segment is 450°C.

3.2 Materials Data

3.2.1 Thermal Conductivity

The mixed pebble bed made up of Li_4SiO_4 pebbles and binary beryllium pebbles follows these relations describing thermal conductivity, with the differential thermal expansions of the pebble bed and the ambient steel structure taken into account, according to [6]:

(A) Thermal conductivity of the mixed pebble bed in the front zone (330 mm)

$$\lambda_{Bed}\,[\mathrm{W/mK}] = 5.478 \times \{1 + 320.2 \times [\alpha_{EXP,BER} \times (T_{m,BER}-20) - \alpha_{EXP,MA} \times (T_{m,MA}-20)]\} \quad (1)$$

(B) Thermal conductivity of the mixed pebble bed in the rear zone (170 mm)

$$\lambda_{Bed}\,[\mathrm{W/mK}] = 4.721 \times \{1 + 206.4 \times [\alpha_{EXP,BER} \times (T_{m,BER}-20) - \alpha_{EXP,MA} \times (T_{m,MA}-20)]\} \quad (2)$$

with $T_{m,BER}$ [°C] as the mean temperature of the beryllium pebble bed,

$T_{m,MA}$ [°C] as the mean temperature of the MANET steel structure,

$\alpha_{EXP,BER}$ [1/K] as the coefficient of thermal expansion of the beryllium pebble bed (Equation 3),

$\alpha_{EXP,MA}$ [1/K] as the coefficient of thermal expansion of MANET steel (Equation 4).

(C) Coefficient of thermal expansion α_{EXP}:

$$\alpha_{EXP,BER}\,[1/K] = 8.43 \times [1+1.36 \times 10^{-3} \times (T_{m,BER}+273) - 3.35 \times 10^{-7}\,(T_{m,BER}+273)^2] \times 10^{-6} \quad (3)$$

$$\alpha_{EXP,MA}\,[1/K] = 9.7382 \times 10^{-6} - 2.2234 \times 10^{-9}\,(T_{m,MA}+273) + 1.4929 \times 10^{-11}\,(T_{m,MA}+273)^2 - 1.0185 \times 10^{-14} \cdot (T_{m,MA}+273)^3 \quad (4)$$

Figure 4 shows a plot of thermal conductivity as a function of temperature for both blanket sectors under the assumption of a mean temperature of the steel structure of 310°C.

The values of the coefficients of thermal expansion for beryllium and steel structure are listed in Table 1, page 13 [7, 8].

3.2.2 Heat Transfer between the Pebble Bed and the Steel Structure

As in Section 3.2.1 above, the influence of the differential thermal expansion of the pebble bed relative to the surrounding steel structure upon the coefficient of heat transfer is taken into account for the beryllium pebble bed. Consequently, a relation [6] can be indicated as follows:

(A) Front zone (330 mm)

$$\alpha_{Bed/W}\,[W/m^2K] = 2120 \times [1+9.239 \times 10^{-4} \times T_W] \times \{1+383.1 \times [\alpha_{BER} \times (T_{m,BER}-20) - \alpha_{MA} \times (T_{m,MA}-20)]\} \quad (5)$$

(B) Rear zone (170 mm)

$$\alpha_{Bed/W}\,[W/m^2K] = 932 \times [1+1.654 \times 10^{-3} \times T_W] \times \{1+196.8 \times [\alpha_{BER} \times (T_{m,BER}-20) - \alpha_{MA} \times (T_{m,MA}-20)]\} \quad (6)$$

Table 3, page 13, contains numbers for $\alpha_{Bed/W}$ at a mean temperature of the structure of 310°C with T_W, the mean local temperature of the coollant tubes [6].

For ease of computation, this heat transfer coefficient was replaced by an equivalent reduced thermal conductivity λ_{red} in temperature calculations for a heat transfer distance s:

$$\frac{s}{\lambda_{red}} = \frac{1}{\alpha_{Bed/W}} + \frac{s}{\lambda_{MA}} \quad (7)$$

3.3 Temperature Calculation

The three-dimensional calculation of the temperature distribution was carried out by means of the ABAQUS finite element (FE) code [9]. The FE grid was generated by means of the GRAFEM software of our CAD system. The 3D FE model contains a horizontal section of the entire blanket, including the first wall, with a poloidal height of 12 mm (Fig. 7).

The temperature calculations are based also on the blanket powers as determined by the Monte Carlo method [10].

Figures 5 and 6 show radial power density distributions in the mixed Li_4SiO_4 beryllium pebble bed and in steel for the central region of the outboard blanket. The maximum power density for the mixed pebble bed is approx. 20 W/cm^3, and for steel approx. 26 W/cm^3.

The surface heat flux density for the first wall contributed by the plasma was assumed to be an average of 40 W/cm^2 and a maximum of 50 W/cm^2, respectively.

Table 4, page 14, lists the power balance and the thermohydraulic data for the model section. Figure 7 shows the computed temperature distribution at the center of an outboard blanket segment. The high local pebble bed temperatures in the region of the bending radii of the cooling tube coils are clearly apparent. When the smallest possible bending radii are observed, the maximum pebble bed temperature is 663°C, which is below the design limit of approx. 700°C. The resultant maximum first-wall temperature of 523°C is also below the permissible level of 550°C.

4 Execution of Temperature Cycling Tests in a Mixed Pebble Bed of Beryllium/ Li_4SiO_4 Ceramic Pebbles with Hairpin Shaped Helium Coils of Pipe

4.1 Basic Principles

The experiment was planned for the breeding blanket concept [2] described above. The test section was designed and manufactured according the breeding blanket consisting of a pebble bed of beryllium and ceramic pebbles penetrated by cooling tubes. The bed contained two pebble fractions:

- Beryllium pebbles of 2 mm diameter.

  They are filled into the blanket segment box first and with care so that the pebble bed had roughly the maximum theoretical bulk density of approx. 60% of the beryllium density. The pebbles were packed closely, and a large number of contact points ensures uniform transfer of power and heat in the pebble bed.

- Pebbles of beryllium and/or Li_4SiO_4 ceramics with diameters of 80 µm to 200 µm.

  These pebbles were filled subsequently. They were distributed throughout the network of voids between the 2 mm pebbles like a liquid. This small fraction was not supposed to be part of the load bearing structure of large beryllium pebbles, but mainly serves to increase blanket density and established the necessary lithium/ceramic ratio. On a lesser scale, it also influenced the thermal conductivity of the pebble bed. The pebble bed described above was permeated by a low-speed helium purge gas flow of 0.1 MPa to simulate the purge gas removing the tritium produced.

4.2 Tasks Underlying the Experiment in HEBLO

The tokamak fusion reactors currently under discussion experience a large number of power cycles (10^3 to 10^5) over the lifetime of a breeding blanket assembly which, in turn, result in temperature cycles in the breeding blanket. Figure 8, at the top, shows a qualitative description of temperature developments in the breeding blanket described above occurring a power cycle at the performance data specified for DEMO (i.e., 2.2 MW/m^2 as the average neutron exposure of the wall).

This is based on the assumption that not only the cooling tubes in the blanket but also all walls surrounding the breeding pebble bed are permeated by coolant gas. Each cycle raises the general temperature level in a central area of the blanket by some 200°C and, in addition, causes a differential temperature of approx. 150°C to be built up between the blanket material and the surrounding steel structure. Factors to be borne in mind in this respect are the differences in the coefficients of thermal expansion (e.g., at 400 °C: $\alpha_{EXP,Martensite}$ = 11.9 x 10^{-6} [1/K]; $\alpha_{EXP,BER}$ = 14.8 x 10^{-6} [1/K]; $\alpha_{EXP,CER}$ = 25.5 x 10^{-6} [1/K]).

Despite frequent temperature cycling, the structure composed of large beryllium pebbles in the pebble bed must be preserved; in particular, no small ceramic pebbles must urge between the larger beryllium pebbles and then, perhaps as a result of excessive contact pressure, be crushed into fine dust. It is also important to prevent excessively large forces from arising between the pebble bed and the surrounding steel structure.

One effective measure in this respect seems to be that an elastic, yet strong, wall exerts an almost uniform pressure on the pebble bed in each phase. The effects which can be achieved in this way, and the optimum contact forces to be selected, were to be determined in the second experiment in HEBLO. That experiment was designed for a maximum of 1000 operating cycles.

4.3 Test Setup in HEBLO

The HEBLO facility can provide a coolant gas flow of approx. 65 g/s of helium at 8 MPa at the inlet of the test section, the temperature of which can be changed cyclically in ramps by up to approx. 160°C. The cycle times (normally, approx. 2 x 300 s) and the temperature levels (normally, approx. 270°C/430°C) can be chosen. Figure 9 shows the realized test section. Because of its availability, 1.4541 type stainless steel was chosen as the material for the test section. The pebble bed was 250 mm high x 90 mm in diameter, corresponding to a volume of approx. 1.6 l. It was penetrated by three hairpin-shaped coolant gas tubes able to expand freely in an upward direction. In this way, the quite extensive thermal expansions of the tubes in an axial direction expected in some phases was uncoupled from those of the test vessel.

A piston driven by a bellows could exert a maximum load of approx. 5 MPa on the pebble bed from the top.

Temperatures were measured at the cooling tubes, in the pebble bed, and at the wall of the vessel. Moreover, strain gages were to be attached to the wall of the vessel.

Cyclic changes could give rise to temperature developments like those shown at the bottom of Fig. 8. The most important measured quantities were the differential temperatures between the wall of the vessel and the pebble bed. Once equilibrium conditions were established, the effects of ΔT_1 (positive) and ΔT_2 (negative) was added up; consequently, attempts were made to achieve $\Delta T_1 + \Delta T_2 = \Delta T_{max}$ (top of Fig. 8). The cooling tubes in the HEBLO test, because of their high temperatures, had an intensifying, i.e. positive, impact on the results.

During the experiment, the pebble bed was permeated by gas at low velocity so that a defined dry helium atmosphere was maintained in the pebble bed despite temperature fluctuations. Figure 10 shows the purging system, which was used in the experiments to measure the pressure loss of a forced purge gas flow.

The purge gas flow was extracted permanently from a battery of helium cylinders and expanded to almost normal pressure. It passed through the pebble bed in the test section from bottom to top and through filters installed at the inlet and outlet of the test section. A clearly arranged control panel outside the HEBLO caisson carried another dust filter, a flowmeter, and a water flask for optical monitoring of the purging process (see also next chapter below).

4.4 Safety Precautions

Beryllium has a toxic effect when present in a respirable form. Consequently, special safety precautions had to be taken in the preparation, operation, and disposal of the test setup.

4.4.1 Preparing the Experiment

The HEBLO test section was filled with the beryllium pebble bed in the beryllium facility of Heraeus, Hanau, by the Goraieb company; the process was carried out in a glovebox into which the upper flange of the test section extended from below (Fig. 11).

These activities comprised the following steps:

- Filling and compaction of the two pebble fractions.
- Assembly of the bellows unit with the piston.
- Flooding of the test section with helium.
- Welding of the top lid and the pipe penetration in the top lid.
- Crack inspection of the assembly welds and leak test.

On the return transport, these purging lines each contained a filter, a closed valve and a screw cap with a blind nozzle at the end to ensure a closed purgegas loop through the mixed pebble bed. The pebble bed was kept under a slight helium overpressure. The piston was forced upon the pebble bed at 1 MPa of N_2 in the bellows.

During assembly in HEBLO, only the two purging lines were screwed to the existing purging system, and the purge gas lines were flooded carefully with helium. Moreover, the pressurized gas line acting upon the bellows were connected.

4.4.2 Running the Experiment

Although the sequence of temperature cycles was controlled automatically, the experiment was conducted only in the presence of an experimentalist to ensure security for component management and the total 8 MPa HEBLO cycle. Flushing the test section with helium was started before an experiment was begun, and was finished after the test section had cooled completely. The purge gas entered a water pool from the offgas tube through small openings. In case it would contained traces of beryllium despite the filter, they were precipitated in the water. This process of wet precipitation is used in mechanical processing of beryllium metal. It is effective enough to allow additional protective measures (such as respiration protection gear) to be abandoned.

When the test section was first commissioned, the temperature ramps were gradually raised to the set level over a number of cycles. The measured data in the test rig and, in particular, the purge gas flow were monitored continuously. In case of anomalies, the cycle had to be interrupted and the plant had to be reduced gradually to a lower temperature level. All these steps were conducted automatically by means of the HEBLO control system. When necessary (e.g. at weekend), the plant was shut down and the coolant gas pressure lowered.

4.5 Experimental Operation

4.5.1 Instrumentation

The pebble bed of the HEBLO test section (dia. 90 x 250 mm height) was penetrated by three hairpin-shaped cooling tubes carrrying the helium gas of the temperature transient test system of the HEBLO loop (Fig. 9). The maximum temperature amplitude was 170 K (260/430°C); the temperature ramp, approx. 30 K/s; and the cycle time, 2 x 300 s. The mechanical load of up to 5 MPa was exerted on the pebble bed by a pneumatically driven pressure piston. Several thermocouples were arranged on the same plane within the pebble bed.

For the duration of the experiment, the temperatures in the pebble bed and the pressure loss of the purge gas flow (Fig. 10) were measured so as to indicate changes in the pebble bed by way of the thermohydraulic conditions. The thermocouple positions are shown in Fig. 12. The temperatures close to the tube walls were indicated by thermocouples ET-1 to ET-3. The central temperatures between the tube legs were measured by thermocouples ET-5, ET-6, and ET-9. Temperature measurements in the respective positions between the tube wall and the center of the pebble bed were performed by thermocouples ET-4, ET-6, and ET-8. The number of temperature cycles in experimental operation totaled 1915 above 200/350°C, of which 1305 cycles were above 260/425°C. The pressure load exerted on the pebble bed by the pneumatic piston was set in steps between 1 and 5 MPa, as shown in Fig. 13.

4.5.2 Results

Figure 14 shows the measured pressure loss of a purge gas flow of 150 cm^3/s over the entire duration of the experiment for a mean pebble bed temperature of approx. 300/400°C (curves (a) and (b)). Increasing the mechanical load on the pebble bed caused a slightly higher pressure loss which, initially, was not balanced out during the first stage of the pressure decrease from 5 to 3 MPa. Only when the pressure was reduced further from 3 MPa to the initial level of 1 MPa, a slight decrease of the pressure loss was observed. This was probably due to a self-locking mechanism in the pebble bed, and to the pneumatic piston being stuck, respectively.

Exerting pressure on the pebble bed also improves thermal conductivity and heat transfer, as can be seen in Fig. 15. That diagram shows the transient temperature curves at the helium gas inlet (curve 1), in the center of the pebble bed (family of curves 2 according to Pos. A, Fig. 12), and at the outer wall of the test section (family of curves 3 according to Pos. B, Fig. 12). Higher pressure loading of the pebble bed was seen to cause a steeper temperature rise in the test rig.

4.6 Post-experiment Examination

After the end of experimental operation, the test section was dismantled at the beryllium laboratory of Heraeus AG, Hanau. Because of difficulties in removing the pressure piston, no single specimens of the pebble bed could be sampled. Consequently, the entire pebble bed was immobilized with a cast resin on epoxybase at the Hot Cells of FZK and examined subsequently [11].

Metallurgical photographs of a plane approx. 20 mm below the pressure piston were made (Fig. 16). These pictures show no damage or deformation of the pebbles. In addition to undestroyed and undeformed Be and Li_4SiO_4 pebbles of all diameters (Fig. 16, frames HEBLO-1-2u/2 and 6), also damage up to destruction of the pebbles was found in a few Be pebbles of 2 mm dia. and in a larger number of Li_4SiO_4 pebbles of 0.2 mm dia. The reasons are fixed internals in the pebble bed space which impeded movement in the pebble bed and, in some of the pebbles, caused unilateral compression and shearing.

4.7 Recalculation

For subsequent simulation of the experiment, transient temperature calculations were carried out with ABAQUS for a selected cycle No. 1046 close to the end of the experimental Phase 1 with 1 MPa piston load (Fig. 13). Figure 17 shows the finite-element model used for the thermocouple measurement plane 80 mm from the upper edge of the bottom lid. Figure 18 shows the helium temperature measured at the inlet and outlet of the test section. Intermediate levels were interpolated linearly for the plane considered. The helium mass flow rate for a single tube was 21.67 g/s. This resulted in a helium velocity of 28.5 m/s and a heat transfer coefficient of 0.2876 x 10^4 W/m^2K. The underlying boundary condition was the measured temperature curve at the outer wall of the sleeve tube (ET-11 according to Pos. B, Fig. 12) (Fig. 19). Unlike the DEMO design, the test rig was made of 1.4541 stainless steel, as mentioned above. For simplicity's sake, the constitutive data of 316L type steel were used as a basis in calculation (see Table 5, page 14).

Figure 20 shows the calculated temperature curve in the pebble bed in the central position of the middle tube coil (ET-6 according to Fig. 12), and in the central position of the bottom tube coil (ET-5), as compared to the measured curves. Good agreement is seen between the calculated and the measured curves. Particularly at the lower position, ET-5, which is closer to the wall of the sleeve tube, agreement in temperature curves is seen to be better than in the central position, ET-6. This is probably due to the radial decrease of the contact pressure caused by differential thermal expansion between the pebble bed and the sleeve wall, which results from the self-locking property of the pebble bed.

This effect is particularly pronounced again in a position close to the bottom cooling tube (ET-4, Fig. 21). In general, the result also shows that superimposing the axial piston pressure upon the entire pebble bed causes heat transfer conditions in the pebble bed to improve over the computed approaches employed in Sec. 3.2, as is evident from the steeper temperature rise as a function of time. Figures 22 to 25 show a number of temperature developments as a function of time for several points in time in the cycle. At the helium inlet (left tube leg), a quick buildup of temperature is seen which levels off along the flow path towards the helium outlet as a consequence of the exchange of energy. The temperature profile, however, has almost fully developed after some 300 s in the heating phase (Fig. 23) and at the end of the cooling phase (t=600s, Fig. 25), and is nearly symmetrical.

5 Summary

The experiment with a mixed beryllium/Li_4SiO_4 pebble bed based on the forerunner concept of a helium cooled breeding blanket was performed successfully. The pebble bed withstood a total of 1915 cycles at a maximum transient load of 30 K/s and temperatures between 270 °C and 450 °C under pressure loading of 1 to 5 MPa without any damage. Recalculation of the experiment exhibited good agreement between the calculation and the measurement. The reliability of the approaches used in computing the thermal conductivity of the pebble bed and the heat transfer coefficient between the pebble bed and the steel wall has thus been confirmed.

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6 References

[1] M. Dalle Donne, E. Bojarsky, U. Fischer, M. Küchle, P. Norajitra, G. Reimann, H. Reiser, G. Sordon, H.D. Baschek, E. Bogusch: The Karlsruhe Helium Cooled Ceramic Breeder Blanket Design for the Demonstration Reactor; Proceedings of the 16th Symposium on Fusion Technology, London, U.K., September 3-7, 1990, vol. 1, pp. 978-82.

[2] M. Dalle Donne, E. Bojarsky, U. Fischer, A. Goraieb, P. Norajitra, G. Reimann, H. Reiser, G. Sordon: Conceptual Design of a Helium Cooled Solid Breeder Blanket Based on the Use of a Mixed Bed of Beryllium and Li_4SiO_4 Pebbles; Proceedings of the 17th Symposium on Fusion Technology, Rome, Italy, September 14-18, 1992, vol. 2, pp. 1326-30.

[3] M. Dalle Donne, U. Fischer, P. Norajitra, G. Reimann, H. Reiser: European DEMO BOT Solid Breeder Blanket: The Concept Based on the Use of Cooling Plates and Beds of Beryllium and Li_4SiO_4 Pebbles; Proceedings of the 18th Symposium on Fusion Technology, Karlsruhe, Germany, August 22-26, 1994, vol. 2, pp. 1157-60.

[4] H. Reiser, K. Müller, D. Piel, G. Reimann: Internal KfK report, September 1994, unpublished.

[5] P. Norajitra, D. Piel, G. Reimann, R. Ruprecht: HEBLO, a Helium Blanket Test Loop for Small Test Sections of Helium Cooled Solid Breeder Blankets; Proceedings of the 19th SOFT, Lisbon, September 16-20, 1996.

[6] M. Dalle Donne: private communication, February 1994.

[7] M. Küchle (comp.): Test Blanket Advisory Group, KfK, February 1990, unpublished.

[8] K. Ehrlich: Internal KfK report, May 1986, unpublished.

[9] Karlsson Sorensen Hibbitt: ABAQUS User's Manual, Version 4.9, Providence, R.I., USA.

[10] U. Fischer: Die neutronenphysikalische Behandlung eines (d,t)-Fusionsrektors nach dem Tokamakprinzip (NET), KfK 4790, Oktober 1990.

[11] E. Kaiser, G. Weih, F. Weiser: Internal FZK report, March 1997, unpublished.

[12] CEA-IRDI: Initial Design Equations for 316L Austenitic Steel; Ref. No. 85.1416, August 1985.

7 Nomenclature

α [W/m^{2}K]	heat transfer coefficient
α_{EXP} [1/K]	thermal linear expansion coeffient
c_p [J/kgK]	specific heat capacity
ΔT [K]	Temperature difference
λ [W/mK]	thermal conductivity
m [kg/s]	mass flow rate
s [m]	thickness

Subscripts:

Bed	pebble bed
BER	beryllium
CER	ceramic
He	helium
MA	MANET
m	mean
max	maximum
red	reduced
W	wall

Table 1: Coefficient of thermal expansion [7], [8] of the beryllium pebble bed and of MANET steel in [10^{-6} x 1/K]

T [°C]	α_{BER}	α_{MANET}
300	14.02	11.45
350	14.42	11.68
400	14.80	11.90
450	15.16	12.09
500	15.51	12.24
550	15.85	12.34
600	16.17	12.40
650	16.48	12.40

Table 2: Thermal conductivity of MANET steel [7], [8]

T [°C]	λ [W/mK]
20	24.2
50	24.4
100	24.7
150	24.9
200	25.2
250	25.4
300	25.6
350	25.7
400	25.9
450	26.0
500	26.2
550	26.3
600	26.5

Table 3: Coefficients of heat transfer [6] in the area close to the wall between the pebble bed and the steel wall under the assumption of a mean structural temperature of 310°C

T [°C]	$\alpha_{Bed/W}$ [W/m^2 K]	
	Front zone (330 mm)	**Rear zone (170 mm)**
300	3600	1700
350	4500	2000
400	5400	2200
450	6400	2500
500	7500	2800
550	8500	3100
600	9600	3400
650	10,700	3700

Table 4: Power balance of a section of DEMO outboard blanket at the torus center with a poloidal height of 12 mm for a solution with mixed pebble beds and tube coils

(A)	Powers generated [W]:	
	First wall	
	- volumetric heat power	6906
	- surface heat power	6380
	Mixed pebble bed including cooling tube	45,726
	Total	**59,012**
(B)	Power extracted [W]:	
	First wall channel (one half)	15,834
	Coolant tube in the breeder zone (one half)	43,178
	Total	**59,012**

(C) Helium mass flow, m_{He}, and temperature rise, ΔT_{He}:

	First wall channels	**Cooling tubes**
m_{He} [kg/s]	0.1230	0.0556
$T_{He,\ inlet/outlet}$ [°C]	251/300.5	300.5/450
ΔT_{He} [K]	49.5	149.5

Table 5: Constitutive data of 316L steel [12]

T [°C]	**λ [W/mK]**	**c_p [J/kg K]**	**α_{EXP} 10^{-6} [1/K]**
20	14.57	476	16.16
50	14.99	482	16.36
100	15.71	491	16.64
150	16.42	499	16.87
200	17.13	508	17.09
250	17.84	517	17.28
300	18.55	526	17.47
350	19.27	535	17.64
400	19.98	544	17.81
450	20.69	552	17.97
500	21.40	561	18.13
550	22.11	570	18.28
600	22.83	579	18.43
650	23.54	588	18.58
700	24.25	597	18.72

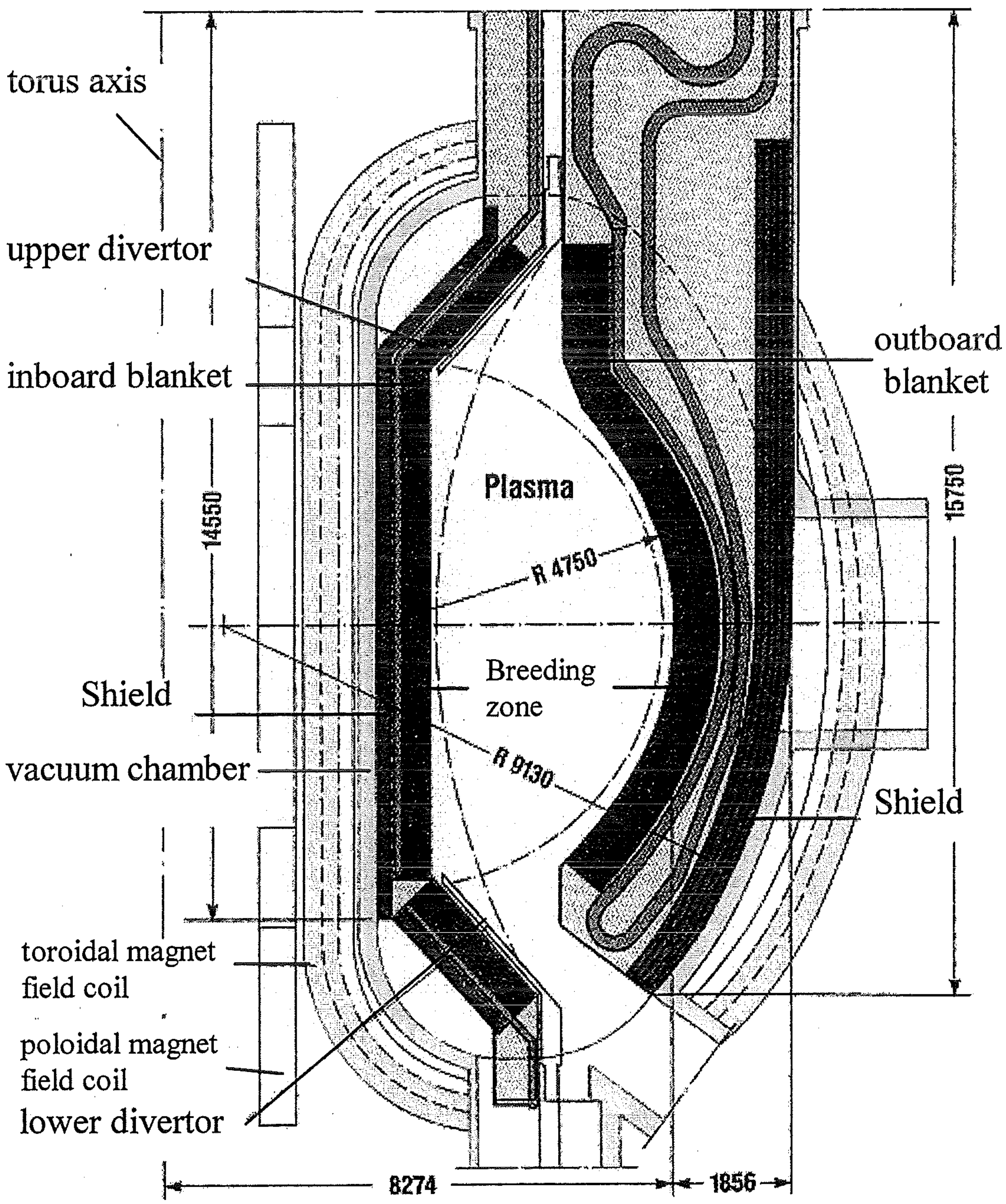


Fig. 1: Vertical cross section through the torus of the European DEMO reactor with ceramic breeder blankets [2].

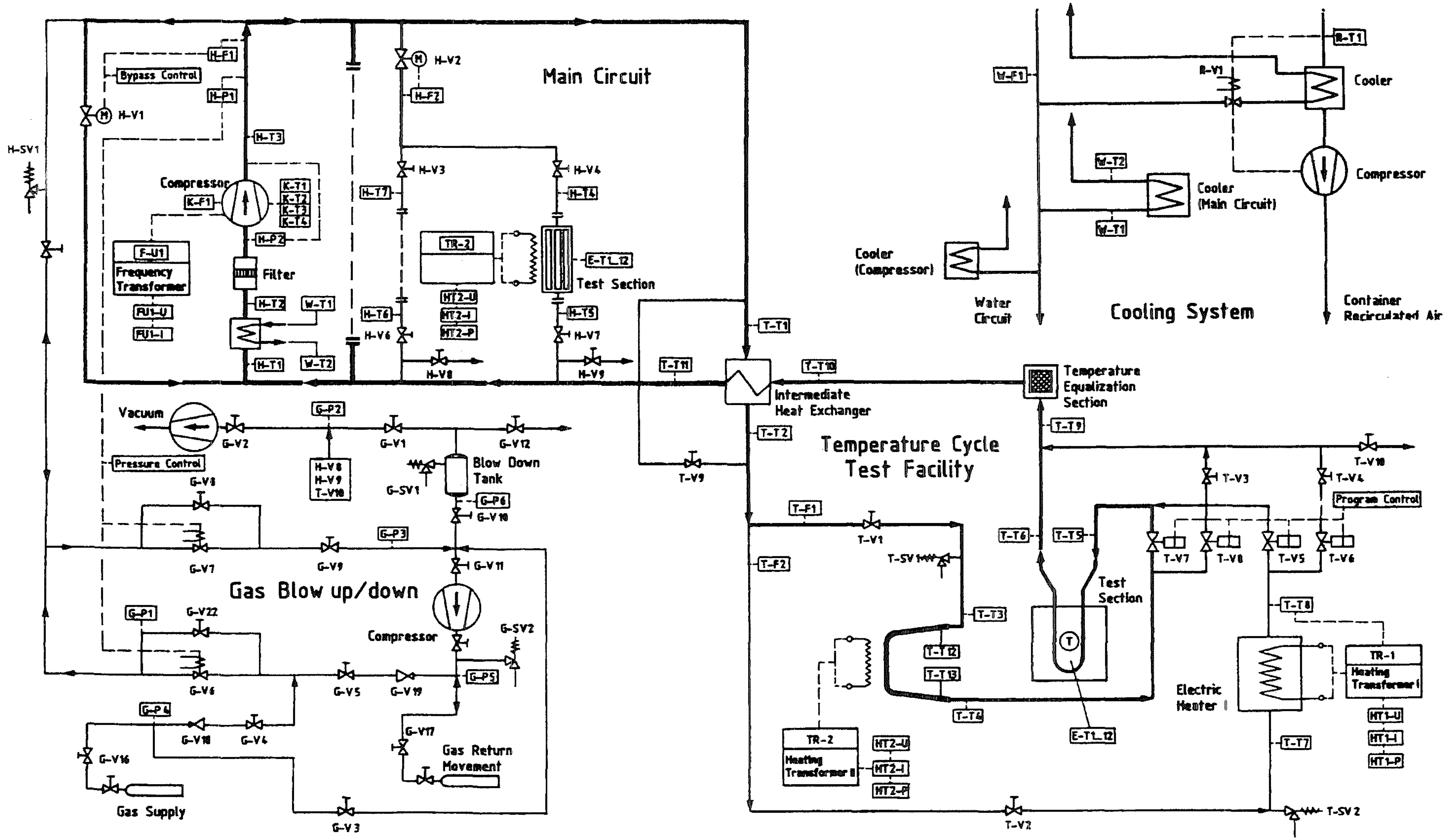


Fig. 2: Flowchart of the Helium Blanket Test Loop (HEBLO) including the test section of the second experiment with mixed pebble bed and hairpin shaped cooling tubes [5].

(Abbreviations: First order: E-T..=temp. monitoring in the test section, F=frequency transformer, G=gas supply, H=main circuit, HT=heater transformer, K=compressor, M=motor, T=test section circuit, TR=transformer, W=water circuit; Second order: F=flow rate, I=current, P= electrical power, pressure, T=temperature, SV=safety valve, U=voltage, V=valve)

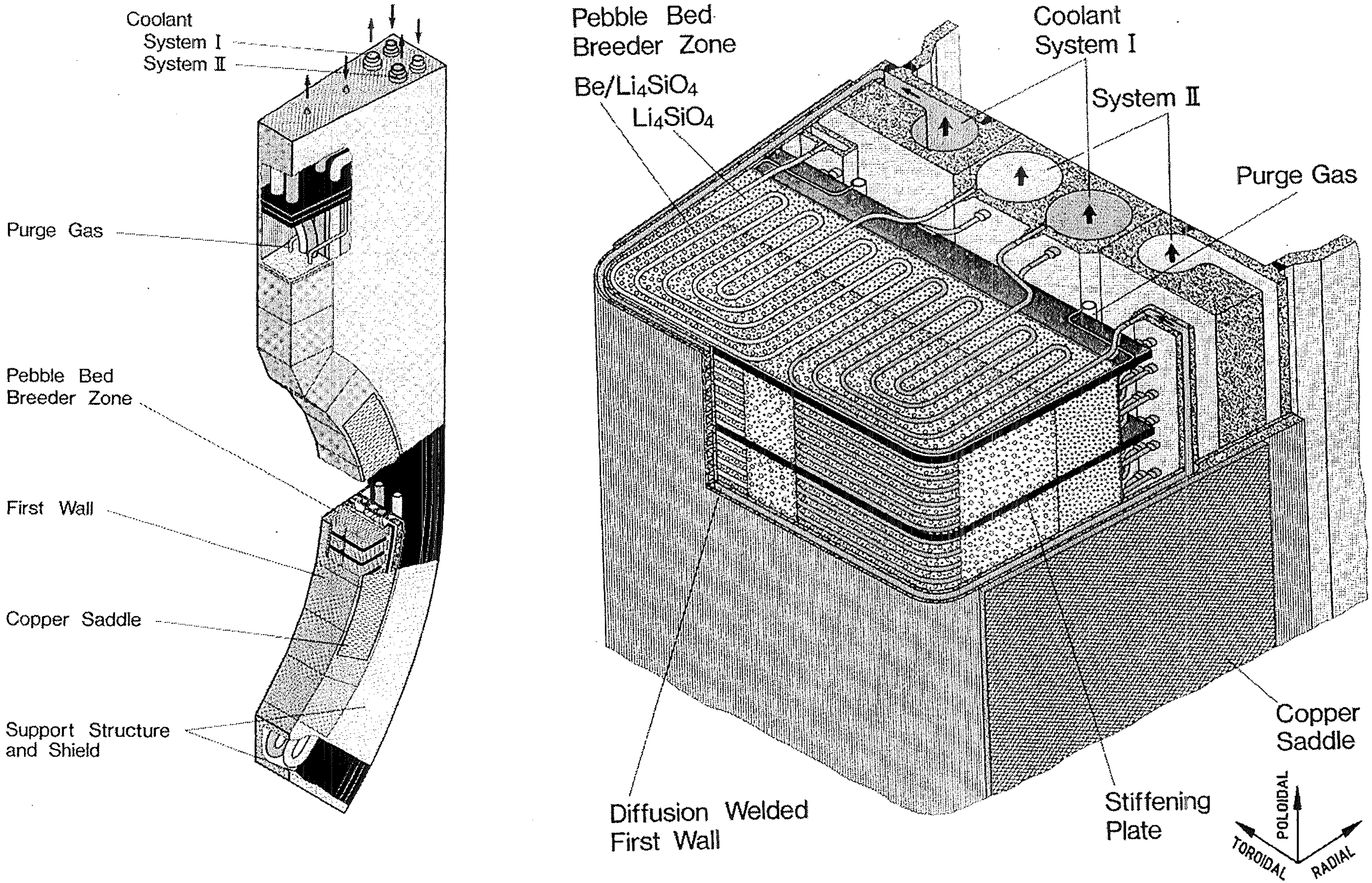


Fig. 3: Layout of an outboard blanket segment for a conceptual solution with mixed pebble bed and hairpin shaped tube coils in an isometric view with a detail of the central torus zone [2].

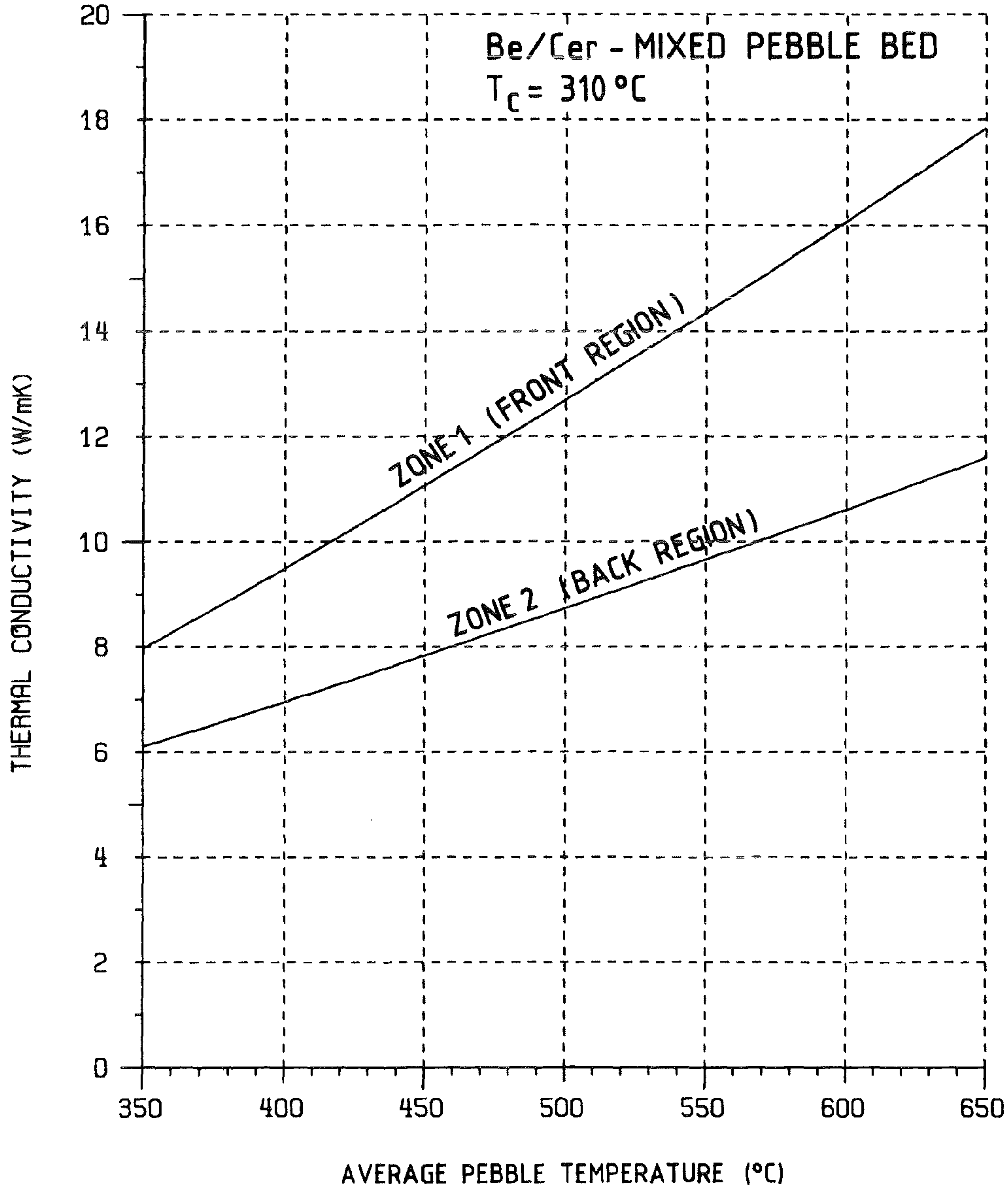


Fig. 4: Thermal conductivity of the mixed Li_4SiO_4/Be pebblebed [6] on the assumption of an average structural temperature of 310°C.

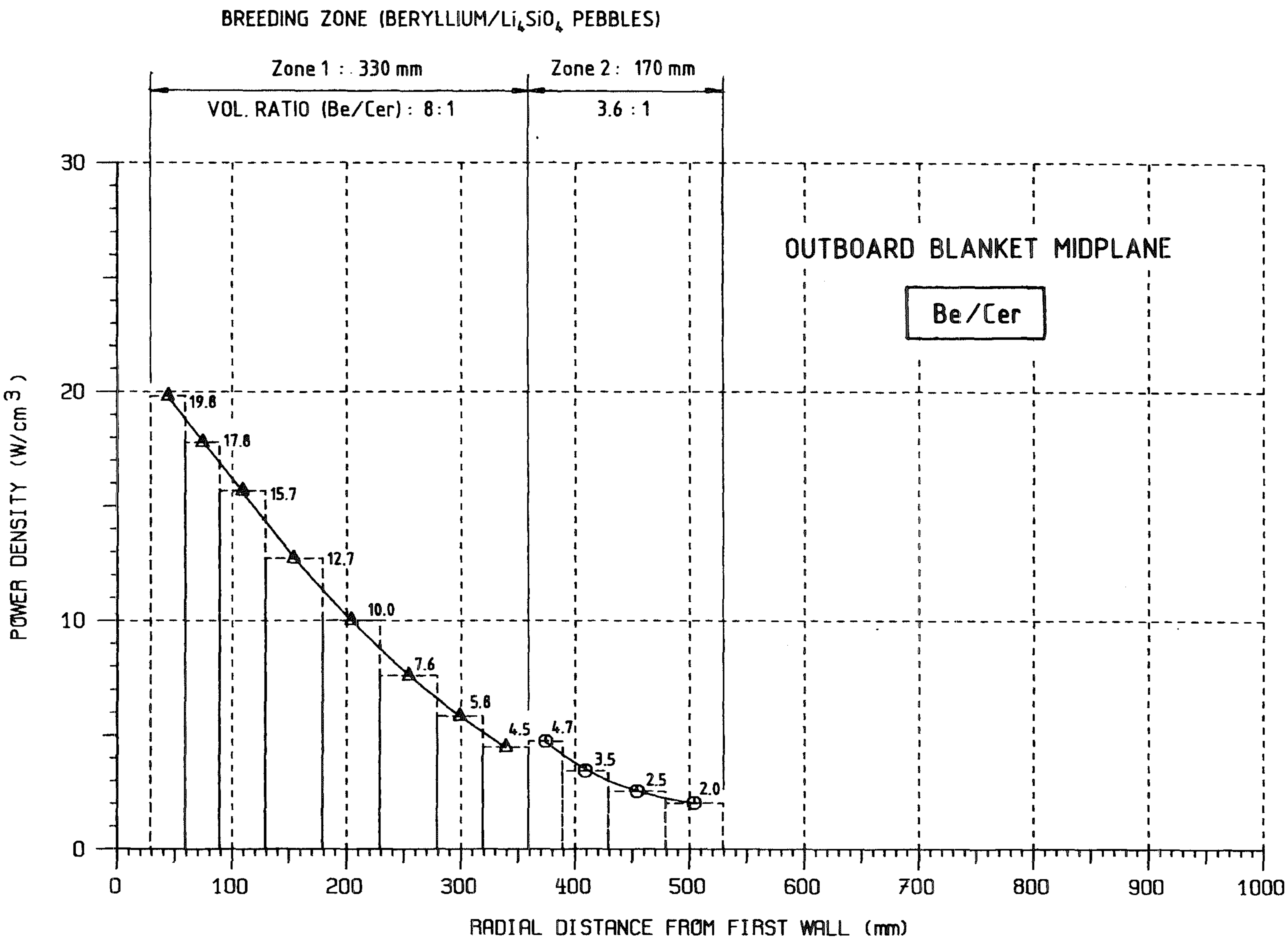


Fig. 5: Radial power density distribution in the mixed pebble bed across the equatorial midplane of the outboard blanket [10].

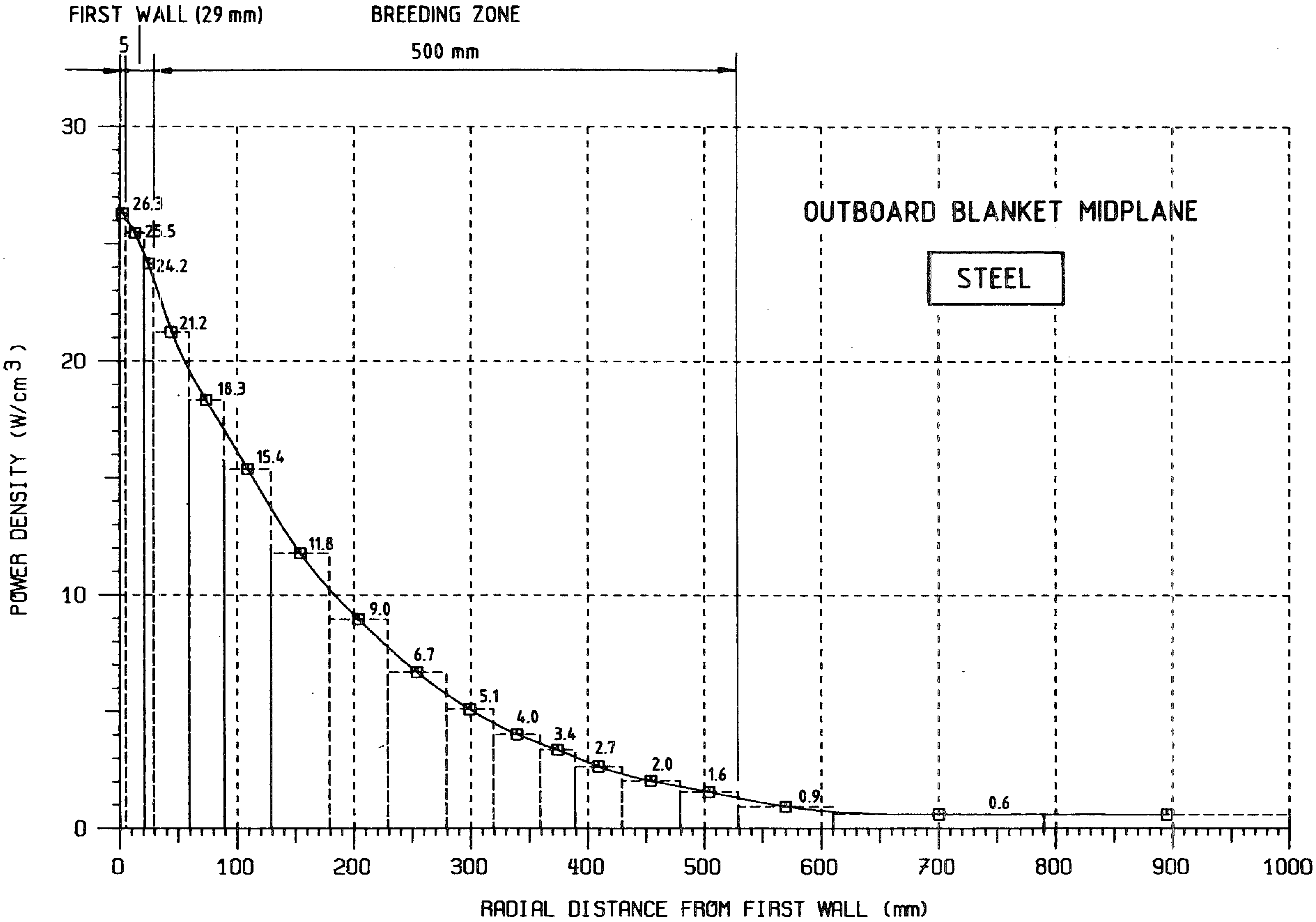
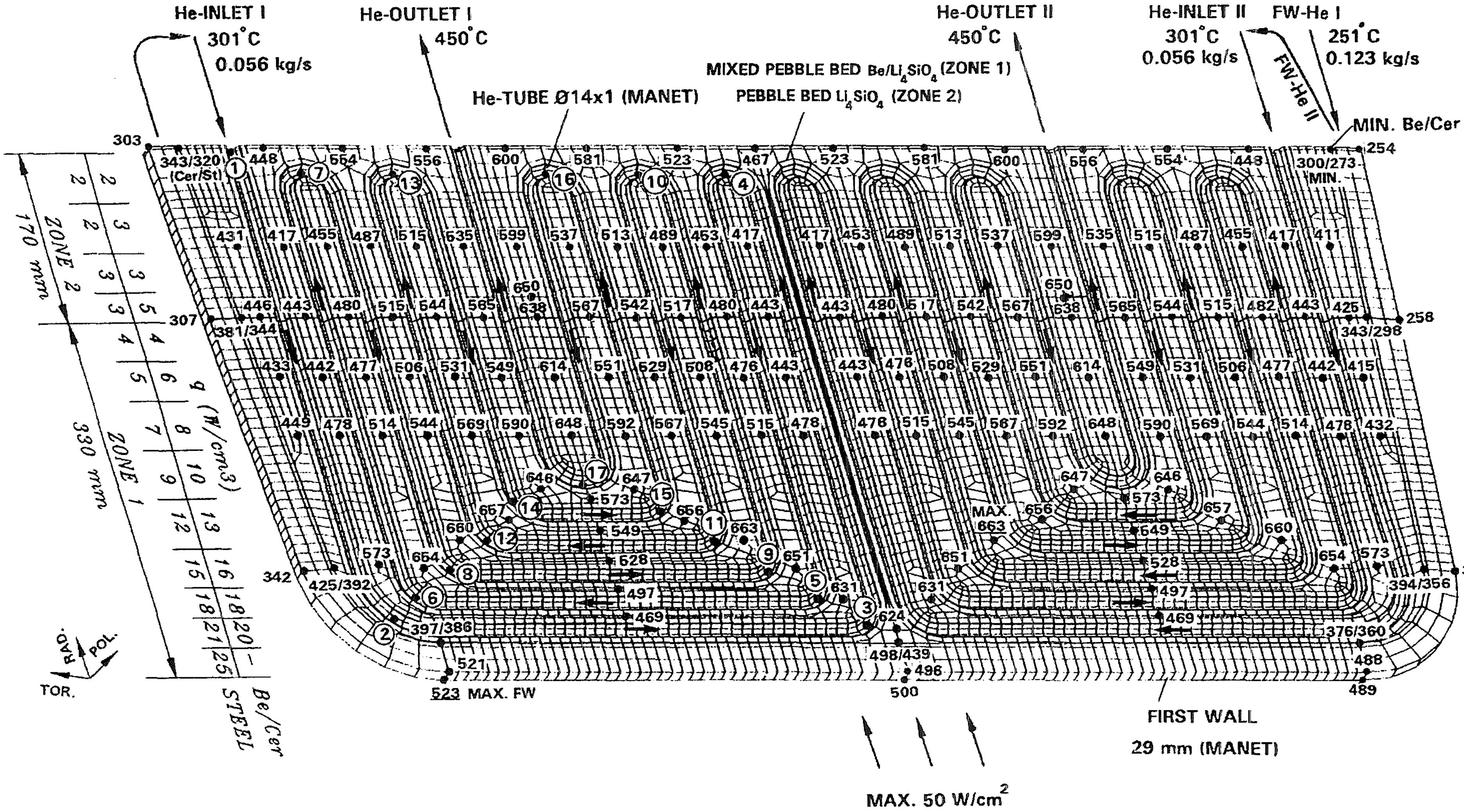


Fig. 6: Radial power density distribution in the steel structure across the equatorial midplane of the outboard blanket [10].



POINT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
He-TEMP. (°C)	301	312	326	335	345	358	367	376	386	394	402	410	417	424	429	436	443	450

Helium mass flow: one coil of tube 0.056 kg/s; one First Wall channel 0.123 kg/s

Fig. 7: Temperature distribution (°C) at the center of an outboard blanket segment for a conceptual solution with a mixed pebble bed and tube coils.

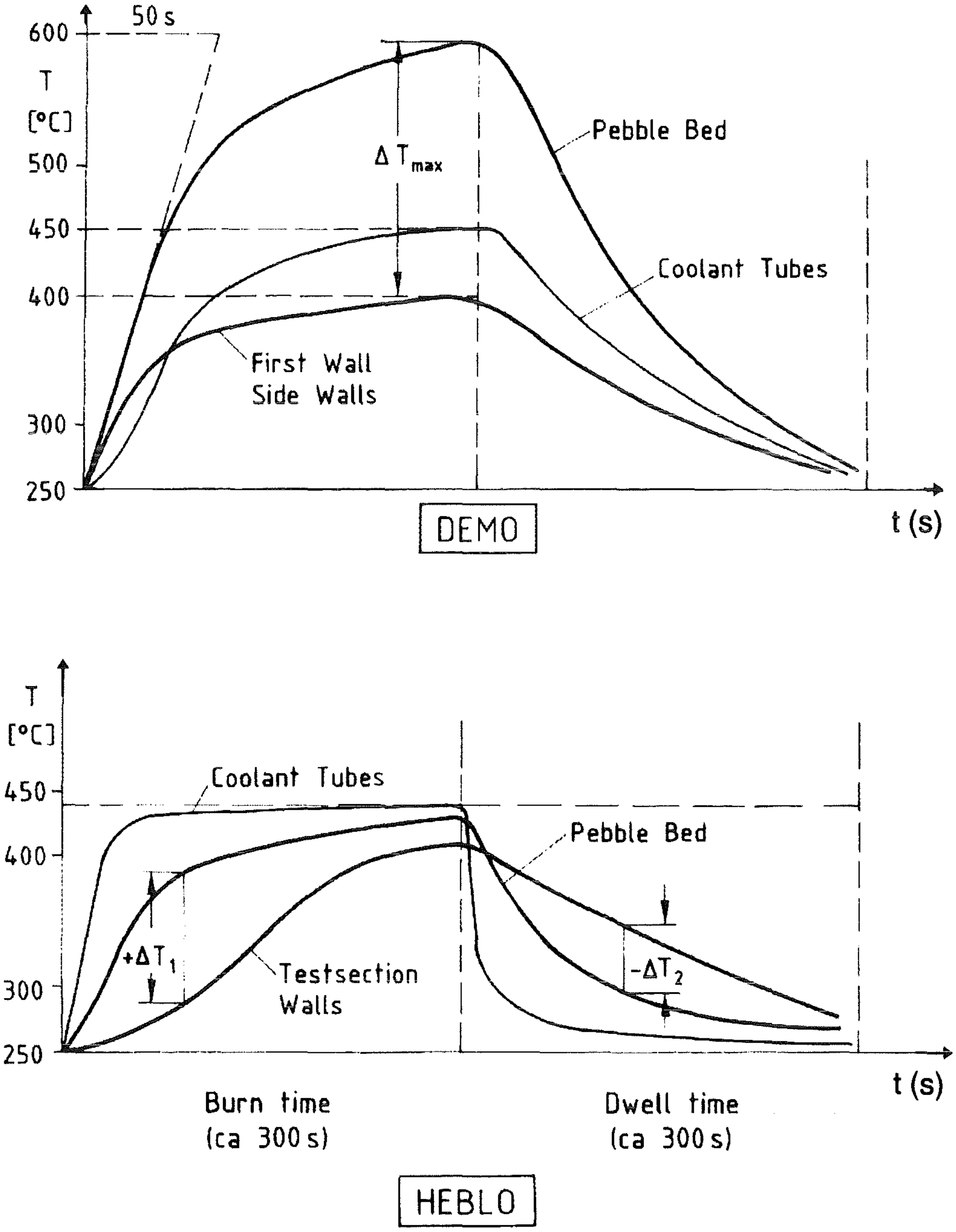


Fig. 8: Qualitative temperature development and gradients in the DEMO blanket (top) and in the HEBLO test section (bottom) during a power transient.

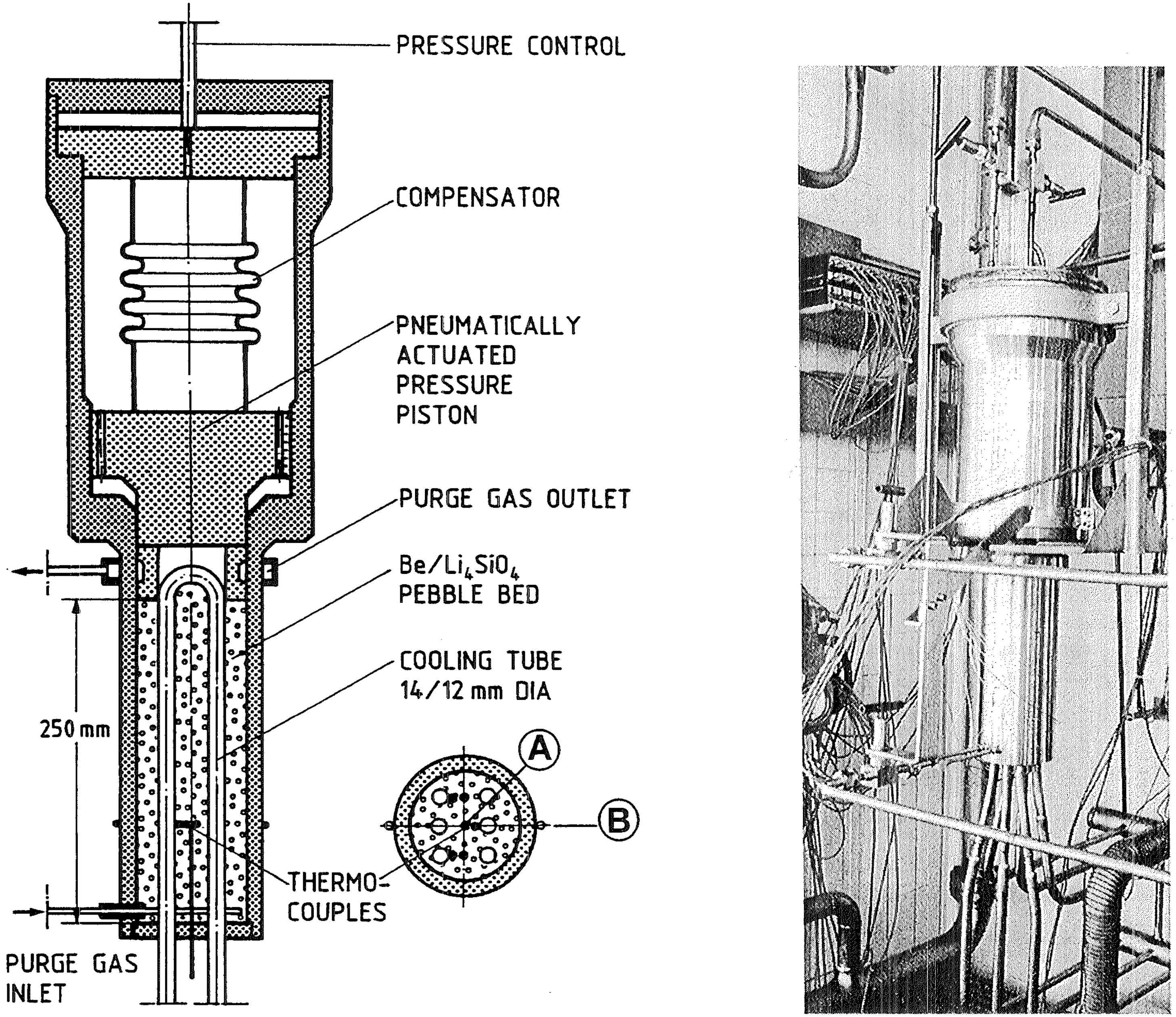


Fig. 9: HEBLO test section with a mixed pebble bed and hairpin shaped cooling tubes.

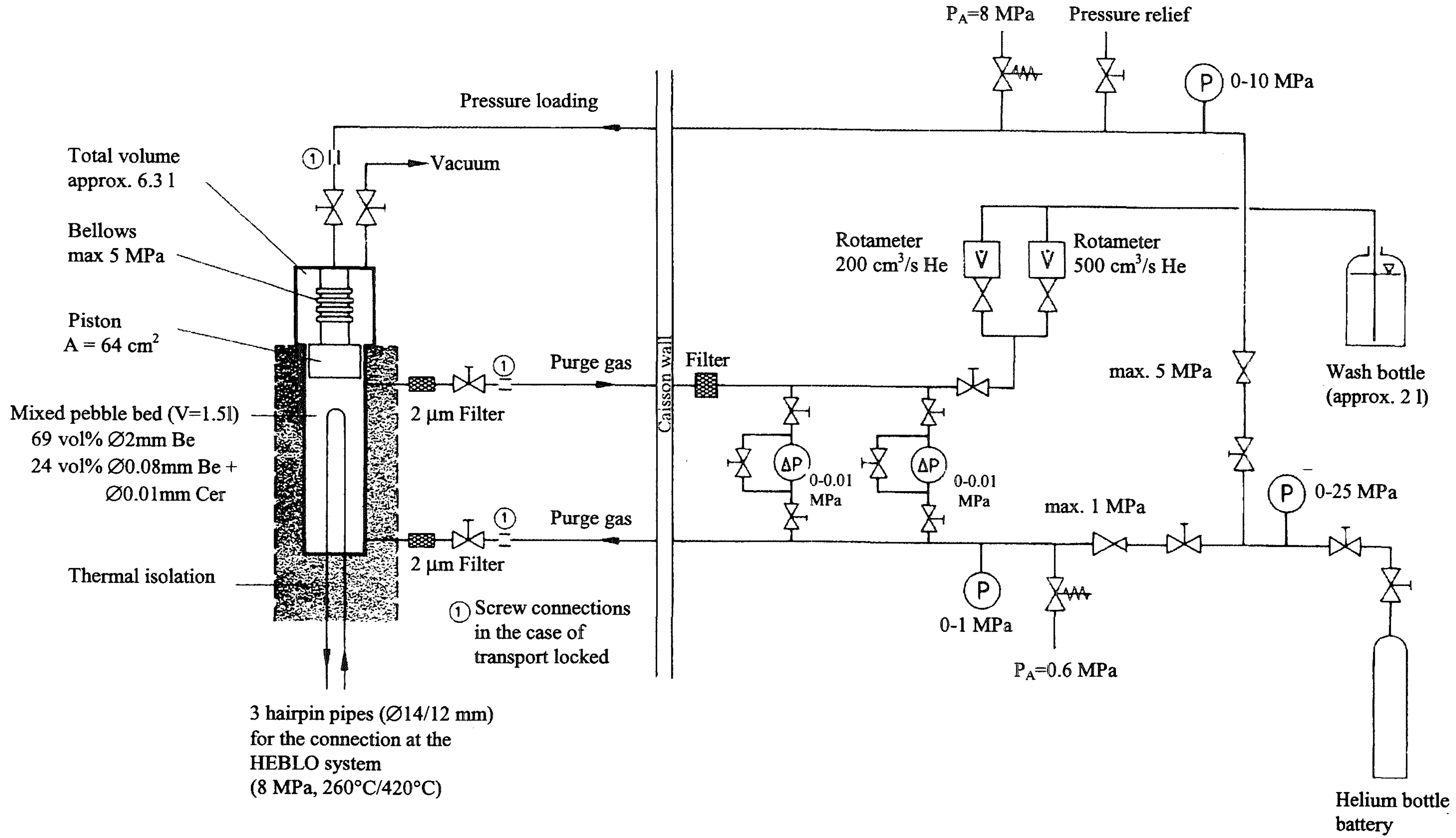


Fig. 10: Purge gas flowchart for the test section with a mixed pebble bed.

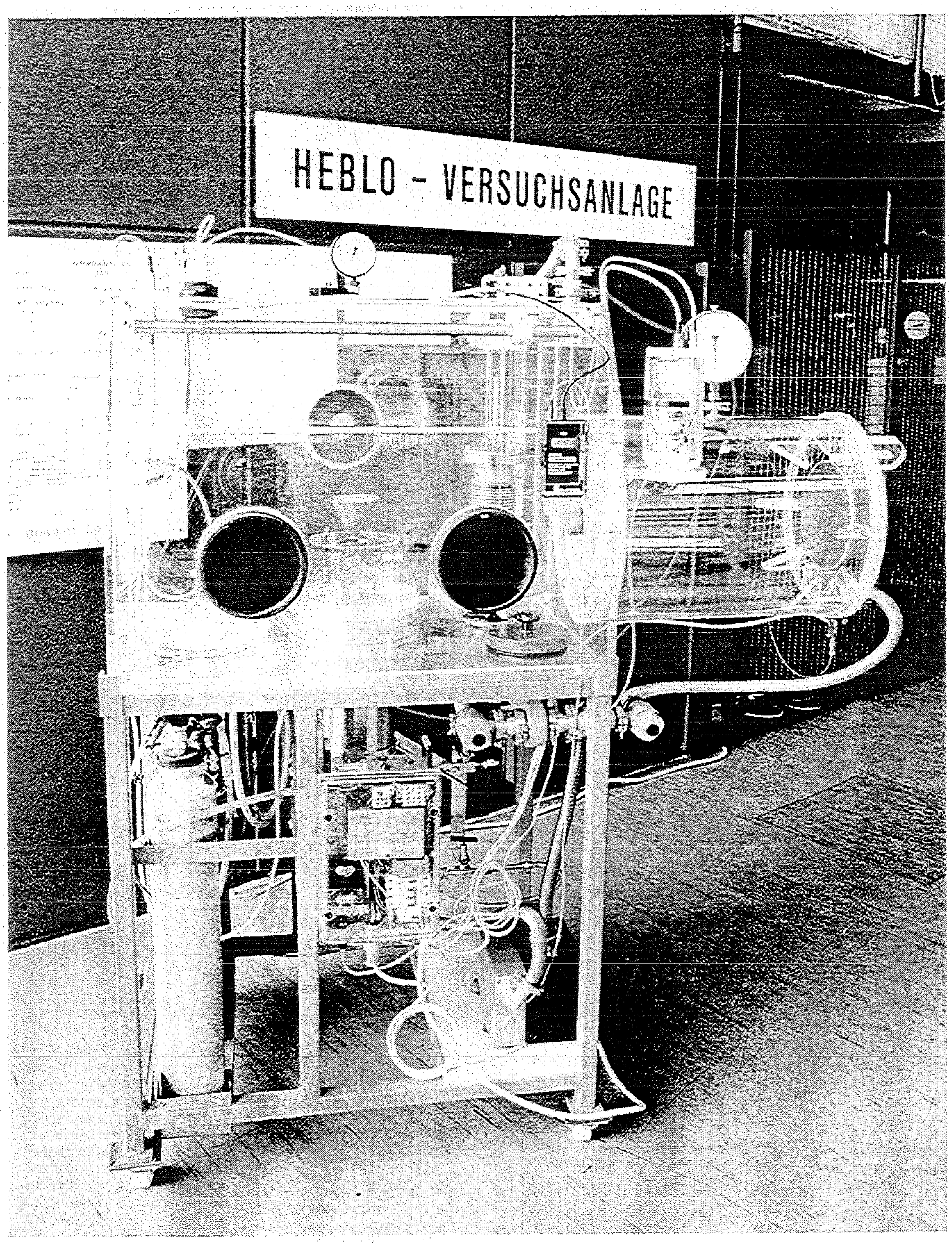


Fig. 11: Glovebox for handling beryllium manufactured by Goraieb company for HEBLO experiments.

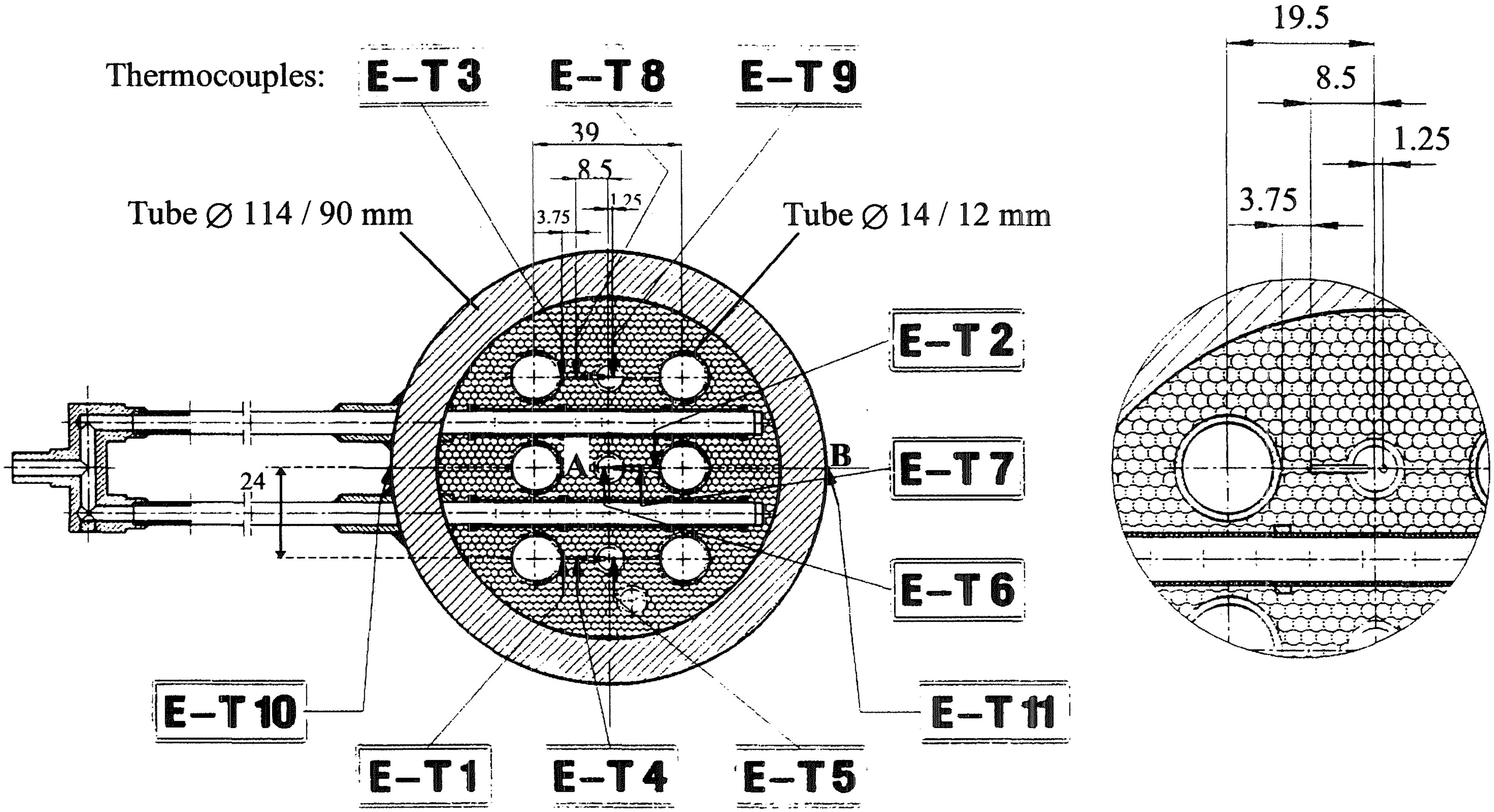


Fig. 12: Arrangement of thermocouples in the second HEBLO test section with a mixed pebble bed in a horizontal plane 80 mm above the bottom plate.

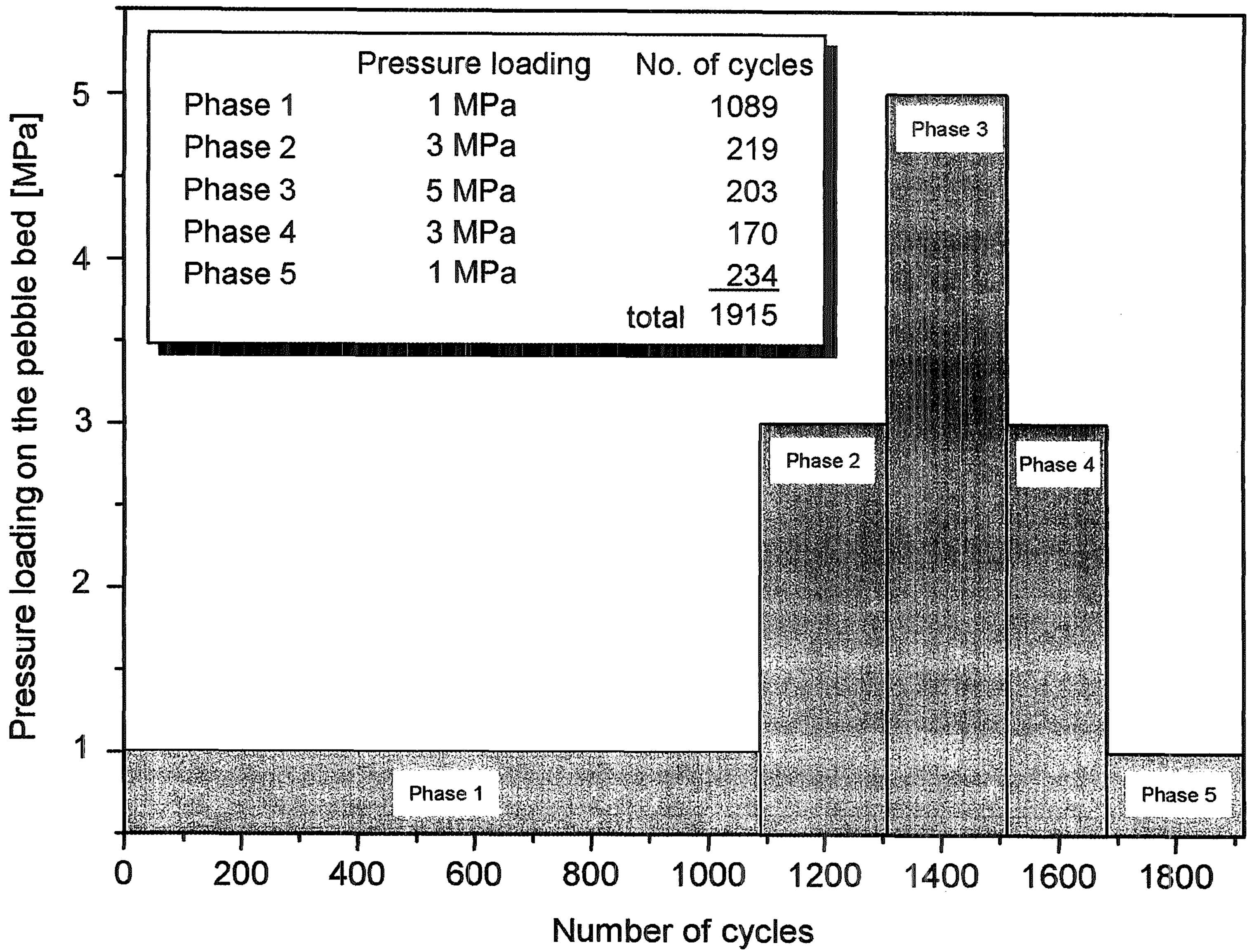


Figure 13: Overview of the test cycles of the second HEBLO experiment with a mixed pebble bed.

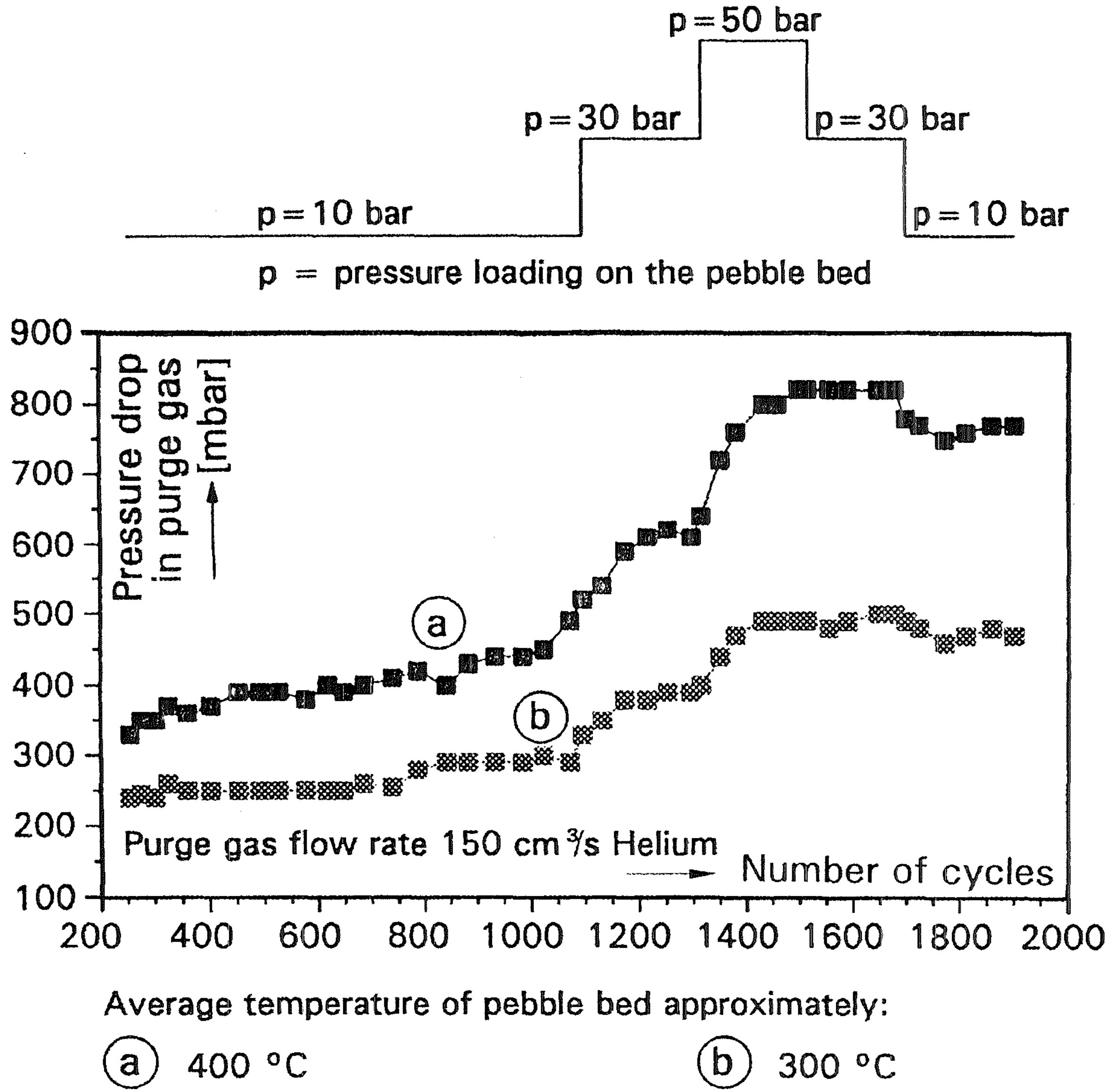
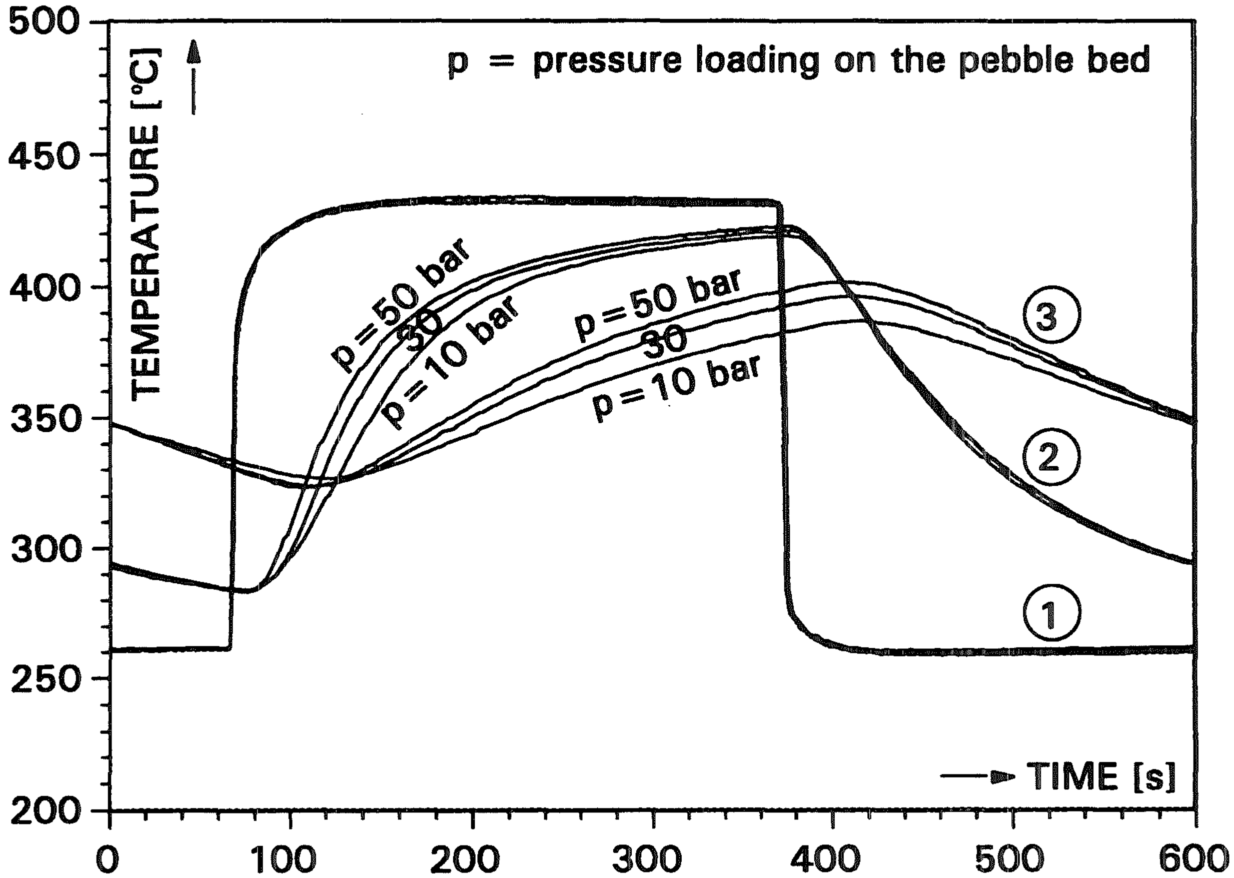


Fig. 14: Measured pressure drop in the purge gas at various pressure loads in the mixed pebble bed in the second HEBLO experiment.



1 Helium gas inlet

2 Center of pebble bed (Pos. A, Fig. 12)

3 Outer wall of test section tube (Pos. B, Fig. 12)

Fig. 15: Measured transient temperature profiles at the helium gas inlet and in the test section during test cycles in the second HEBLO experiment.

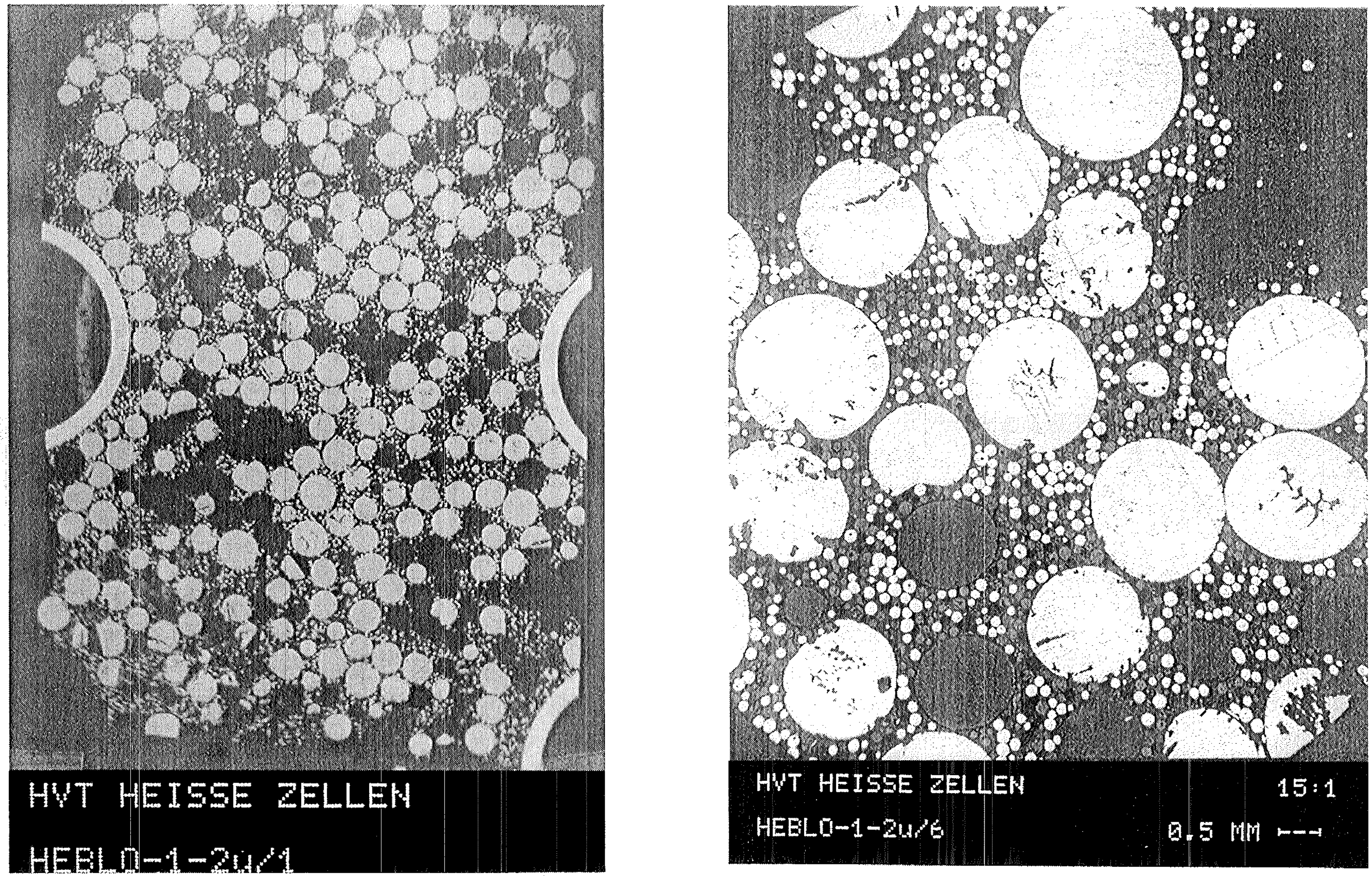


Fig. 16: Metallurgical photographs of the mixed Be/Li_4SiO_4 pebble bed in the second HEBLO experiment taken at a section below the pressure piston made by the Hot Cells of FZK [11] (2.7x and 15x, respectively, bright: Be, dark: Li_4SiO_4).

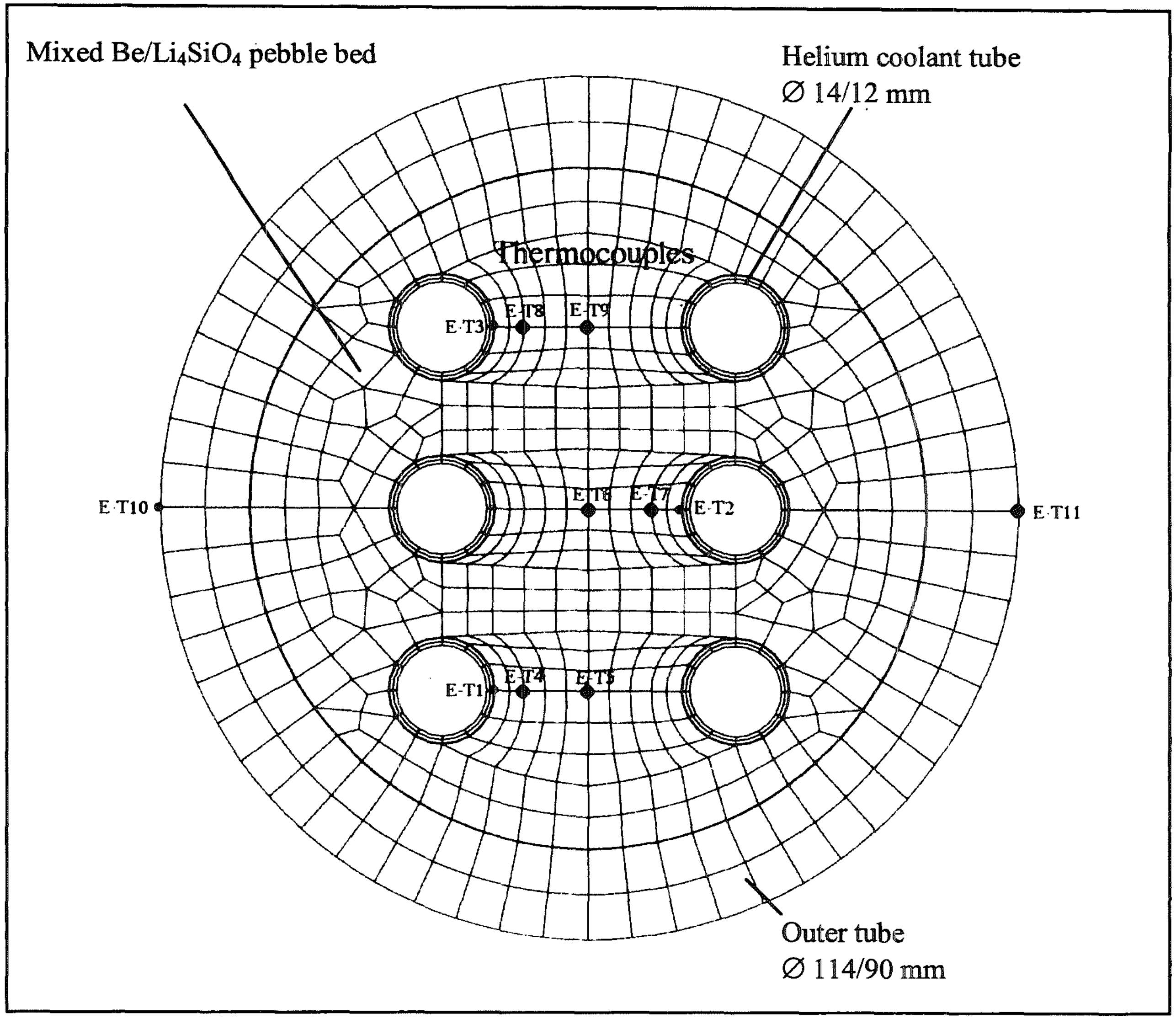


Fig. 17: 2D finite-element model for the horizontal cross section of the second HEBLO experiment.

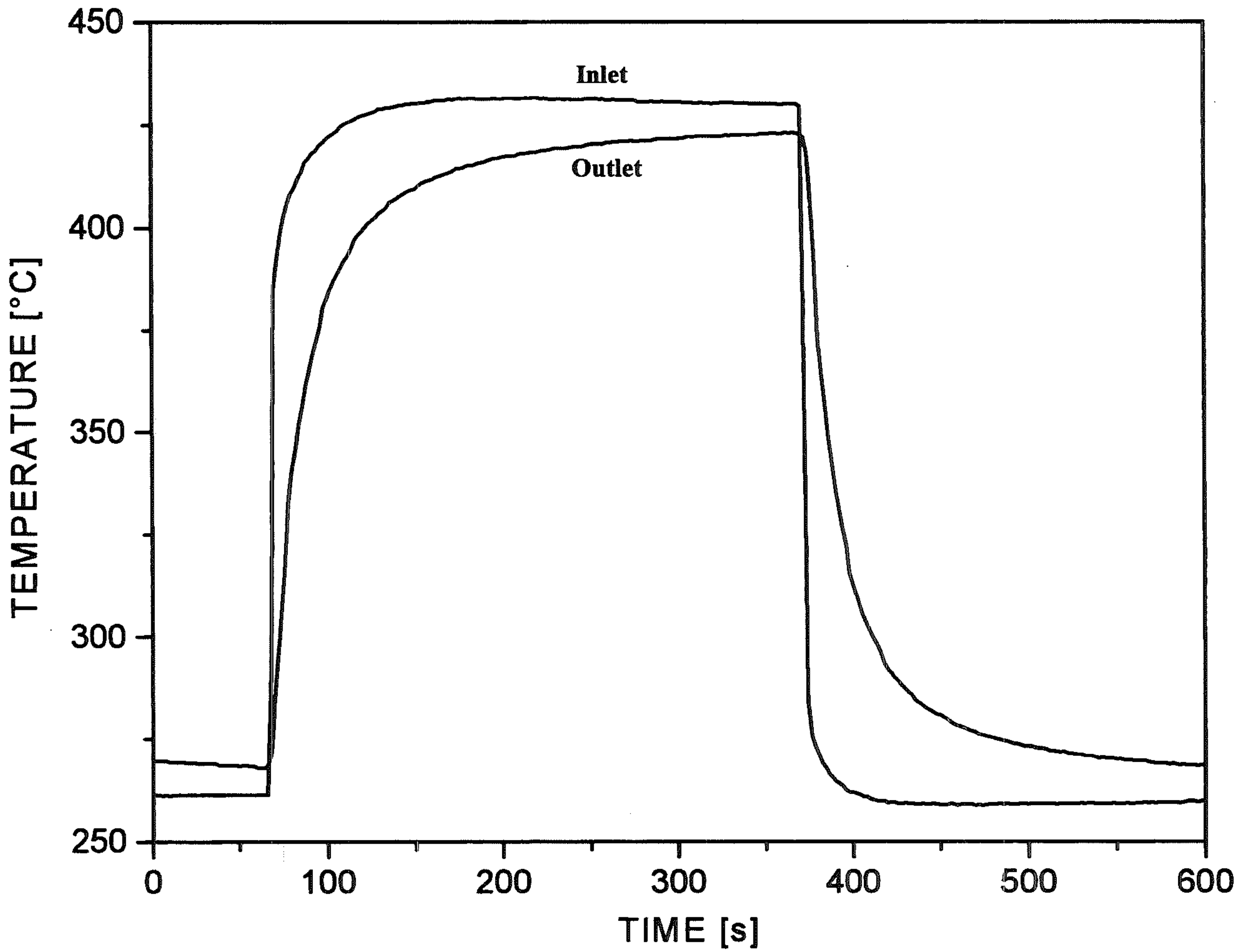


Fig. 18: Measured helium inlet and outlet temperatures over cycle No. 1046 (Δt = 600 s).

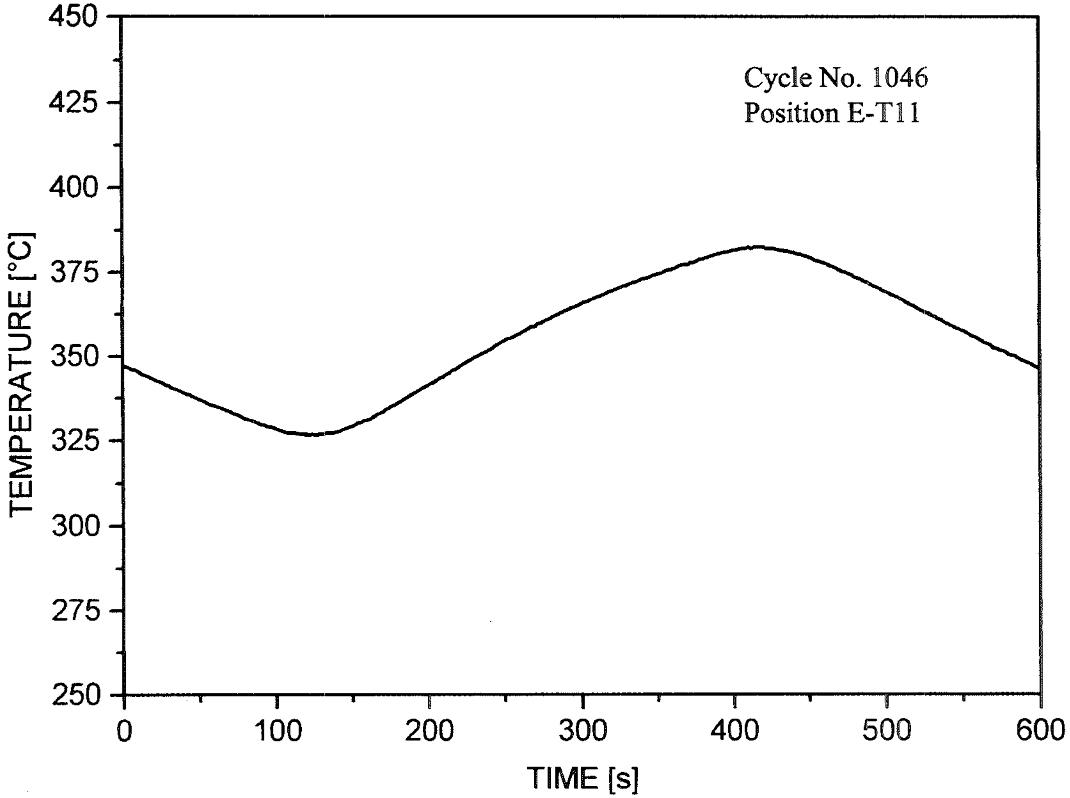
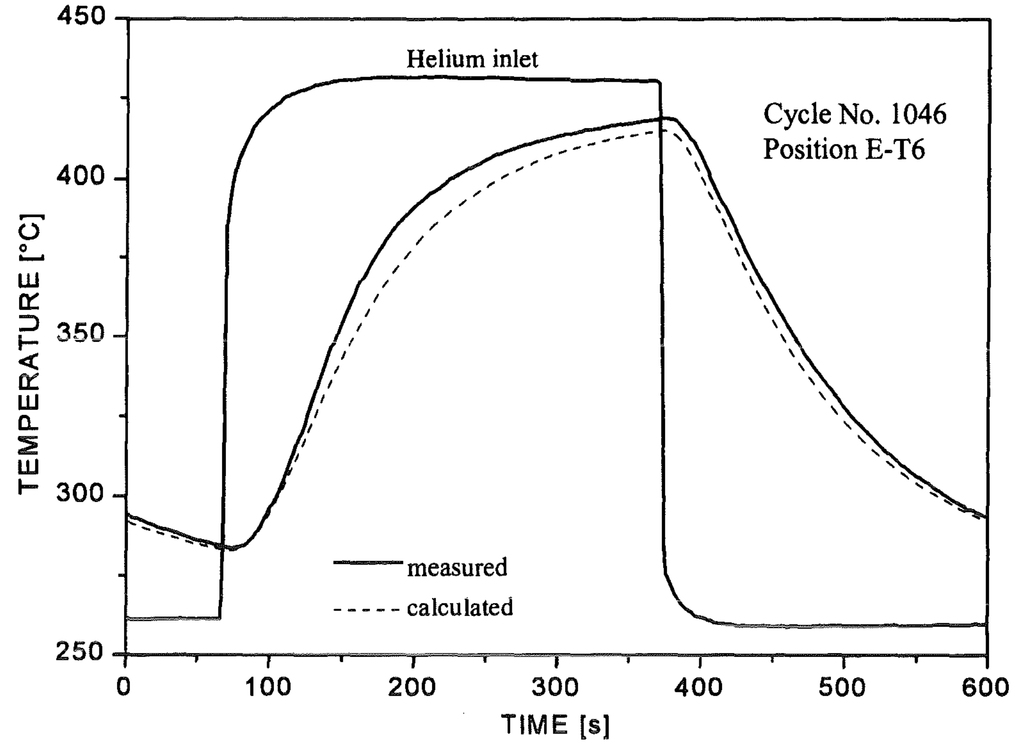


Fig. 19: Measured temperature at the outer tube wall of test section (ET-11, according to Fig. 12, Pos. B).



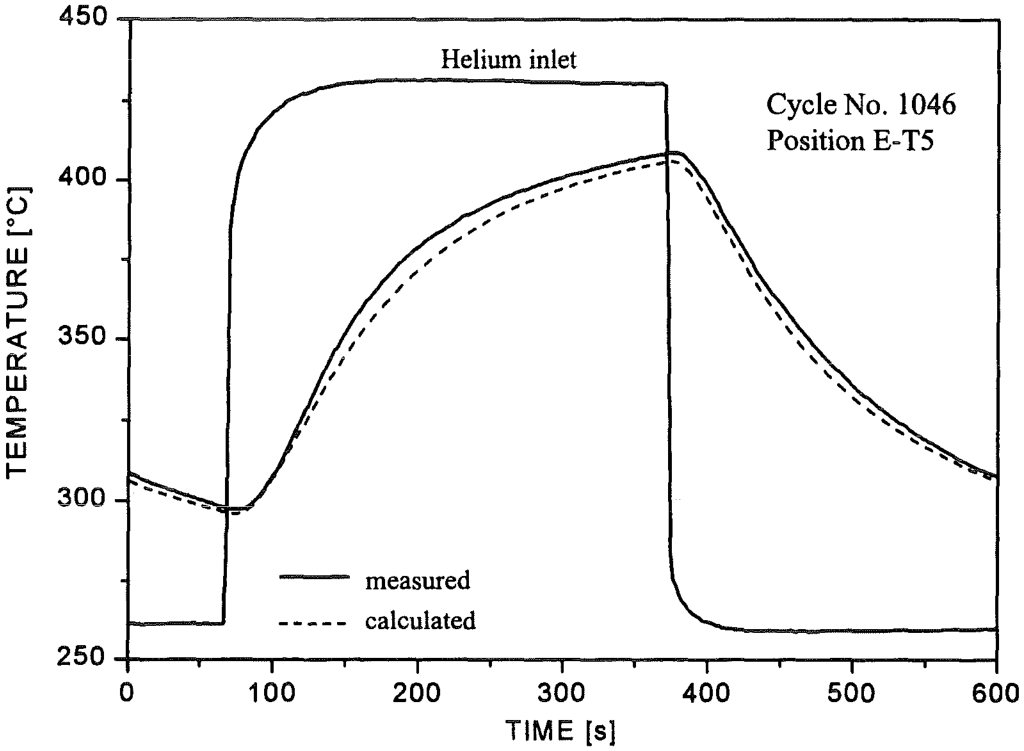
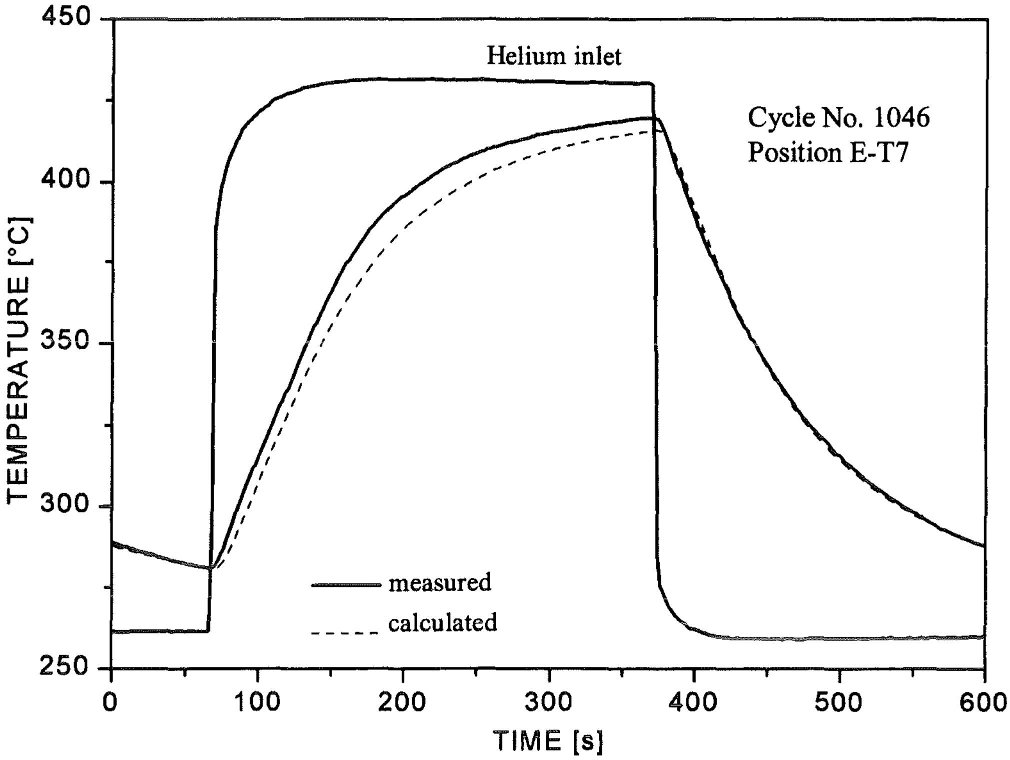


Fig. 20: Measured and calculated temperatures in the pebble bed in the middle of the hairpin tubes (ET-6 and ET-5, according to Fig. 12).



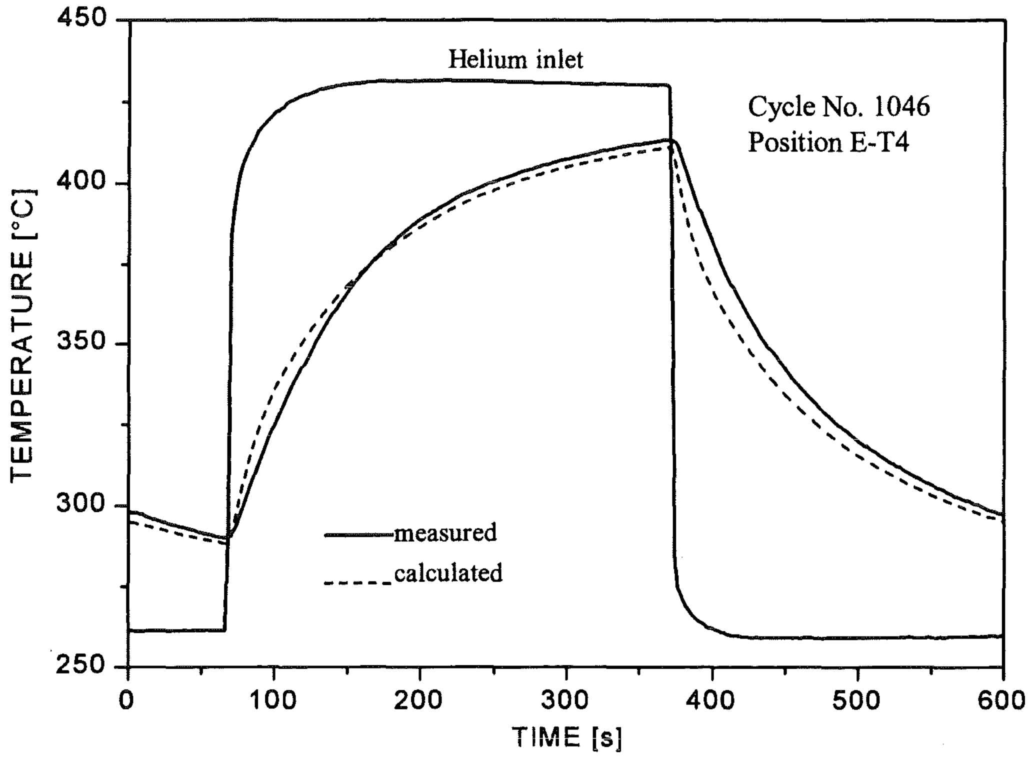


Fig. 21: Measured and calculated temperatures in the pebble bed in the zone between the middle of the hairpin and the tube wall (ET-7 and ET-4, according to Fig. 12).

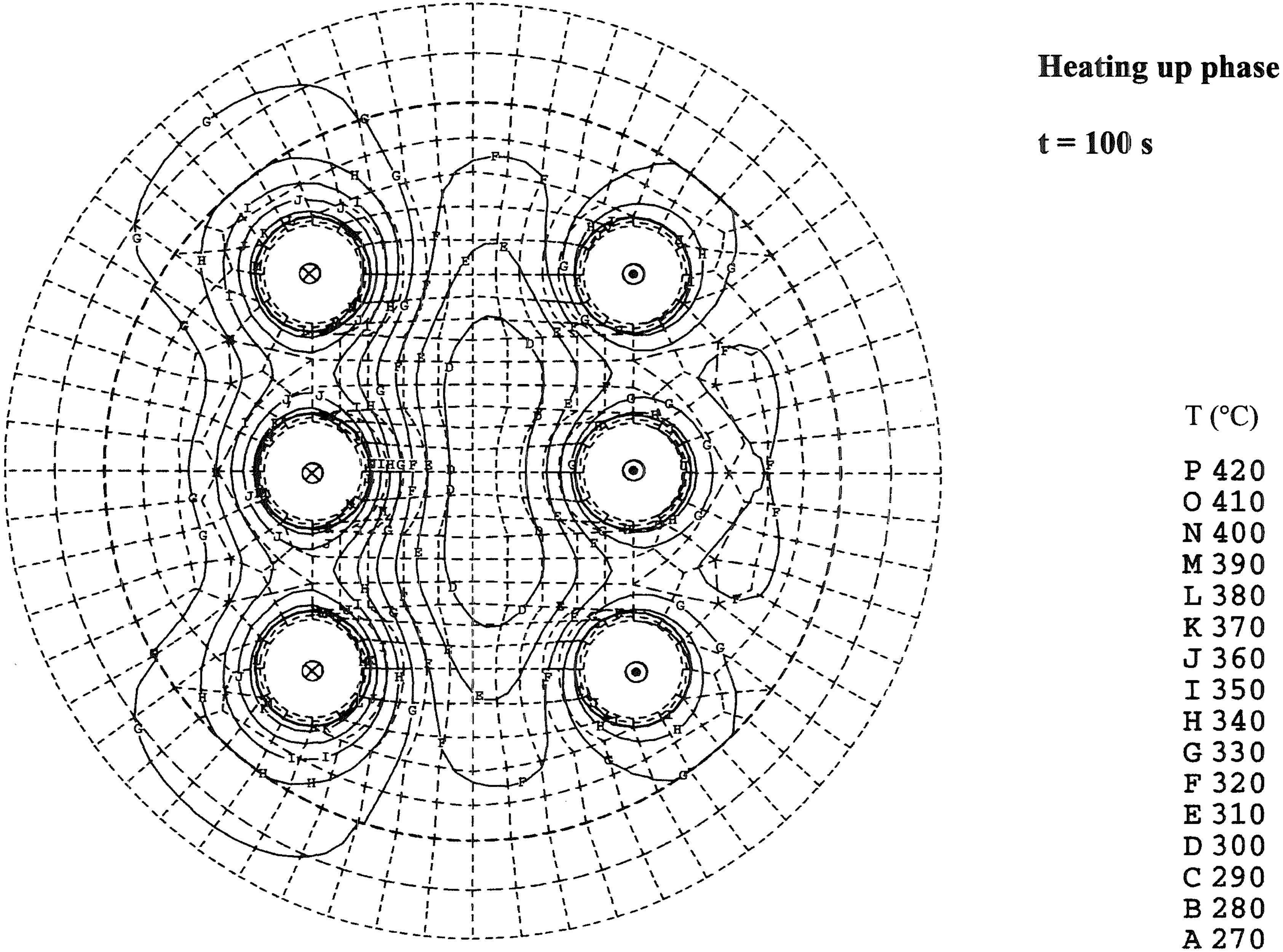


Fig. 22: Calculated temperature profiles in the pebble bed during the heating phase (t =100 s).

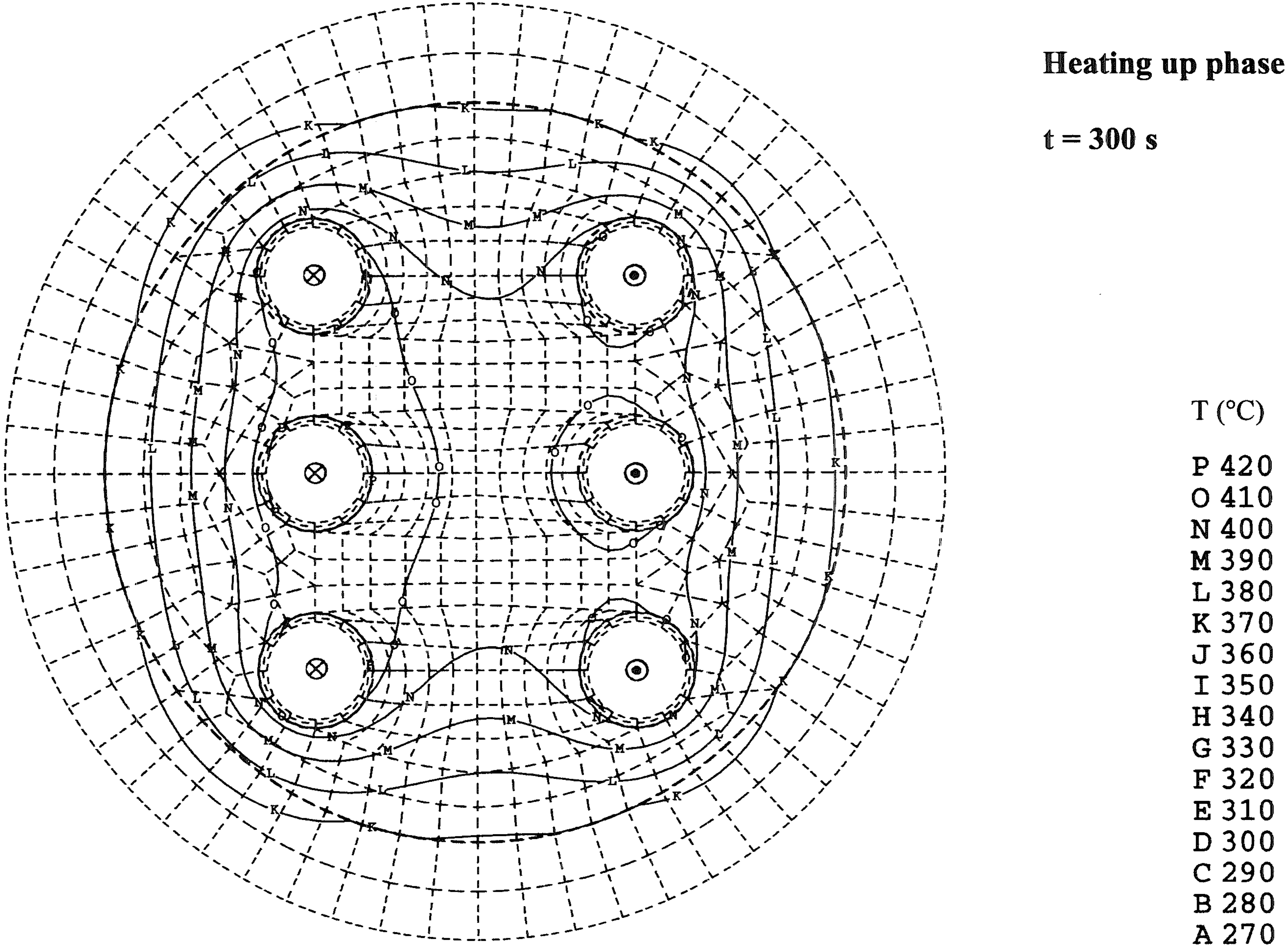
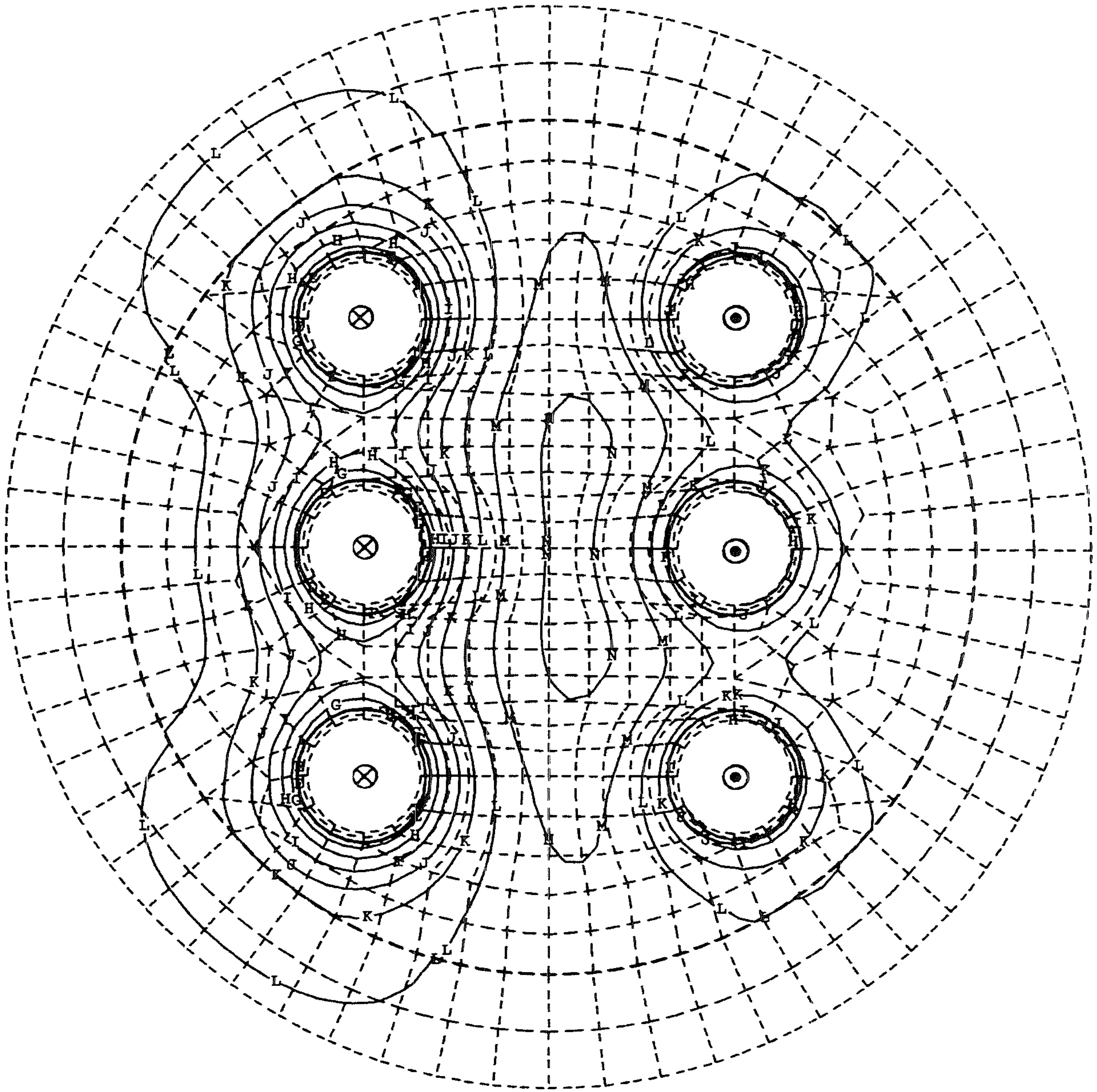


Fig. 23: Calculated temperature profiles in the pebble bed during the heating phase (t =300 s).



Cooling down phase

t = 400 s

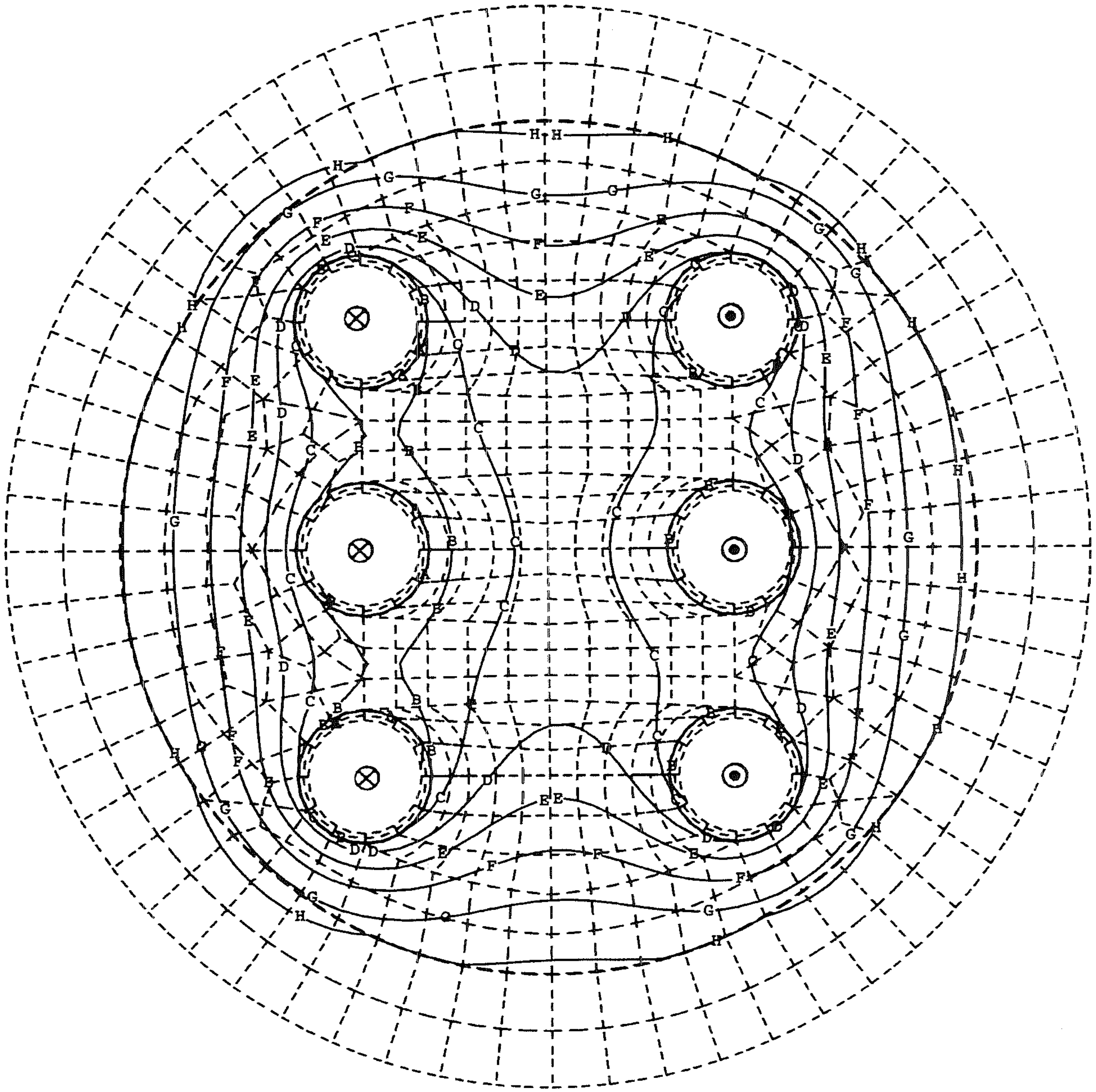
T (°C)

P 420
O 410
N 400
M 390
L 380
K 370
J 360
I 350
H 340
G 330
F 320
E 310
D 300
C 290
B 280
A 270

Fig. 24: Calculated temperature profiles in the pebble bed during the cooling phase (t =400 s).

Cooling down phase

t = 600 s



T (°C)

P 420
O 410
N 400
M 390
L 380
K 370
J 360
I 350
H 340
G 330
F 320
E 310
D 300
C 290
B 280
A 270

Fig. 25: Calculated temperature profiles in the pebble bed during the cooling phase (t =600 s).