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DRILLED-CORE STORAGE HEATER FOR A HYPERSONIC TUNNEL

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16. Abstract

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SUMMARY

A design for a graphite drilled-core storage heater for supplying heated nitrogen gas to a hypersonic propulsion facility was developed using results from a transient-heat-transfer program. Hole size and spacing were determined from the results of the computer program and from consideration of thermal stress and cost factors.

A model of the proposed matrix design was fabricated and tested in a pilot storage heater facility to evaluate thermal stress limitations and to compare performance of the heater with predictions based on the heat-transfer calculations.

Thirteen cycles of heating and blowdown operation were run with the pilot heater at conditions simulating the maximum thermal stress in the lower sections of the proposed large heater core. No cracking or deterioration of the matrix had occurred during the test program. Measured matrix temperatures were only in fair agreement with the results of a two-dimensional transient-heat-transfer program, but the discrepancies are believed to be due to thermocouple installation errors.

INTRODUCTION

The Lewis Research Center Hypersonic Propulsion Facility utilizes an inductively heated graphite storage heater to heat nitrogen which is then mixed with cold oxygen to form a synthetic air for propulsion testing. The original configuration for the heater was a graphite susceptor, 1.83 meters in diameter and 8.5 meters long with 9.2-centimeter-thick walls, filled with 6.35-centimeter-diameter graphite balls. The susceptor is heated inductively by external, water-cooled, copper induction coils using a 180-hertz power supply.

An alternate drilled-core design was proposed because of the failure of several of the susceptor sections in the existing heater, probably due to thermal stresses in the graphite. Cored zirconia bricks have been proposed for storage heaters (refs. 1 and 2) and are currently in use in pilot heater designs. The cored-brick design allows higher mass flow rates through the heater than the conventional pebble heater because the lower pressure drop lessens the bed lift limitation where pressure drop equals the bed weight. In addition, for fixed mass flow rate, proper choice of matrix geometry allows greater heat-storage capacity and a closer approach of gas exit temperature to matrix temperature than the pebble bed.

The design limitation for the cored ceramic matrix was found to be the thermal stresses developed in the web between holes due to the temperature difference between the gas and the matrix (ref. 2). Thin webs are desirable to minimize thermal stress but are not optimal for heat storage. Since the thermal and structural properties of selective grades of graphite are considerably better than those of ceramics at elevated temperatures, the design restrictions are expected to be much less severe with graphite.

The present investigation was directed toward determining a near-optimum core configuration for the existing heater for a fixed core size and mass flow requirement based on heat transfer, thermal stress, and cost factors. The basic design was tested at 1/7 scale in a pilot heater, primarily to evaluate the structural integrity of the matrix when exposed to the same thermal stress levels as will be encountered in the larger heater. A secondary objective was the comparison of measured matrix and gas temperatures to predictions from a design heat-transfer program.

SYMBOLS

A_f matrix face area

C_p gas specific heat

D_H hole diameter

h heat-transfer coefficient

k thermal conductivity of solid

N_{Nu} Nusselt number, $h/D_H k$

N_{Pr} Prandtl number, $C_p \mu / k$

N_{Re} Reynolds number, $D_H \rho u/\mu$

N_{St} Stanton number, $\dot{q}/\rho u C_p(T_o - T_g)$

$\dot{q}$ heat-transfer rate

R nondimensional radius, r/r_o

r radius

S_t tangential stress

S_z axial stress

$s/_D$ hole-spacing-to-diameter ratio

T temperature

T_m defined by eq. (5)

T_{bi} initial matrix temperature of constant-temperature plateau

u gas velocity

$\dot{W}$ mass flow rate

z axial distance

α coefficient of linear expansion

ϵ Young modulus

μ viscosity

ν Poisson ratio

ρ gas density

Subscripts:

a outer radius

g gas

o inside radius

HEAT-TRANSFER DESIGN

The heater matrix performance was evaluated for a range of hole sizes and hole-spacing-to-diameter ratios for drilled holes spaced on an equilateral triangular pitch. Performance evaluation was based on blowdown time for fixed mass flow and gas temperature drop. Factors limiting the range of hole sizes and spacing are the drilling costs and thermal stress.

A one-dimensional computer program was utilized for the design optimization which calculates the time - axial temperature history of the matrix and gas. The program was originally written for design of pebble bed heaters but was modified for the drilled-core configuration by substituting the convection equation for turbulent flow in a tube (ref. 2)

$$N_{St} = 0.023\, N_{Re}^{-0.2}\, N_{Pr}^{-2/3} \qquad (1)$$

for the relation developed in reference 3 for the pebble bed heater

$$N_{St} = 0.4\, N_{Re}^{-0.437}\, N_{Pr}^{-2/3} \tag{2}$$

The usual assumptions of infinite heat conductivity in the radial direction and zero conductivity in the axial direction allowed solution of the transient equations of heat transfer by finite difference methods. The initial axial temperature profile is arbitrary and gas flow rate is invarient with time.

A two-dimensional transient heat conduction-convection program was used to compare results of the experimental temperature measurements. The program was a modification of the General Dynamics/Astronautics variable-boundary transient heat conduction computer program (ref. 4). Modifications included provisions for forced convection. Heat transfer in the drilled holes was computed with the Dittus-Boelter equation

$$N_{Nu} = 0.023\, N_{Re}^{0.8}\, N_{Pr}^{0.4} \tag{3}$$

which differs from equation (1) only in the exponent of Pr.

The matrix was divided into nodes in the radial and axial directions. The hole density was assumed to be uniform in the region bounding the drilled area and zero in the outer region. The following assumptions or limitations were observed:

(1) Finite conduction between nodes, both in the radial and axial directions

(2) Graphite properties variable with temperature; thermal conductivity variable with grain direction and adjusted for the presence of the holes

(3) Arbitrary initial axial matrix temperature profile; assumed uniform radial temperature profile

(4) No radiation interchange across the holes or plenum

(5) Variable fluid mass flow rate with time during heater pressurization; mass flow per hole assumed to be uniform

(6) Convection interchange not allowed between adjacent radial nodes

(7) No fluid mixing allowed in the plenums separating vertical sections of the matrix

(8) Fluid density and viscosity variable with temperature; heat capacity assumed to be constant at an average value

Results of One-Dimensional Heat-Transfer Program

Table I lists the various combinations of hole size, spacing, mass flow rate, and initial temperature profile in the matrix. Computations were performed for three alternate profiles shown in figure 1. Profiles B and C assumed linear slopes to the maximum matrix temperature of 2775 K at heights of 2.44 and 3.66 meters. These profiles approximately bracketed the average temperature gradients measured during heating tests of the original configuration at lower maximum temperature levels. Profile A was estimated for the new configuration with additional insulation below the matrix to reduce heat loss to the support plate. Matrix height was fixed at 8.5 meters.

The results are shown in figure 2 as exit gas temperature as a function of running time. The effect of heater mass flow rate is shown in figures 2(a) and (b) for a hole size of 2.54 centimeters, s/D of 1.4 and 1.6, and initial matrix temperature profile A. The flow rate of 59 kilograms per second is close to the lift limit for the original heater design with graphite balls and determined the throat size for the design of the hypersonic facility nozzles. Since pressure drop is not a limitation for the drilled-core design, calculations for higher mass flows were made. The effect of s/D for a hole size of 1.9 centimeters is shown in figure 2(c) for profile A, and the effects of initial profile for hole sizes of 1.27 and 1.9 centimeters are shown in figure 2(d). Hole sizes smaller than 1.27 centimeters and s/D larger than 2.0 were not run because of drilling cost and thermal stress considerations. Increases in running time occur for decreasing hole size and increasing s/D, but the gains in run time would appear to yield diminishing returns outside of the range considered.

The results of figure 2(c) are crossplotted in figure 3 for temperature decrements of 50° and 100° C. The curves flatten for s/D in the range of 1.8 to 2.0. A temperature drop of 100° C for a run time of 120 seconds (1.9-cm holes) would be acceptable from the facility viewpoint, since at maximum mass flow rate, the hot nitrogen from the heater is diluted with cold nitrogen and oxygen, resulting in a mixture temperature drop of only 60° C.

Figure 4 shows the results of calculations for a larger core (1.81 m) and greater height (9.15 m), which can be accommodated by slight redesign of the existing heater core. The mass flow rates bracket the hot nitrogen flow rate required for Mach numbers of 5 to 7. Calculations for the pebble bed were performed for a uniform initial bed temperature of 2775 K using the heat-transfer relation of equation (2) and the original bed configuration. The lower temperature drop of the drilled-core design compared to results of figure 2(c) is due to the lower mass flux (more holes for the increased diameter) and to increased core height. Pressure drop for this configuration is quite low, and no attempt was made to determine mass flow limitations of the core design. Thermal stress considerations are expected to be limiting in the design and will depend on the grade of graphite considered.

Thermal Stress

The analysis of the thermal stress developed by the radial temperature gradient in the matrix material around a hole is given by reference 2. The holes in the matrix are arranged with an equilateral triangular spacing, and the geometry for the heat-conduction problem is approximated by a cylindrical tube in which the area at the outer radius r_a is set equal to the area of the hexagon described by the maximum-temperature isotherms (fig. 5).

The maximum stress during cooling of the matrix is the tensile stress at the hole surface r_o. The radial stress is zero, so that the tangential and longitudinal stresses are given by

$$S_t = S_z = \frac{\alpha\epsilon}{1 - \nu}(T_m - T_o)$$

The mean temperature T_m is defined by

$$T_m = \frac{2}{r_a^2 - r_o^2}\int_{r_o}^{r_a} Tr\,dr \tag{5}$$

The mean temperature difference is determined by equating the radial heat conduction from the cylinder to the heating of the fluid per unit length for quasi-steady-state conditions

$$T_m - T_o = \frac{D^2}{8}\,\frac{C_p}{k}\,\frac{\dot{W}}{A_f}\,\frac{\partial T_g}{\partial z}\,R_{a,3} \tag{6}$$

where

$$R_{a,3} = R_a^2\left[\frac{R_a^4\left(\ln R_a - \frac{3}{4}\right) + R_a^2 - \frac{1}{4}}{\left(R_a^2 - 1\right)^2}\right]$$

$$R_a = \frac{r_a}{r_o} = 1.05\ s/D$$

and $\partial T_g/\partial z$ is the axial gas temperature gradient determined from the heat-transfer program.

The limiting temperature difference for crack initiation can be specified from the properties of graphite (ref. 5) and equation (6) as

$$T_m - T_o = \frac{S_t(1 - \nu)}{\alpha \epsilon}$$

For Union Carbide grade-PGX graphite, a good structural-quality graphite available in large sizes, minimum tensile strengths allow a temperature difference of 80° C across the grain, or 105° C with the grain direction.

The radial temperature difference between the average web temperature and the temperature at the hole surface was calculated from equation (6). The axial gas temperature gradient was obtained from the one-dimensional transient-heat-transfer program for the case of 1.9-centimeter-diameter holes and initial matrix temperature profile A as a function of s/D. The results are shown in figure 5. At an s/D of 2.0, a safety factor of 1.53 to 2.0 results, depending on grain orientation. Thermal stress levels may be reduced by reducing the slope of the initial temperature distribution (e.g., profiles B and C), or by reducing the web thickness in the region of maximum axial temperature gradient near the bottom of the core without excessive performance loss.

The configuration chosen for the hypersonic facility heater was 1.9-centimeter-diameter holes with a s/D of 2.0. The choice was made on the basis of performance with acceptable cost and a limitation on the allowable thermal stress due to the radial temperature gradient at the hole surface. The use of 1.27-centimeter-diameter holes will double the number of holes required and approximately double the drilling cost, with only marginal gains in performance. The use of 2.54-centimeter-holes with s/D much greater than 1.6 would result in unacceptable thermal stresses.

There remains a question of the combined thermal stresses, especially near the periphery of the cylinder, where the hole density must be lower to ensure sealing surfaces against gas leakage from the pressure vessel annulus bypassing part of the core. An experiment was designed to determine if a thermal stress problem existed, either between holes or at the outer surface of the cylinder. Stresses between holes can be modeled with the use of equation (6), for the same hole geometry, if the products of mass flux and axial temperature gradient are equal.

The model was designed to simulate the bottom portion of the facility heater; the maximum axial gas temperature gradient occurring at about 0.5 meter from the bottom. Thermal stresses near the outer edge of the drilled core could not be readily scaled because of differences between the pilot and full-scale insulation and cylinder size. The undrilled outer portion of the cylinder was left thicker than in the proposed design for the large heater to ensure that the thermal stresses would be conservatively large.

EXPERIMENTAL METHOD

The pilot heater is shown in figure 6. The core was 26.7 centimeters in diameter and was fabricated from CS-grade graphite (equivalent to PGX for smaller sizes). The core consisted of four stacked sections 1.63 meters in total height, with plenums separating the sections to redistribute the gas flow (see fig. 8). Thirty-one holes, 1.9 centimeters in diameter were drilled on a 3.8-centimeter triangular pitch. The graphite sections are shown in figure 7.

The graphite core was wrapped with 5 centimeters of graphite felt insulation and silica fiber cloth. The insulated core was centered inside a water-cooled copper coil in the pressure vessel and heated inductively with a 200-kilowatt, 3000-hertz power supply.

Instrumentation

The drilled core was instrumented with tungsten/tungsten-26-percent-rhenium (W/W-26Re) thermocouples to monitor matrix and plenum gas temperatures. Thermocouple locations and construction are shown in figure 8. The matrix thermocouples were inserted through holes drilled radially into the core and cemented in place. The gas thermocouples were constructed with a slot machined into the end of the tungsten sheath, and the junction was positioned at the slot to allow for gas flow over the thermocouple junction. Exit gas temperature was measured with a W/W-26Re thermocouple shielded with a tungsten tee alined with the flow direction. The thermocouple was located at the centerline of the 5-centimeter-diameter duct, 1.07 meters downstream of the heater exit. Nitrogen gas flow rate was measured with a venturi flowmeter. Venturi Δp, heater annulus pressure, matrix Δp, and gas inlet and exit temperature were recorded on a light beam oscillograph. Matrix temperatures were recorded with a high-speed digital recording system.

Test Procedure

The graphite core was inductively heated over a period of 3 to 5 hours at a maximum power supply setting of 20 percent under positive nitrogen purge pressure. Heating was continued until a maximum matrix temperature of 2000 to 2150 K was obtained. On reaching the desired temperature, the power supply was put on cyclic operation at low power setting to maintain temperature as sensed by a radiation pyrometer. The matrix was allowed to soak at this condition for 1 to 2 hours to stabilize the axial temperature profile.

During the blowdown, heater power was turned off, the vent stack valve opened, and the heater pressurized with nitrogen. Pressurization time was 15 to 20 seconds, and the steady-state run time 90 to 110 seconds. A total of 13 heating and blowdown cycles were run at approximately the same values of bed pressure (6.9×10^{6} N/m^{2}), flow rate (0.95 kg/sec), and initial temperature profile. After each blowdown, the nitrogen supply valve was closed, allowing the heater to depressurize through the test section nozzle. During the entire test period, the heater was kept inerted with nitrogen.

RESULTS AND DISCUSSION

Temperature Measurements

Initial axial temperature profiles are shown in figure 9. The symbols represent the average for the run series, and the height of the vertical line the temperature range. Differences between symbols at different radial locations could not be attributed to the radial temperature profile since they were also located at different circumferential locations. Inspection of the induction coil after the test series revealed that it was eccentrically located with respect to the core over much of its axial length, so that it is believed that differences between initial thermocouple readings at the same axial location are due primarily to nonuniform circumferential heating.

Matrix temperature history is shown in figure 10 for six axial locations and three radial positions within the matrix. Computed results from the two-dimensional heat-transfer program are also indicated. Agreement between measured and calculated matrix temperatures are reasonable up to $z = 48.2$ centimeters. Poor agreement between measured and calculated matrix temperatures at the same radial locations is obtained at $z = 66$ centimeters and above. It appears that, except for the initial matrix cooling during pressurization of the heater (0 to 20 sec), the measured matrix cooling curves compare more favorably with calculated temperatures closer to the outer radius. Radial conductivity along the thermocouple sheath or electrical breakdown of the alumina insulation at temperatures above 1640 K may contribute to these disparities.

Exit gas temperature history during blowdown is shown in figure 11. Calculations using the one-dimensional and two-dimensional programs are shown for comparison. Results of the two-dimensional program are the area-averaged temperatures over the convective nodes. Initial temperature differences of 300° C decreasing to 140° C toward the end of the run probably represent losses from the gas to the graphite test section walls or to bypass leakage of cold gas around the heater core. Results of the two computer programs agree at longer blowdown time. Differences at the run start are attributed to the pressurization time. The ramped flow is programmed for the two-dimensional program but not for the one-dimensional program.

Plenum gas temperature measurements were much closer to the matrix temperature measurements than to calculated gas temperatures at corresponding nodes in the matrix. Since the gas velocity in the plenum was very low, the heat balance to the thermocouple junction was influenced largely by radiation and conduction from the graphite. It was not feasible for this installation to use shielded, aspirated, thermocouple probes.

Appearance After Tests

Figure 12 shows a sectioned drilled core after 13 cycles of operation. Original tool marks are still visible within the holes and on the exterior of the cylinder. No evidence of cracks were found either in the webs or at the external diameter of the core.

Several of the thermocouples were found to have broken sheaths and broken alumina insulators when removed from the matrix. It is not known whether these were broken during installation or in use.

CONCLUDING REMARKS

A drilled graphite core was proposed for a storage heater to supply heated nitrogen to a hypersonic tunnel. Hole size and spacing were varied using a one-dimensional transient heat-transfer program to determine heater performance for a fixed nitrogen mass flow and external core geometry. Subject to the limitations of drilling cost and thermal stress, a hole size of 1.9 centimeters and an $s/D = 2.0$ were selected for the hypersonic facility heater design.

A model of the proposed core design was tested by running a series of heating and blowdown tests in a pilot storage heater to investigate thermal stress cracking and to verify performance predictions. No cracks developed in the matrix after 13 runs which simulated maximum axial temperature gradient in the proposed design.

Temperature measurements of the heater exit gas and matrix were in fair agreement with calculations based on a two-dimensional transient heat-transfer program which included conduction and convection. Differences between measured and computed matrix temperatures appeared to be related to thermocouple installation.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 6, 1970,
722-03.

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TABLE I. - DRILLED-CORE CONFIGURATIONS

[Matrix diameter, 1.68 m (5.5 ft); matrix height, 8.5 m (28 ft).]

Hole diameter, D_H		Hole-spacing-to diameter ratio, s/D	Mass flow rate, $\dot{W}$		Initial axial matrix temperature profile
cm	in.		kg/sec	lb/sec	
2.54	1	1.4	59	130	A
		1.4	68	150	
		1.4	90.8	200	
		1.6	59	130	
			68	150	
			90.8	200	
			68	150	Uniform temperature
1.9	0.75	1.4	59	130	B
		1.4			A
		1.6			
		1.8			
		2.0			
1.27	0.50	1.4	59	130	B
		1.4	59	130	C

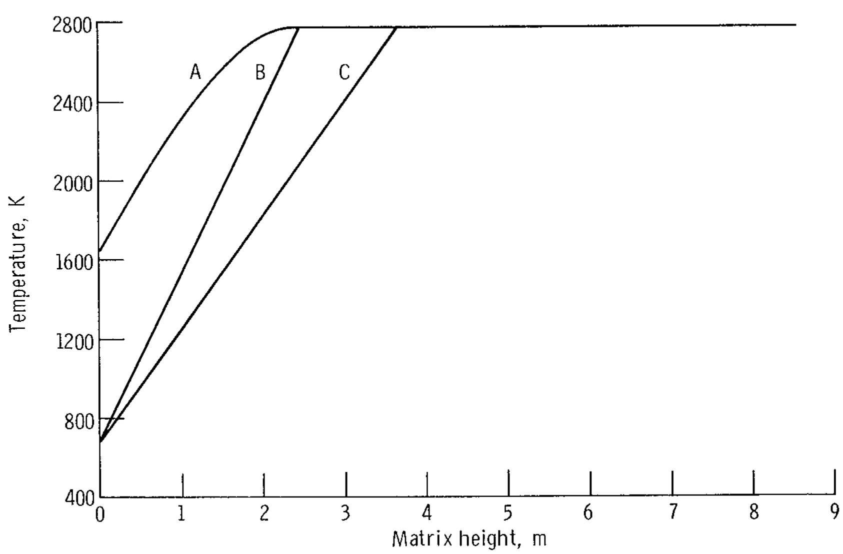
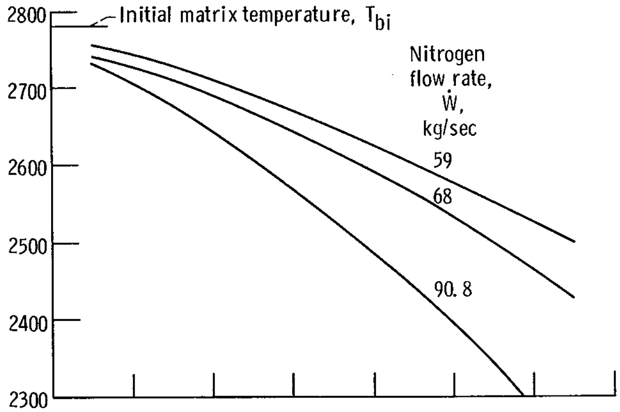
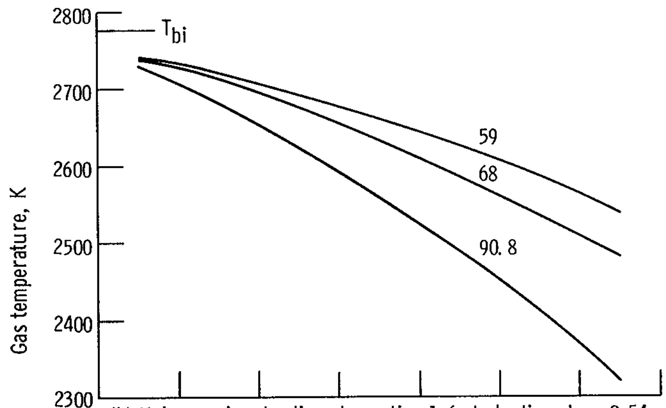


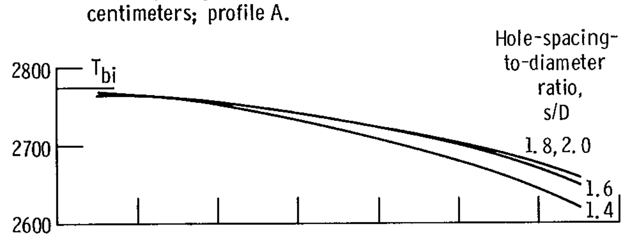
Figure 1. - Initial axial matrix temperature profiles.



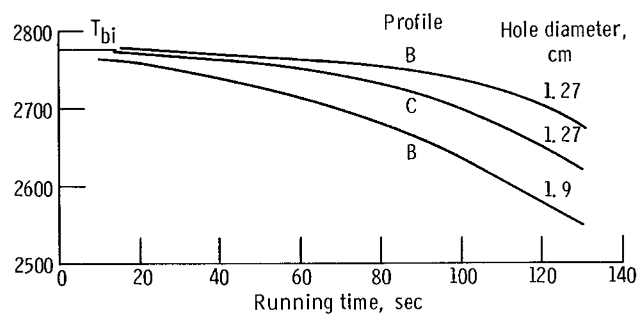
(a) Hole-spacing-to-diameter ratio, 1.4; hole diameter, 2.54 centimeters; initial matrix temperature profile A.



(b) Hole-spacing-to-diameter ratio, 1.6; hole diameter, 2.54 centimeters; profile A.



(c) Effect of hole-spacing-to-diameter ratio; hole diameter, 1.9 centimeters; nitrogen flow rate, 59 kilograms per second; profile A.



(d) Effect of hole size and initial matrix temperature profile. Hole-spacing-to-diameter ratio, 1.4; nitrogen flow rate, 59 kilograms per second.

Figure 2. - Heater exit gas temperature decay.

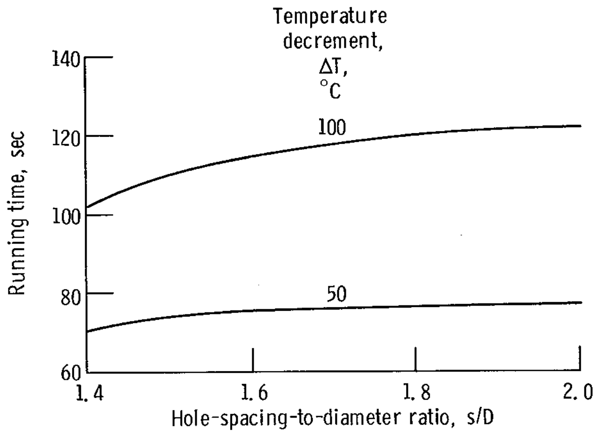


Figure 3. - Variation of run time with hole-spacing-to-diameter ratio. Hole diameter, 1.9 centimeters; nitrogen flow rate, 59 kilograms per second; profile A.

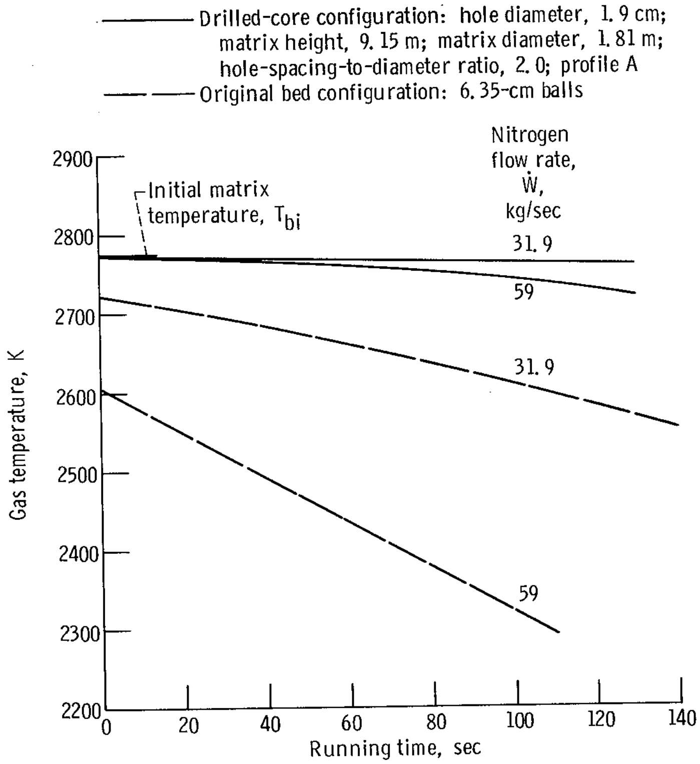


Figure 4. - Performance comparison of drilled core with pebble bed.

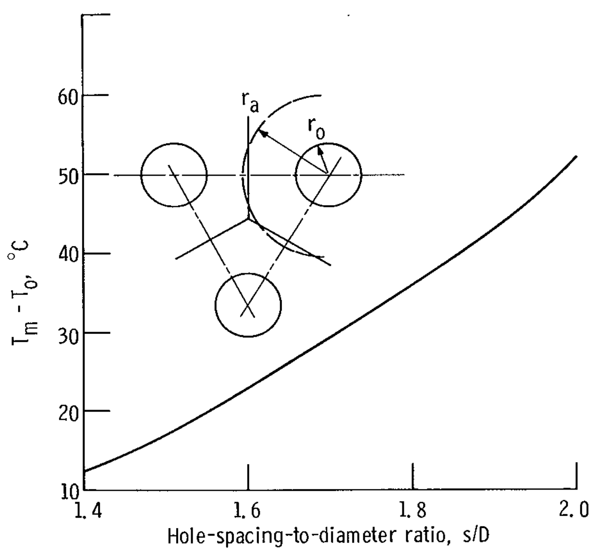


Figure 5. - Radial temperature difference in web. Hole diameter, 1.9 centimeters; nitrogen flow rate, 59 kilograms per second; profile A.

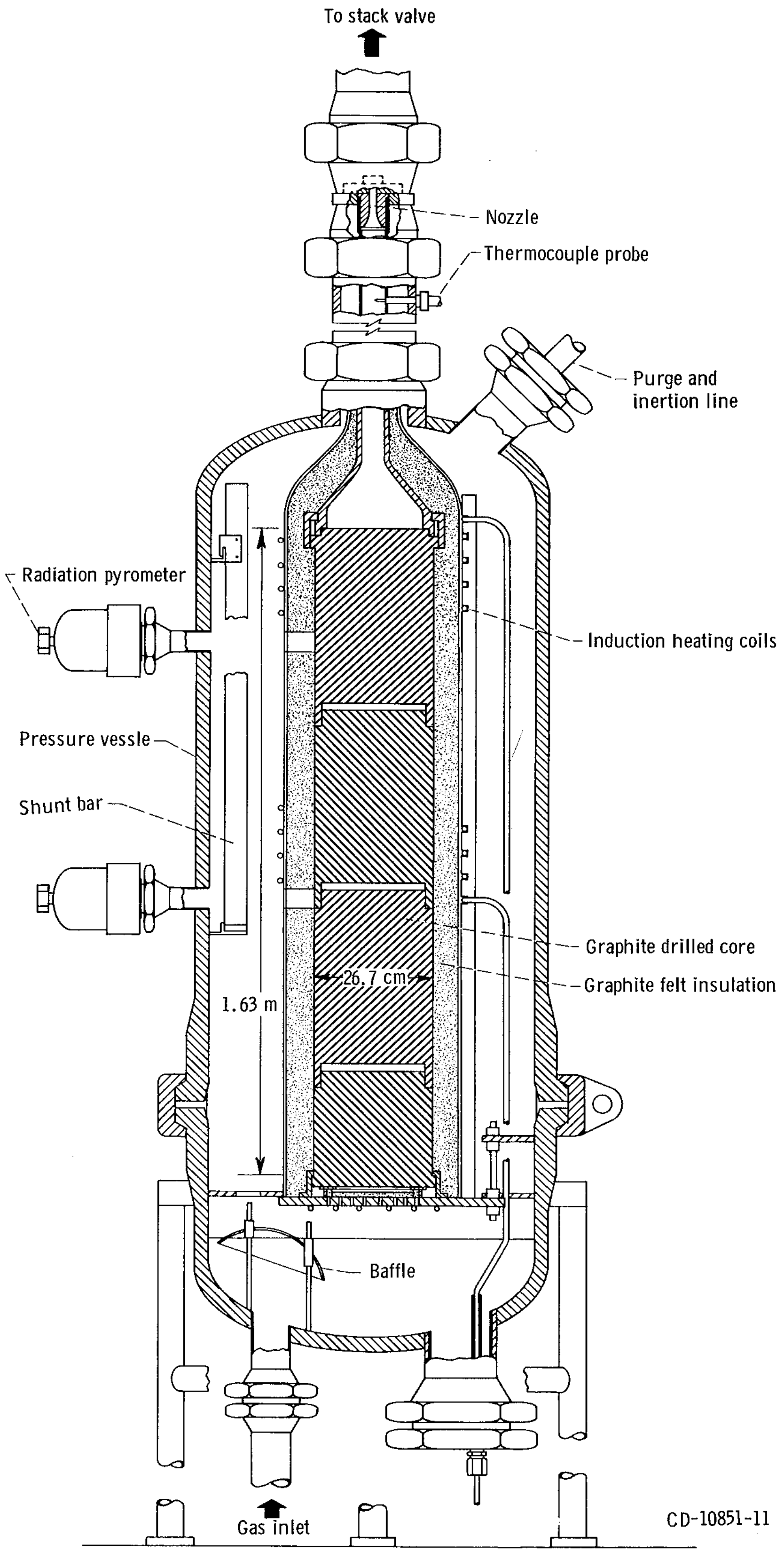


Figure 6. - Pilot graphite heater.

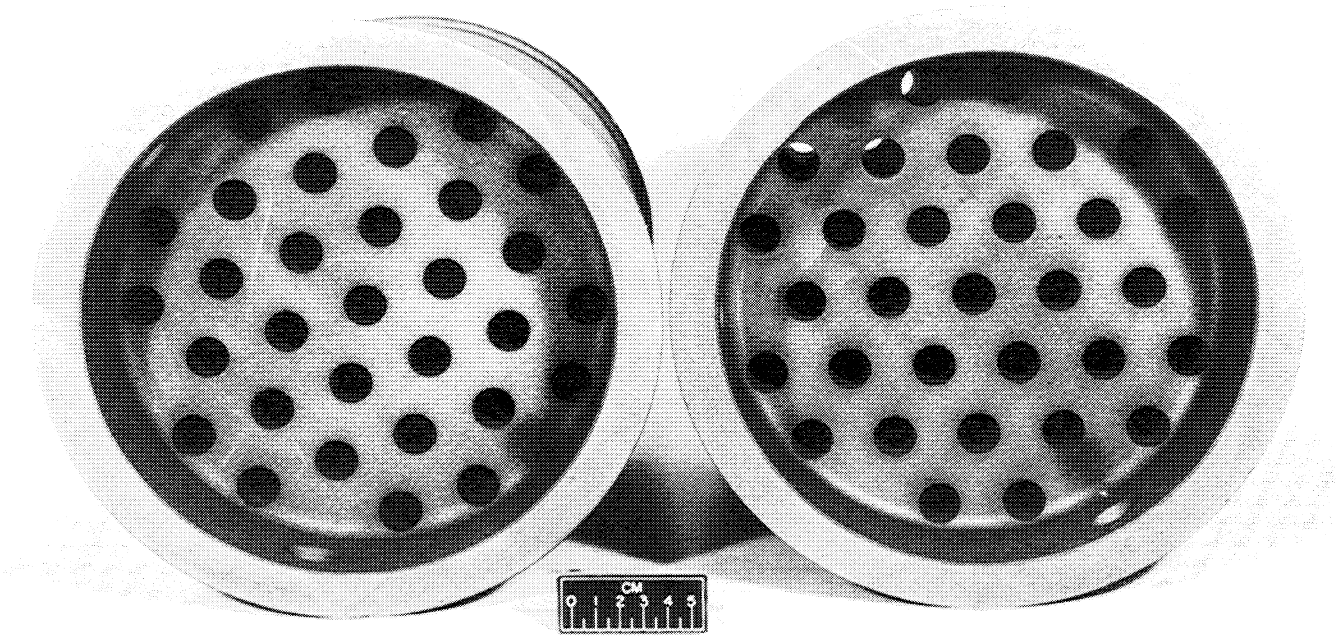


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Figure 7. - Drilled-core sections - bottom.

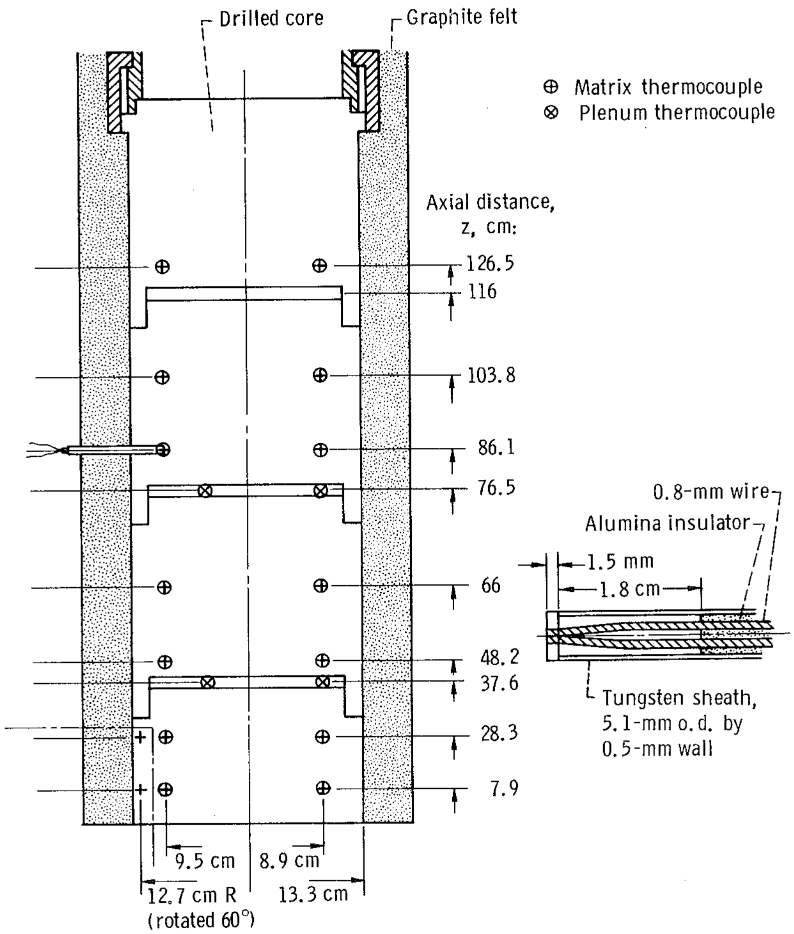


Figure 8. - Drilled-core assembly and thermocouple locations.

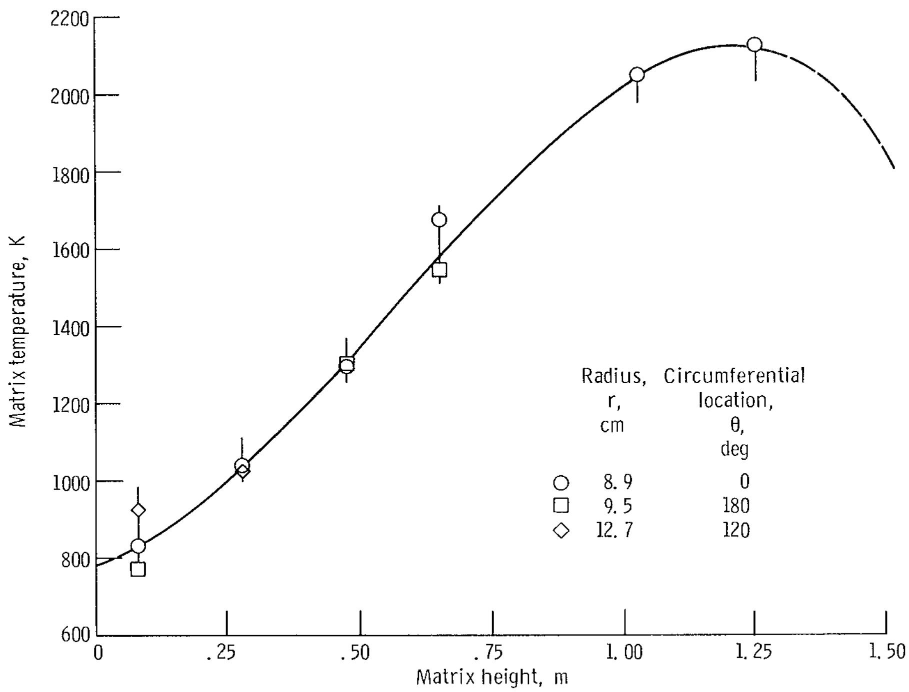


Figure 9. - Initial matrix temperature profile.

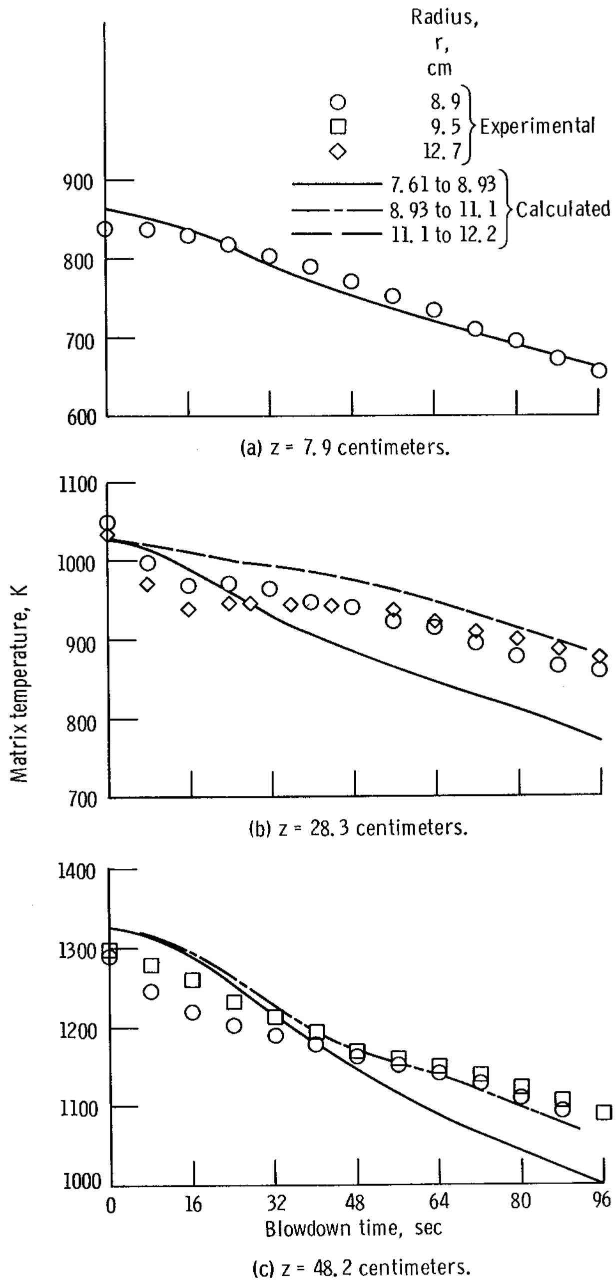
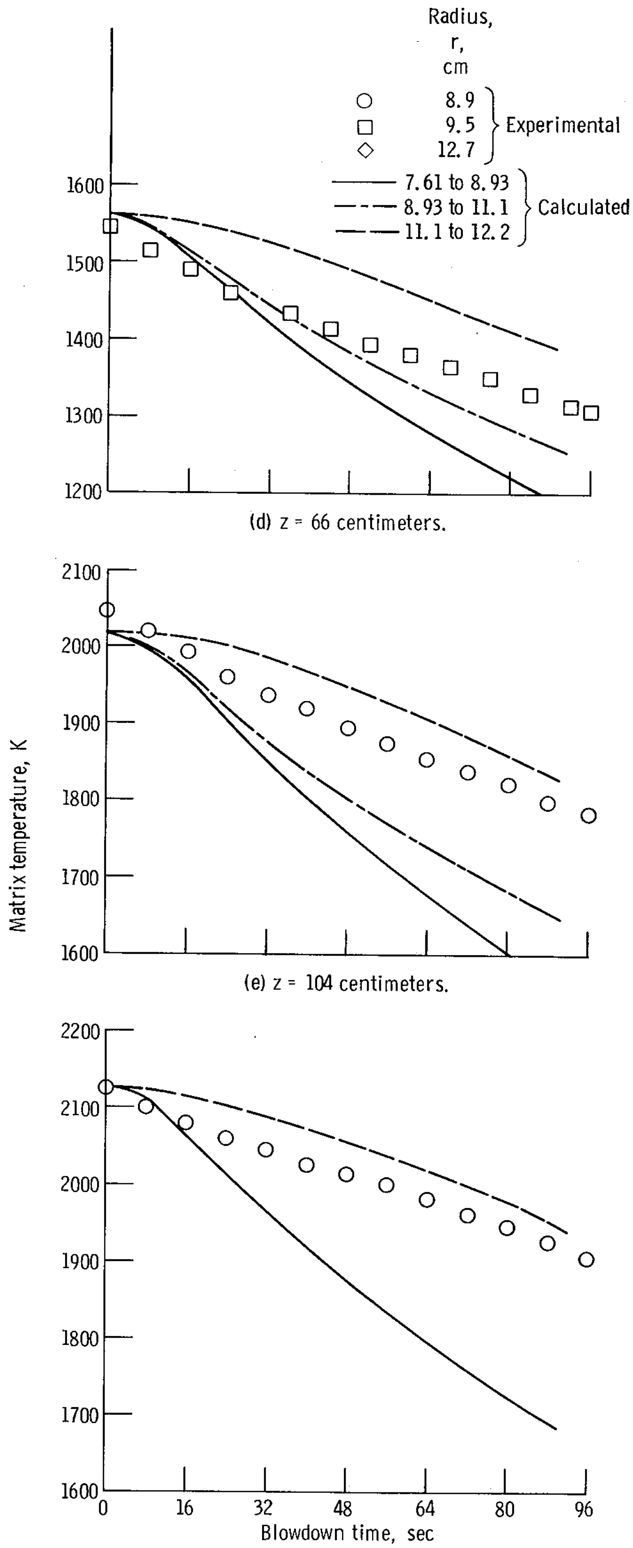


Figure 10. - Pilot heater matrix temperatures at various axial distances z.



(f) z = 126 centimeters.

Figure 10. - Concluded.

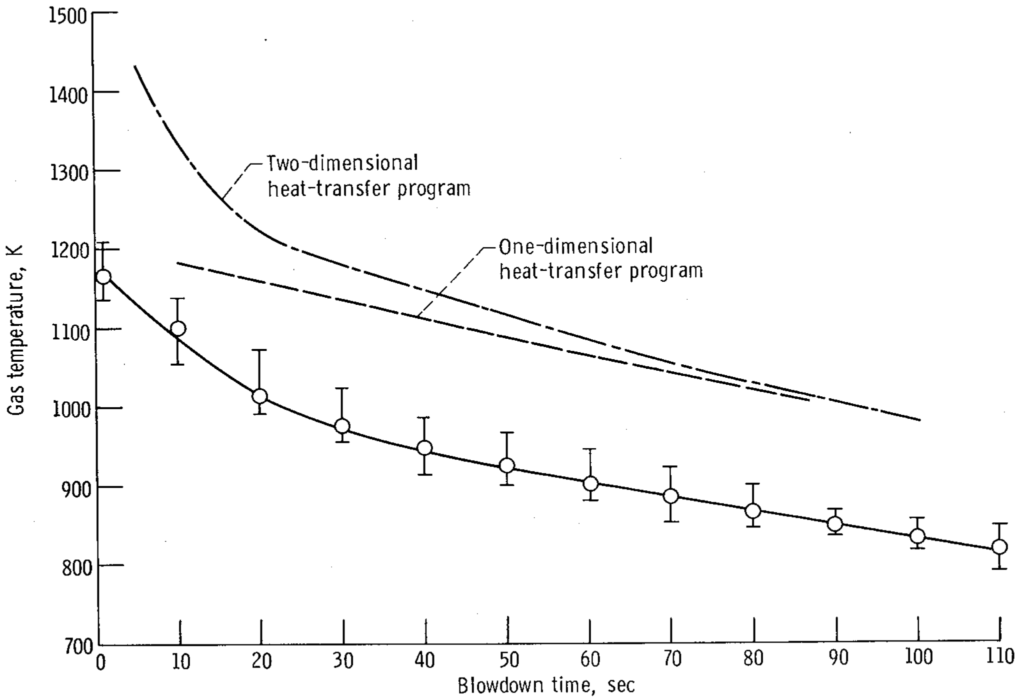


Figure 11. - Pilot heater gas outlet temperature.

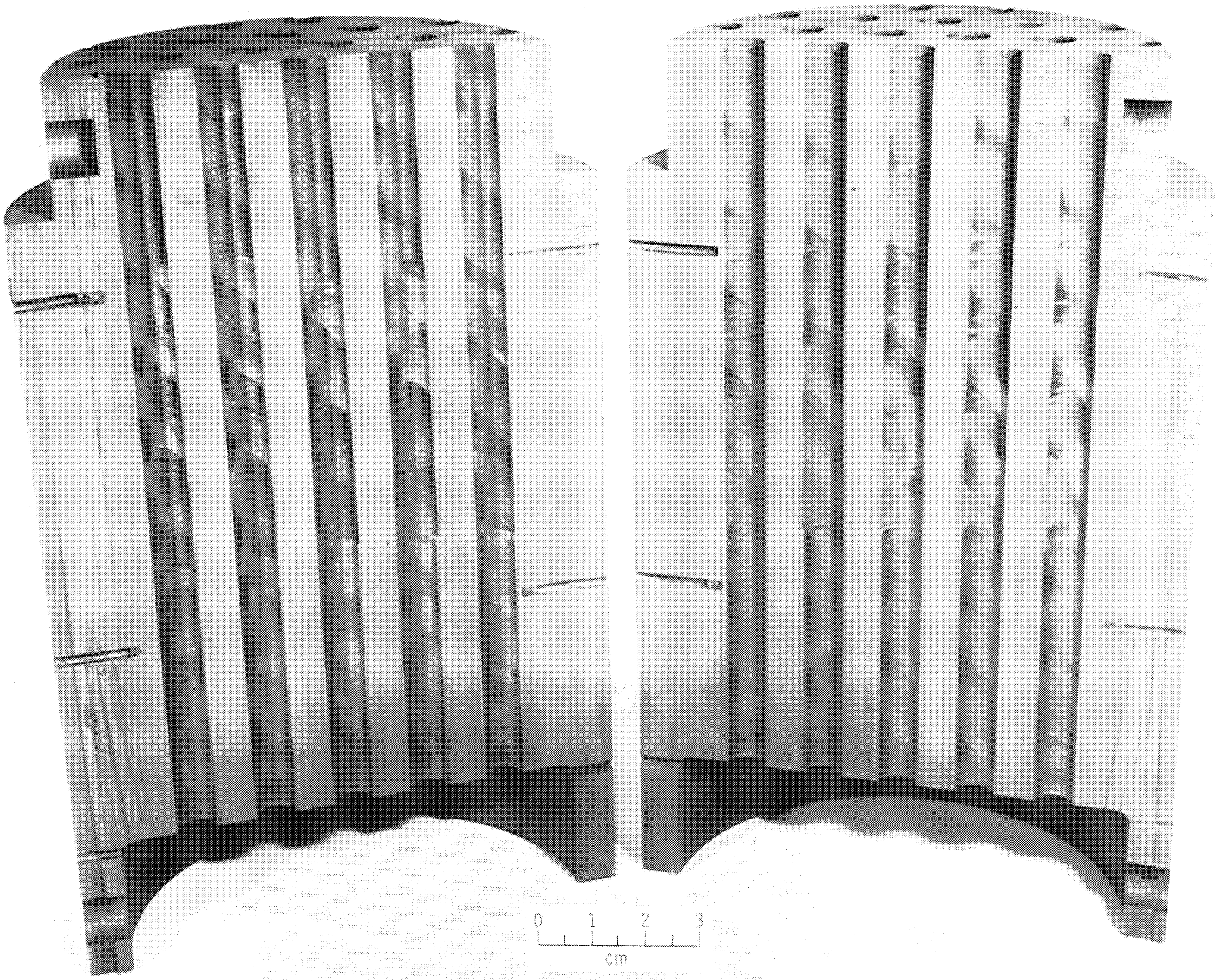


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Figure 12. - Drilled graphite core sectioned after cycling tests.