NASA CR–134531

EXPLORATORY DEVELOPMENT OF A GLASS CERAMIC AUTOMOBILE THERMAL REACTOR

by R. E. Gould and R. W. Petticrew

Owens-Illinois, Inc.
Toledo, Ohio 43666

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS3-14334

FORWARD

The research described herein, which was conducted by Owens-Illinois, Inc. Development Center, was performed under NASA Contract No. NAS 3-14334. The NASA Project Manager was Mr. Phillip L. Stone, Materials & Structures Div., NASA Lewis Research Center.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

The primary objective of this program was to develop a glass-ceramic thermal reactor capable of surviving the severe mechanical, thermal, and chemical conditions present in an automotive exhaust gas environment. The glass-ceramic selected for the program was CER-VIT® C-129, a lithia alumina silicate material.

The basic elements of the program consisted of reactor design (which included various laboratory tests of the glass-ceramic material), reactor fabrication, and reactor evaluation by both mechanical shock and thermal endurance testing.

Reactors of three basic designs patterned after the Dupont Type II circumferential flow reactor, were subjected to engine-dynamometer endurance testing and/or vehicle road tests. Although none of the reactors met the dynamometer endurance test goal of 600 hours, one of the reactors did perform successfully for about 330 hours at peak gas temperatures of about 1065° C (1950° F).

From the analysis of all the failed reactors, it was concluded that the primary problem was associated with the great difference in thermal expansion between the glass-ceramic main body and the metal support structure (corrugations and housing). With the very low thermal expansion of the glass-ceramic, and the higher-than-anticipated reactor housing temperatures resulting from uncooled operation during testing, contact between the glass-ceramic main body and the expanding metal support structure could not be maintained at temperature. Under the cyclic test conditions, the unsupported glass-ceramic was not strong enough to withstand the mechanical vibration from the test engines and thus it failed. None of the glass-ceramics evaluated showed evidence of chemical degradation.

The results indicated that the use of glass-ceramics required either close control of the reactor housing temperature or perhaps an improved design to assure that contact between the glass-ceramic main body and the metal support structure would be maintained under essentially all temperature conditions. Air cooling the corrugations or a redesign to move the metal support structure away from the high-temperature areas were considered. The latter alternative was followed and the re-design accomplished. One reactor of the new design was fabricated and delivered to NASA. Preliminary testing of this reactor at NASA at an internal gas temperature of 1065° C (1950° F) resulted in considerable lower reactor housing temperatures, indicating that this design would most probably perform better in endurance testing than did the early designs.

INTRODUCTION

Two major pollutants in automobile exhaust gases are carbon monoxide and hydrocarbons. A promising device to rid the exhaust gases of these pollutants is a thermal reactor (Reference 1). This device replaces the ordinary cast iron manifold on internal combustion engines. Materials of construction must be able to withstand the severe thermal exposures generated by combustion within the reactor. Problems not yet solved for reactors of all-metal construction include durability under normal operating conditions (925 to 1065° C - 1700 to 1950° F) in an oxidizing environment and the severe temperature generated within the core when a "spark outage" occurs (failed plug, ignition wire, etc.). Under "spark out" conditions, raw gasoline is discharged from one or more cylinders into the hot core of the reactor and material temperatures may exceed 1065° C (1950° F). For the development of long-life reactors capable of surviving the most severe and even normal engine operating conditions, the use of non-metallic materials offers greater potential than metals.

Non-metallic reactors, previously tested by the automobile industry and others, have generally been a two piece non-metallic core supported within a metal housing. Although some examples of spallation or erosion (and even melting) have been reported, it has generally been attested that the non-metallic (ceramic) cores simply "break". (Unpublished data made available to Owens-Illinois, Inc.). Failure modes have not been sufficiently identified. Other problems found in ceramic thermal reactors include deterioration of the insulation between the core and housing, and difficulties in the matching of ceramic/metal seals and supports.

The primary goals for this program were as follows:

1. Demonstrate fabrication of complex glass-ceramic reactor components.

2. Incorporate into the reactor designs a support structure capable of protecting the glass-ceramic materials against the severe conditions of engine vibrationuse, road shock and reactor operation.

Environmental conditions include temperatures greater than or equal to 1065° C (1950° F), severe thermal and mechanical shock, and erosion and corrosion from the the hot exhaust gases.

The reactor designs were also to be potentially capable of reducing emissions. The Dupont Type II circumferential flow reactor, which had proved to be effective in emissions control, was to be used as a model. The reactor life goal for thermal endurance testing was 600 hours.

Full size reactors of several designs were fabricated and subjected to mechanical and thermal shock by means of both vehicle road testing and engine-dynamometer testing. The reactor designs, fabrication, test procedures and test results are described in this report.

REACTOR DESIGN, MATERIALS AND FABRICATION

Basic Reactor Designs

Three basic reactor designs were used during the performance of this program. The overall diameter of the reactors was 11.4 cm (4.5 in.), the length was 55.9 cm (22.0 in.) and the internal volume was about 2459 cu. cm. (150 cu. in.). The reactors were designed to replace the exhaust manifold on either side of a 495 x 10^{-5} meter^{3}, (302 cu. in.) Ford V-8 engine. The glass-ceramic used in the reactors was Owens-Illinois CER-VIT® material. The housings were steel.

The three basic reactor designs are shown in Figures 1, 2 & 3. In reactor Design I (Fig. 1), the exhaust gas entered the central chamber through four ports and passed through an open honeycomb matrix to the exhaust outlet port. The honeycomb matrix had a web thickness of about 0.025 cm. (0.010 in.) and a distance across the webs of about 0.170 cm. (0.067 in.). A schematic of the matrix is shown in Fig. 4. A closed-end honeycomb matrix around the open matrix was used to provide both thermal insulation and mechanical support. The reactor core, open matrix, closed matrix and end pieces were cemented together to form a monolithic structure. A corrugated metal structure (Ref. 2) was used to support the monolithic glass-ceramic main body and protect it from contact with the metal reactor housing. The corrugations and the face sheet to which they were spot-weld attached were about 0.013 cm. (0.005 in.) thick. The corrugation strips were 1.9 cm. (0.75 in.) wide and were on 5.56 cm. (2.19 in.) centers. Each inlet port and the exhaust-outlet port were also supported by metal corrugations and were to "float" with the reactor housing.

In reactor Design II (Fig. 2), the exhaust gas entered the outer annulus, passed to the reactor core through several holes in the core wall, and finally exited through the exhaust outlet port. A closed-end honeycomb matrix was again used to provide thermal insulation and mechanical support. A corrugated metal structure again provided final mechanical support for the monolithic main body.

Reactor Design III (Fig. 3), was a modification of Design II and was actually introduced later in the program than Designs I and II. Most of the support of the main body in the Design III reactor was provided by corrugations and metallic rings around the conical ends of the main body.

A typical assembled reactor is shown in Fig. 5.

Glass-Ceramic Selection and Evaluation

The selection of the glass-ceramic to be used on this program was based on several considerations. Once the material was selected, an extensive testing effort was conducted to verify and be supportive of the final reactor designs. The several test programs are delineated in the following sections.

Material Selection and Physical Properties - There were several candidate CER-VIT® compositions for the reactors to be fabricated under the contract. After careful reviews, CER-VIT® material C-129 was selected. The properties of this material are as follows:

1. Modulus of Rupture
   - a. Room temperature 69.0 MN/meter^2 (10.KSI.)
   - b. 816° C (1500° F) 89.6 MN/meter^2 (13.KSI.)
   - c. 1038° C (1900° F) 69.0 MN/meter^2 (10.KSI.)
2. Coefficient of Thermal Expansion

   $+2.0 \times 10^{-7}/°$ C (0-700° C) (32-1292° F)
3. Dimensional Stability

   Less than 250 parts per million change in length after 2,000 hours at 1040° C (1900° F).
4. Compatibility of solid material and matrix structure. (Both structures exposed to 1040° C (1900° F) for 250 hours and then measured for change in length.)
   - a. Solids changed 83 parts/million.
   - b. Matrix changed 150 parts/million.

Other considerations were:

1. A proven refractory cement sealant material was available for use with C-129.
2. The C-129 chemical composition offered minimum difficulty in heat treatment.
3. Solid and matrix materials were known to be compatible during fabrication.

4. C-129 was readily fabricable into tubing and into a matrix structure.

Engine Exhaust Compatibility Testing - Although it was assumed that automobile engine exhaust (at least when using unleaded gasoline) would not be harmful to the glass-ceramic, it was decided to verify this on an engine test. Compatibility Specimens measuring 3.0 cm. wide x 5.2 cm. long x 0.32 cm. thick (1.2" wide x 2.1" long x 0.13" thick) were made and delivered to NASA Lewis where they were subjected to exhaust gases at 1040° C (1900° F).

The specimens were clamped into a special exhaust manifold in such a manner that the exhaust gases from a NASA Lewis test engine would impinge directly onto the material. The specimens were then subjected to an engine cycle which brought the specimen temperature up to 1038° C (1900° F) within two (2) minutes and held it at that temperature for ten (10) minutes. The specimens were then cooled to a temperature of 315° C (600° F) in three (3) minutes by idling the engine. They were held at that temperature for at least five (5) minutes. The above cycle was repeated 100 times. The specimens were then examined for any harmful effects. The only detectable effect was a grey discoloration which is common to all exhaust system components.

Pressure Drop Testing of Matrix Material - Since the Design I reactor used matrix as a flow passage, it was necessary to determine the pressure drop of candidate matrix configurations having different tube diameters, so as to aid in picking the most appropriate one. Two pressure drop specimens were fabricated using 9.1 cm. (2.4") diameter CER-VIT® material pipe having a length of 25.4 cm. (10"). Both pipes were filled with matrix material, one measuring 0.17 cm. (0.067") across the webs and the second measuring 0.10 cm. (0.4") across the webs. The results of the pressure drop measurements are shown on Figures 6 and 7. Neither specimen had excessive pressure drop but the 0.17 cm. (0.067") specimen had a drop of approximately one-half that for the 0.10 cm. (0.04") matrix.

Compressive Strength Testing of Matrix Material - Since matrix strength was an important item, it was also necessary to determine the compressive strength of the two matrix configurations so as to doubly verify the selection of the most appropriate one. Compressive strength test specimens were fabricated from both 0.17 cm. (0.067") channel size and 0.10 cm. (0.040") channel size matrix material. The specimens measured 5.1 cm. x 2.5 cm. x 2.5 cm. (2" x 1" x 1") and were cut so that loading was always applied parallel to the 5.1 cm. (2") length, regardless of passage orientation. The specimens were divided into four (4) groups of six (6) specimens each.

The grouping for the six measurements are as follows:

Group A - 0.17 cm. (0.067") passages with passages parallel to the applied force.

Group B - 0.17 cm. (0.067") passages with passages perpendicular to the applied force.

Group C - 0.10 cm. (0.04") passages with passages parallel to the applied force.

Group D - 0.10 cm. (0.04") passages with passages perpendicular to the applied force.

The results are shown in TABLE I.

As indicated, the compressive strength is much higher when the loading is parallel to the passages. The strength of the matrix is at least one order of magnitude less when the load is applied perpendicular to the passages. The effect of the size of the tubing on the strength is not so great as is the effect of the direction of loading. The strength of the 0.17 cm. (Group B) was higher than the (Group D) 0.10 cm. (225 psi versus 73 psi, when the load was applied perpendicular to the passage). Based on the pressure drop data and the compressive M.O.R. D[illegible] , the decision was made to use 0.17 cm. (0.067") channel size matrix material in the fabrication of the reactors for this contract.

Thermal Testing of Glass-Ceramic Main Bodies - It was important to verify that the closed end matrix did indeed provide sufficient insulating qualities. Therefore, full scale Design I and Design II glass-ceramic main bodies (without end closures) were fabricated for thermal testing. The thermal testing consisted of two parts:

1. Gas at 1040° C (1900° F) was injected into the combustion areas until an equilibrium condition was reached. Thermocouple measurements were made at the exterior circumference of each structure.
2. After examination, each structure was subjected to a temperature rise from ambient to 1040° C (1900° F) within two (2) minutes and cooled to ambient within three (3) minutes for ten (10) cycles.

Heated gas for both tests was supplied by a gas blow torch. Air for cooling was supplied by a pressure blower rated at 481 cu. meters/hrs. (1700 cfh) at 284 grams (10 oz.) pressure. The test setup is shown in Figure 8. The outer surface temperature for the Design I main body was 195° C (380° F). This equilibrium temperature was reached in forty-six (46) minutes. The outer surface temperature for the Design II main body reached an equilibrium temperature of 210° C (410° F) after approximately twenty-six (26) minutes. The gas temperatures for the thermal cycling tests were recorded every thirty (30) seconds. After testing was completed, the structures were examined and no deleterious effects were noted.

This test clearly showed that the glass-ceramic main bodies were acceptably designed particularly from the standpoint of insulating capability. As a result, several entire reactor assemblies were fabricated for both mechanical and thermal testing.

Fabrication of Experimental Test Reactors

Five full size reactors of the three different designs were fabricated for mechanical and thermal testing. In general the C-129 glass-ceramic parts for all of these experimental reactors were made by existing glass manufacturing techniques. The glass ceramic main bodies were about 9.5 cm. (3.8 in.) in diameter. The closed end honeycomb matrix in each case was about 2.2 cm. (.5 in.) thick. The cylindrical outer liners were about 7.6 cm. (3 in.) in outer diameter and the cylindrical inner cores were about 5 cm. (2 in.) in outer diameter. Both the liners and cores were about .03 cm. (.12 in.) in thickness.

The metal corrugation support structure is described in the prior section "Basic Reactor Designs". The corrugations were positioned around their respective ceramic parts with a slight pre-load to hold the parts firmly in place, particularly during cold start-up. The metal corrugations were made of RA 330 steel. The housings for the first two reactors were 316 stainless steel. Each reactor housing was sealed on the ends by means of metal plates and a V-band coupling.

Extensive thermocoupling was utilized to determine temperatures at various locations throughout each reactor.

REACTOR TESTING AND RESULTS

Mechanical Testing

Vibration Table Testing - A Design I reactor was subjected to vibration testing at NASA - Lewis as a preliminary check of its overall integrity.

The reactor was mounted on the vibration table as hown in Figure 9. Accelerometers were attached at several locations. The reactor was vibrated in three directions.

These are as follows:

1. Oscillated vertically, perpendicular to the axis of the reactor.

2. Oscillated horizontally, parallel to the axis of the reactor, and

3. Oscillated horizontally perpendicular to the axis of the reactor.

In each mode of testing, the reactor was subjected to 1, 2, and 3 G loads at the test console and the frequency varied from 5 to 200 Hertz. These conditions were expected to be representative of actual automotive applications. The reactor was inspected after each mode of testing. No evidence of any damage to the reactor was noted. Although this reactor was tested in the "cold" condition, it's survival increased the confidence level for the overall reactor design.

Vehicle Testing - The second mechanical test of the overall reactor design was a test on a 1971 Model F-100 Ford Pickup Truck.

To perform this test, a 1971 Model F-100 Ford Pickup Truck with a 495. x 10^{-5} meter ^{3} (302 cu. in.) V-8 engine, with standard suspension was used. Only one bank of the engine was modified to accept reactor installation. A modified Design II reactor was installed. (Modification to be described later). An air injection system was also installed on the engine. The reactor is shown in Fig. 10. The reactor was subjected to actual conditions of use by both freeway and in-city driving.

Specifically, the truck with the reactor installed was used as a plant vehicle for various tasks around the plant. Daily trips were made for various pickups and deliveries. In this way it was exposed to all types of road surfaces and varied driving conditions, including a very rough railroad crossing. After a total of 2413 kilometers (1,500 miles) had been accumulated, the reactor was removed and inspected. The reactor showed no ill effects, other than a slight staining from the products of combustion. It was then used as a spare reactor during the thermal endurance testing.

Thermal Endurance Testing

The purpose of this testing was to evaluate the thermal performance and durability of all reactor designs under severe engine operating conditions. The testing was of a thermal endurance nature conducted on engine-dynamometer test stands with a target reactor life of 600 hours. All of the engine-dynamometer tests were conducted at Teledyne-Continental Motors, Muskegon, Michigan under another NASA contract (NAS3-13483). The endurance test cycle is shown in Figure 11. Five reactors were subjected to this endurance test cycle. The results are summarized in Table 2 and discussed in the following sections. Non-leaded gasoline was used although subsequent testing (Ref. 3) has shown that it is likely that at least low-lead gasoline could have been used without deleterious effects on the glass-ceramic.

Preliminary Testing - Figure 12 shows one of the two reactors (one Design I and one Design II) subjected to the endurance test cycle. Figure 13 shows the locations of the thermocouples which were used to monitor temperatures during the thermal endurance testing. These reactors were mounted on one of three Ford 495 x 10^{-5} meter^3 (302 cu. in.) V-8 test engines. The reactors were run through one complete cycle of approximately 32½ hours, and the engine was shut down for reactor inspection. Upon removal from the engine both reactors were found to be broken. The reactors were returned to Owens-Illinois and disassembled. Photographs were taken of each step to aid in the analysis of the causes of failure. The analyses indicated that in each case, reactor failure had originated with the failure of a ceramic inlet port. This permitted exhaust gas to bypass the reactor cores thus creating hot spots along the reactor housings. Since the housings were securely fastened to the engine head, they could only expand in a plane parallel to the plane of mounting. As a result, the housings undoubtedly bowed and broke the glass-ceramic main bodies due to the bending forces on them. The reactor breakage of the DesignI main body is shown in Figure 14. During the failure analysis, it was also noted that small particles of broken glass-ceramic had jammed into many of the open matrix passageways. This would have caused an increase in back pressure, further increasing the amount of gas bypassing the reactor core, and thus further increasing housing temperatures and bending forces.

Several of the remaining ceramic ports appeared to have been "hammered" as evidenced by chipping on the periphery of the ends toward the engine. It was believed that the metal flanged retainer plates, which were supposed to hold in place the corrugations surrounding the ports (and consequently the ports), had in several instances moved enough beneath their gaskets to contact and vibrate against the ceramic ports. It was therefore concluded that the two totally broken ports had failed due to the above cause. It was apparent that the port areas had to be redesigned. In addition to the conclusion concerning the port areas, it was also concluded that the Design I reactor which used matrix material for a gas passage was overly vulnerable to passage blockage by any foreign material which might enter the reactor.

As a result of the failure analyses, the Design I reactor was discontinued due to reasons given above, the Design II reactor was modified and the Design III reactor was introduced.

For the modified Design II and the Design III reactors the ceramic port areas were redesigned to eliminate all flat gaskets and metal flanged retainer plates. The seal around the ports was made by using gaskets of carbon impregnated asbestos around an Inconel spring. The housings were changed from stainless steel to low carbon steel to reduce bending stresses due to thermal expansion. The metal corrugations around the glass-ceramic main bodies for radial support was increased from one to two layers and the housing diameter increased concurrently. The corrugation sites, however, were reduced to about one-third that for the original Design II. Finally, a glass-ceramic "band" was bonded around and at the center of the main bodies for lateral location.

The Design III reactor, again, is shown in Figure 3. The modified Design II reactor was identical to Design III except that it had flat ends as in the original Design II.

Testing of Modified Reactors - A modified Design II and a Design III reactor were delivered to Teledyne and placed on test. The Design III reactor immediately developed a hot spot, and upon examination, it was discovered that the outer pipe contained a large solid inclusion which had caused it to fail quickly due to thermal expansion differences. A replacement Design III reactor was fabricated and put on test along with the modified Design II reactor. The temperatures of these reactors were monitored and control was maintained by a thermocouple extending into the reactor outlet port. At the end of approximately 2½ cycles (85 hours), it was observed that a crack had developed in the Design III reactor and it was removed from test. Examination of this reactor revealed that the resilient mounting had relaxed enough to allow the glass-ceramic main body to move. Once relative motion was permitted between the housing and the reactor core, failure became imminent.

The Design III reactor was replaced on the test stand with the modified Design II reactor which had been in road service on the Ford Pickup truck for approximately 2413 kilometers (1,500 miles) and testing was continued. The original modified Design II reactor failed after 330.5 hours of testing and the reactor which had replaced the Design III reactor failed after 253.5 hours of testing. Examination of the failed reactors revealed that the glass-ceramic band on each was "scuffed". This showed that unpredicted and deleterious motion of the main glass-ceramic body had again occurred and had undoubtedly led to the failure.

The CER-VIT® material from these reactors was examined carefully and showed no signs of chemical attack, erosion, corrosion, or any deleterious effects from the exhaust gasses except a small amount of staining due to deposits of the various products of combustion.

DISCUSSION OF RESULTS AND RECOMMENDATIONS

From the analysis of the failures of the modified Design II reactors and the Design III reactor, it was concluded that the primary problem was associated with the great difference in thermal expansion between the glass-ceramic and metal support system. With the near zero thermal expansion of the CER-VIT® material and the high uncooled reactor housing temperatures (468° C, 875° F) which were about 150° C (300° F) hotter than would be expected on a vehicle (Ref. 2) contact between the ceramic and the expanding metal support could not be maintained at operating temperatures. Under the cyclic test conditions, the unsupported glass-ceramic main bodies were not strong enough to withstand the mechanical vibration from the test engine and thus they failed. The glass-ceramic reactor on the NASA vehicle, on the other hand, has survived over 33,800 Km. (21,000 miles) under severe and varied road conditions. The results of the failure analyses and the NASA vehicle test indicated that the use of glass-ceramics required either a closer control of the reactor housing temperature or an improved design that would maintain continuous positive contact between the ceramic and the support housing under esentially all temperature conditions. Several design alternates were considered and it was decided to further modify the Design II reactor. Longitudinal matrix would not be used but three longitudinal glass-ceramic ribs would be attached to the glass-ceramic main body. These would keep the metal corrugations away from the heat as shown in Figure 15.

The design of this reactor was completed and one was fabricated and delivered to NASA.

CONCLUDING REMARKS

The CER-VIT® glass-ceramic C-129 selected for this program showed no evidence of chemical attack or loss of properties in any of the tests performed. However, it did appear that improved mounting methods must be employed due to the very low thermal expansion of the CER-VIT® material. The large difference in expansion between the glass-ceramic and the metal housing, if not properly accounted for in the reactor design, will result in the glass-ceramic main body being able to move freely during reactor operation. In this unsupported condition it will eventually break. An attempt has been made to overcome this problem with a redesigned reactor. One reactor of this new design was supplied to NASA. Preliminary testing of this reactor has shown significantly lower housing temperatures. This indicates that a design that would probably be more successful in endurance testing has been developed.

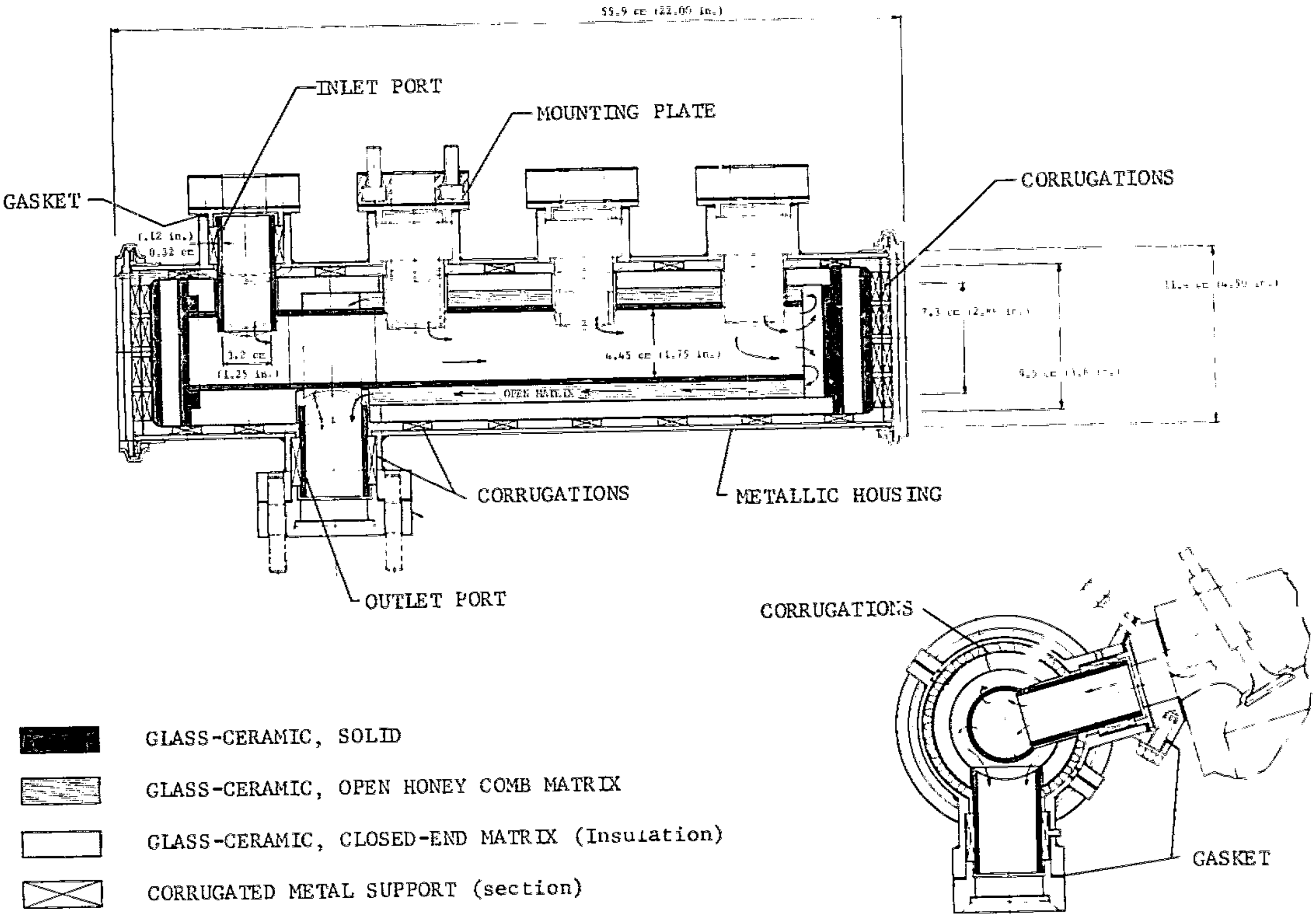


Figure 1 Glass-ceramic thermal reactor, Design I

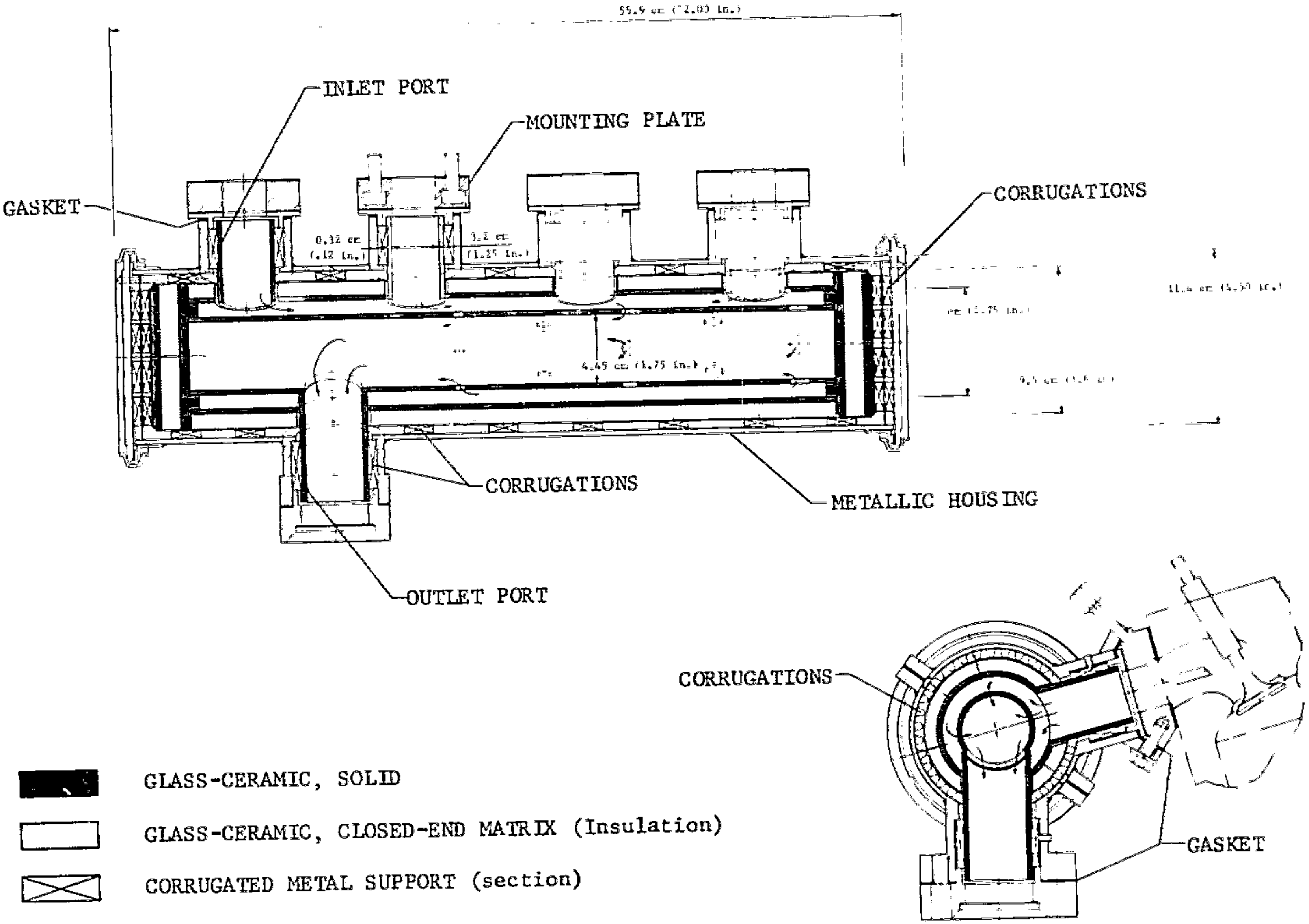


Figure 2 Glass-ceramic thermal reactor, Design II

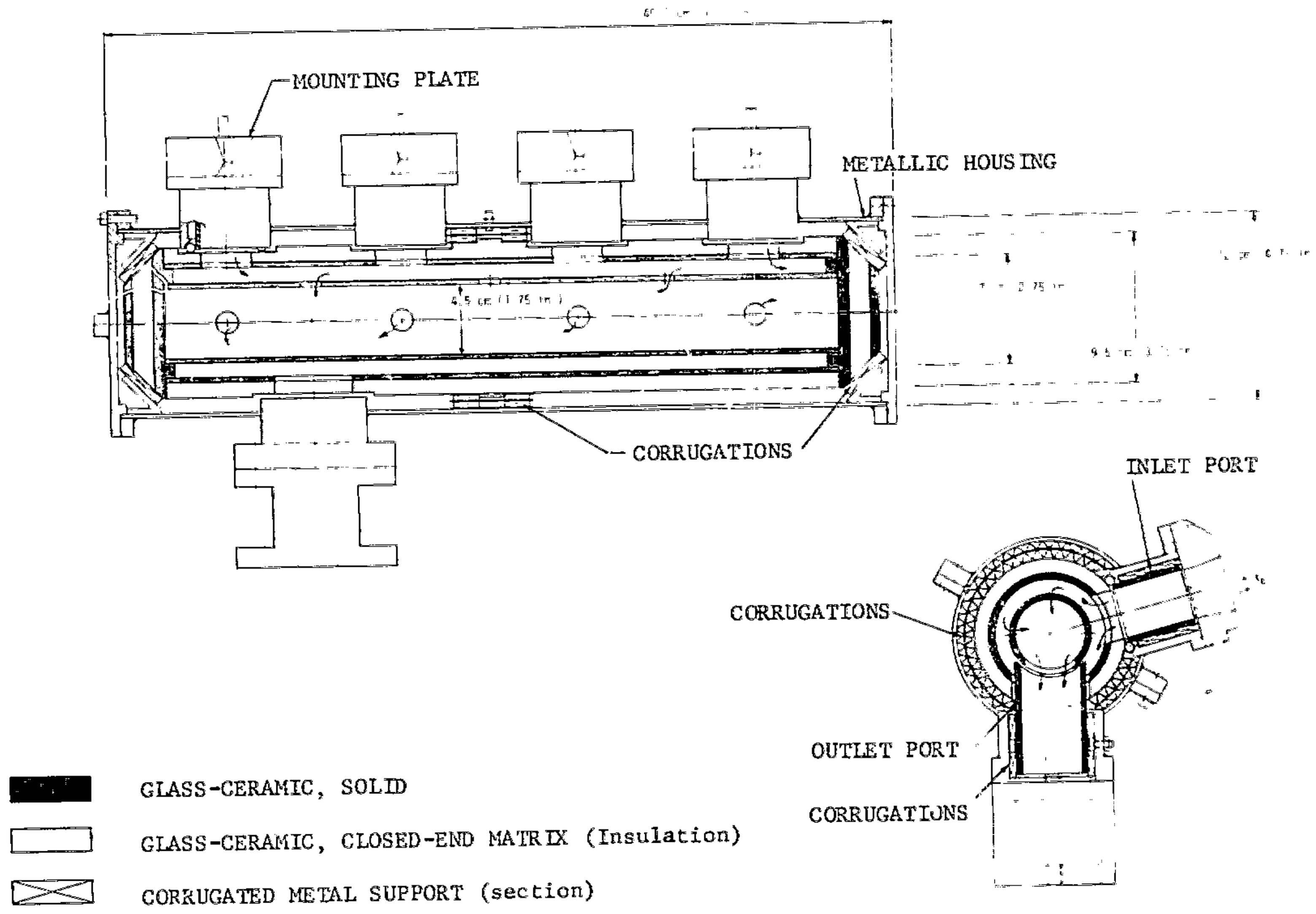


Figure 3 Glass-ceramic thermal reactor, Design III

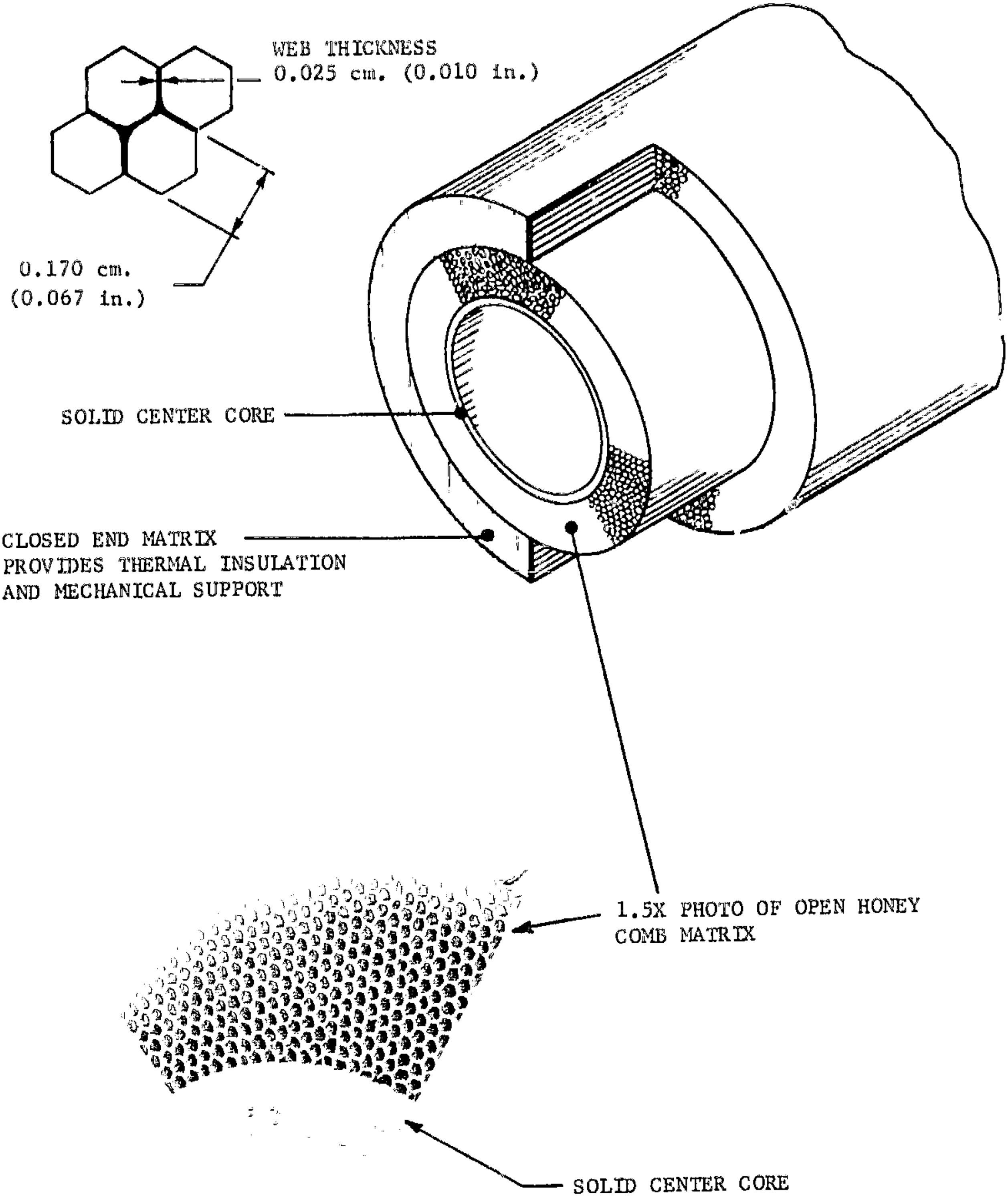


Figure 4 Isometric view of glass-ceramic matrix

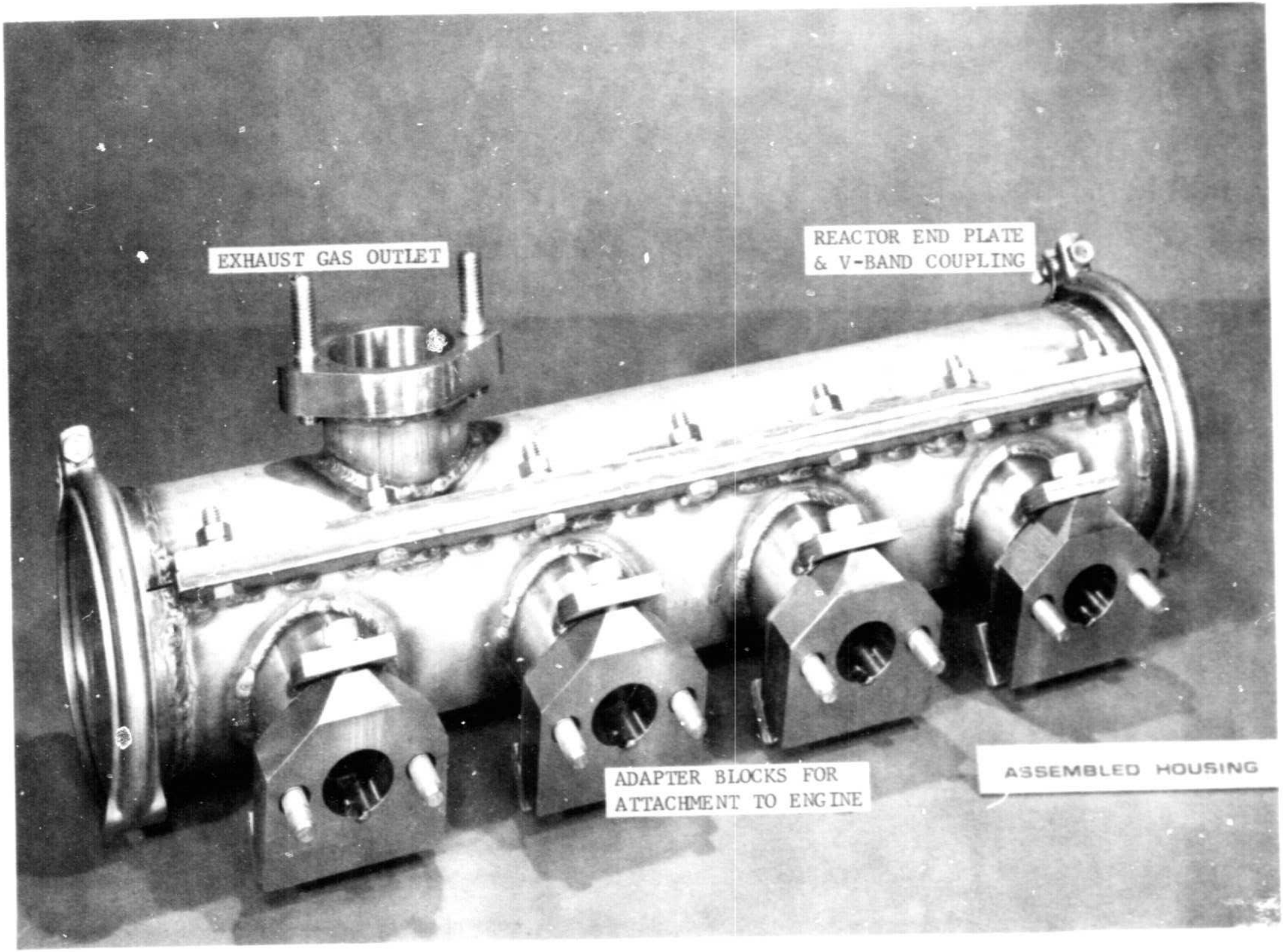


Figure 5 Assembled reactor

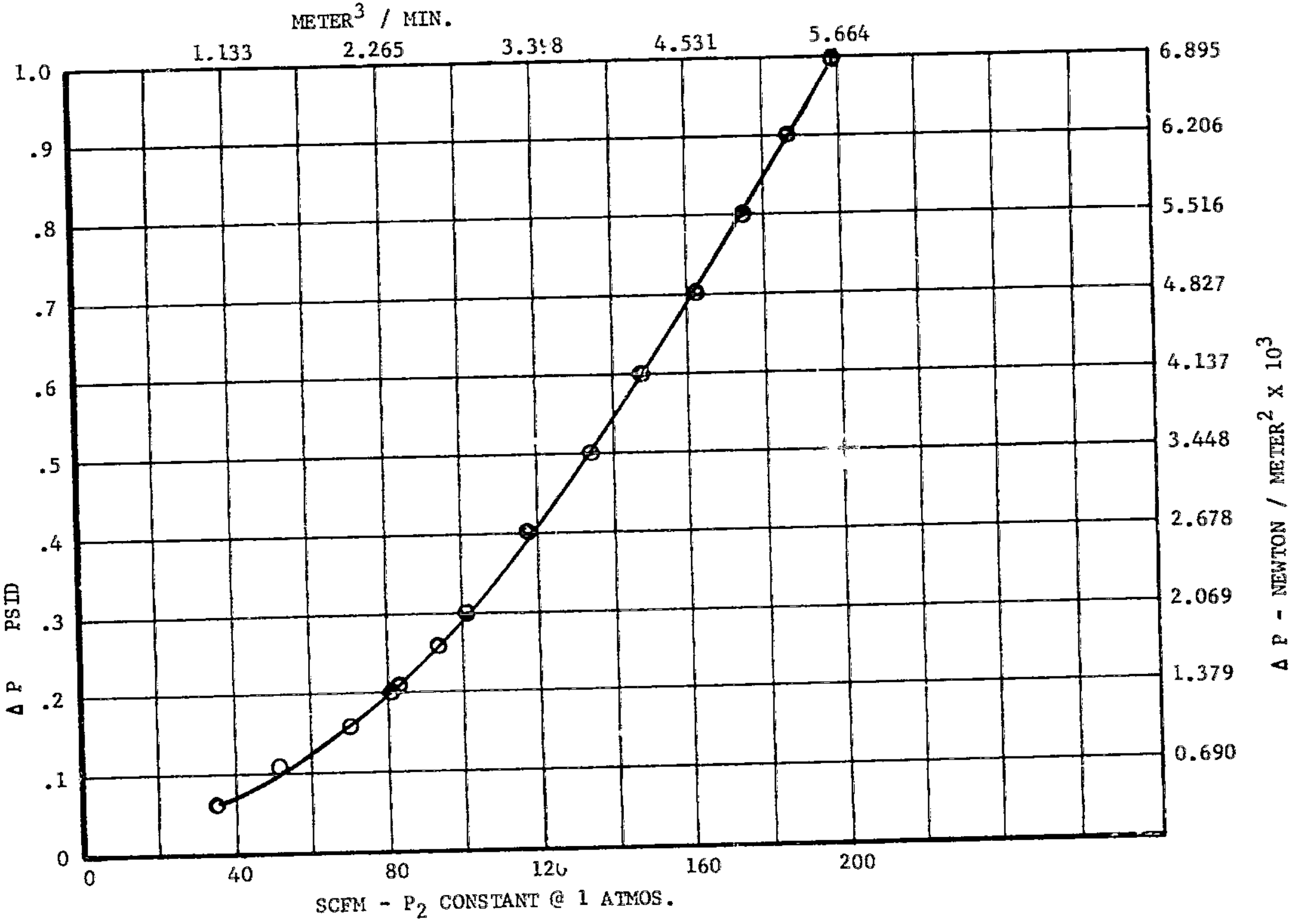


Figure 6 Pressure drop test of 0.17 cm (.067 in.) laminar flow element

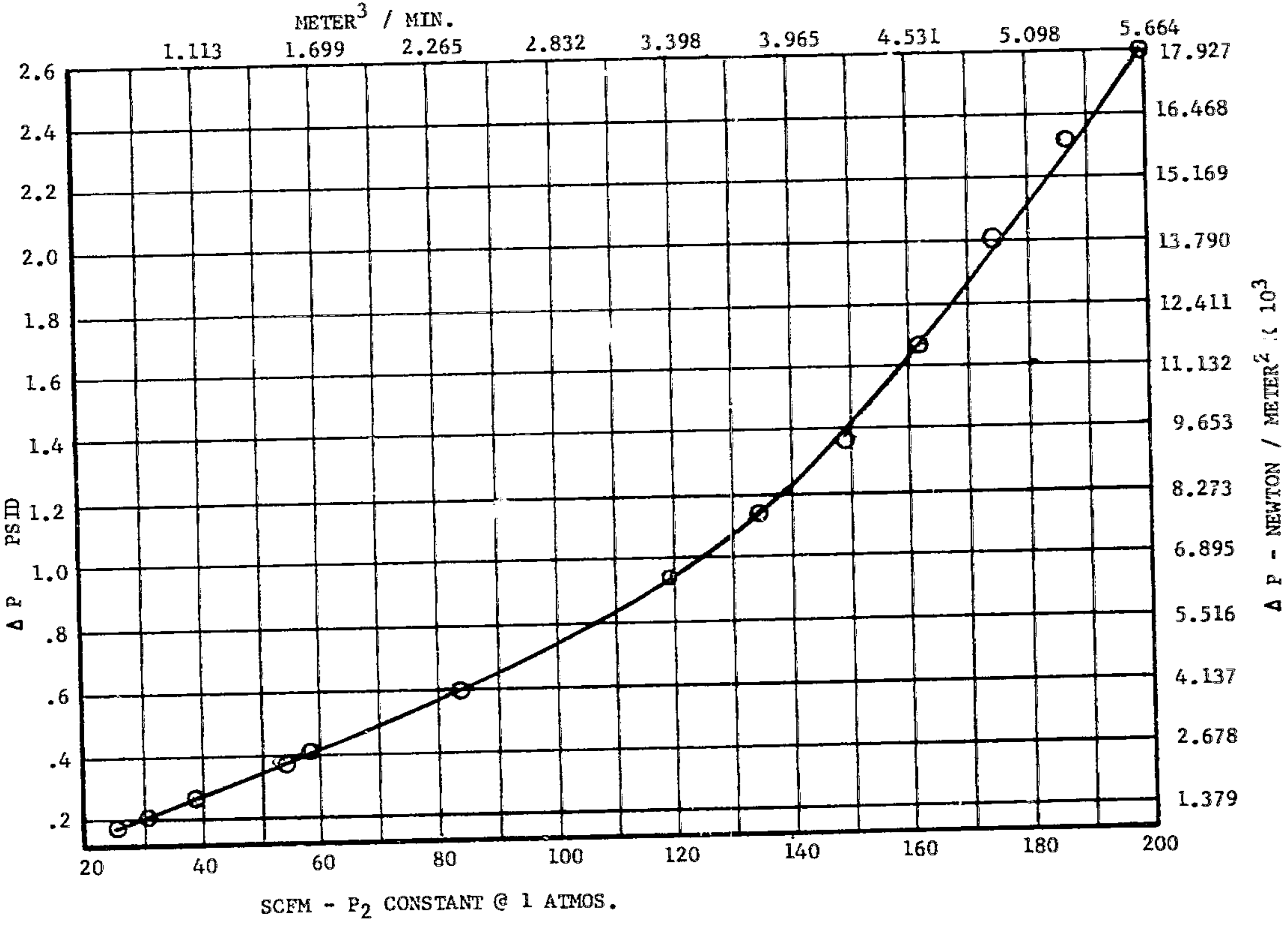


Figure 7 Pressure drop test of 0.10 cm (.040 in.) laminar flow element

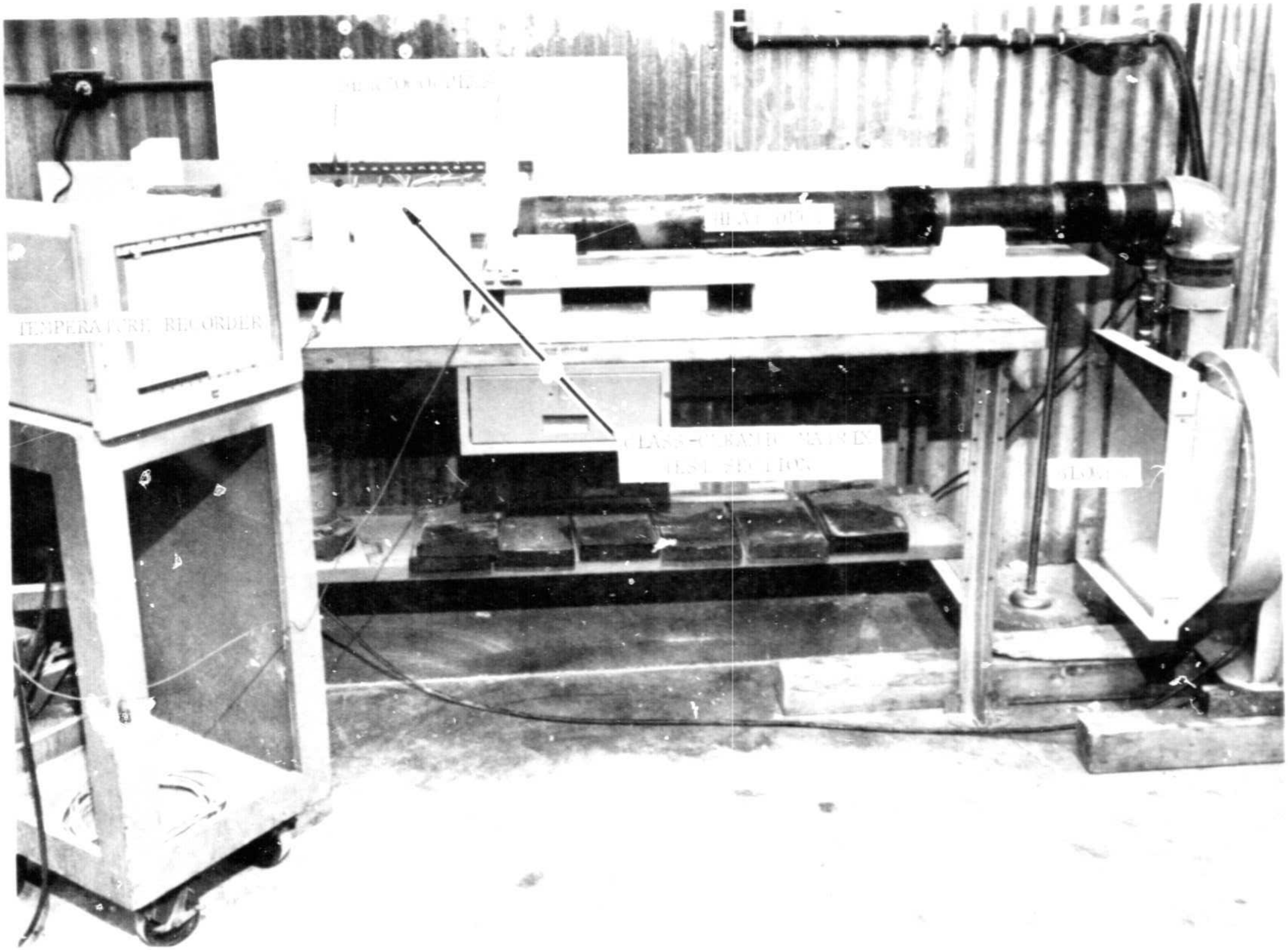


Figure 8 Thermal, test set-up

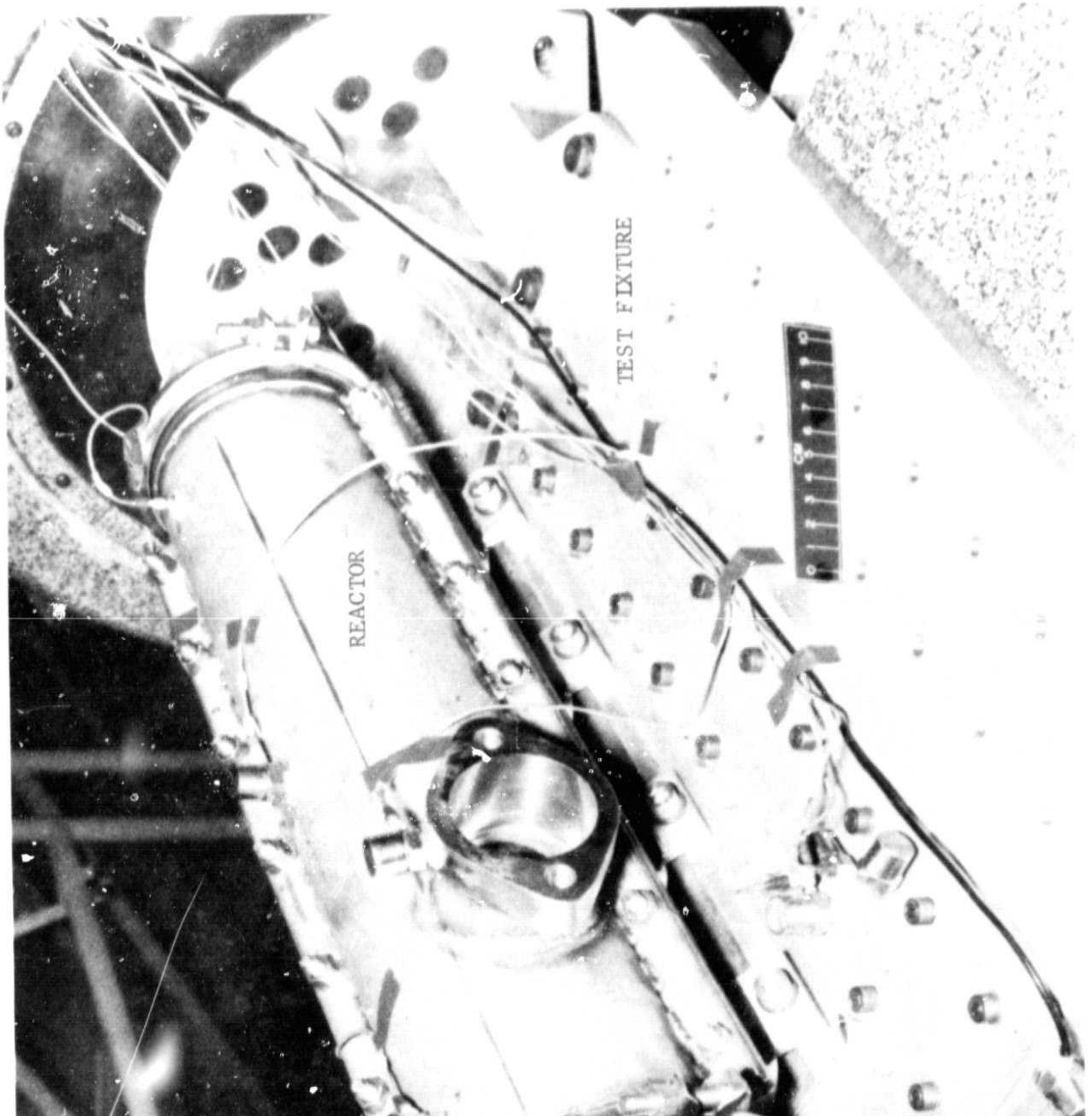


Figure 9 Vibration table test set-up

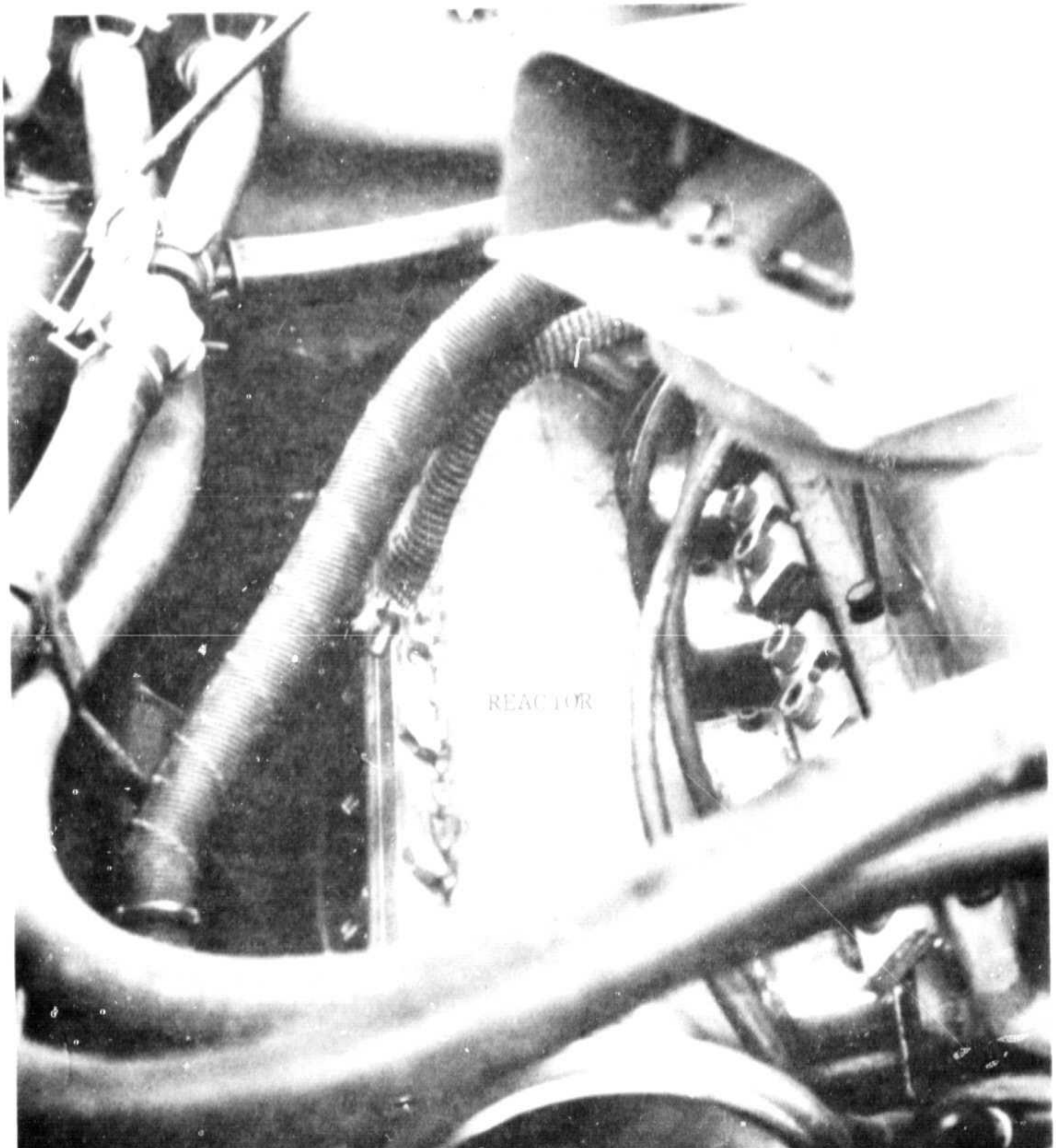
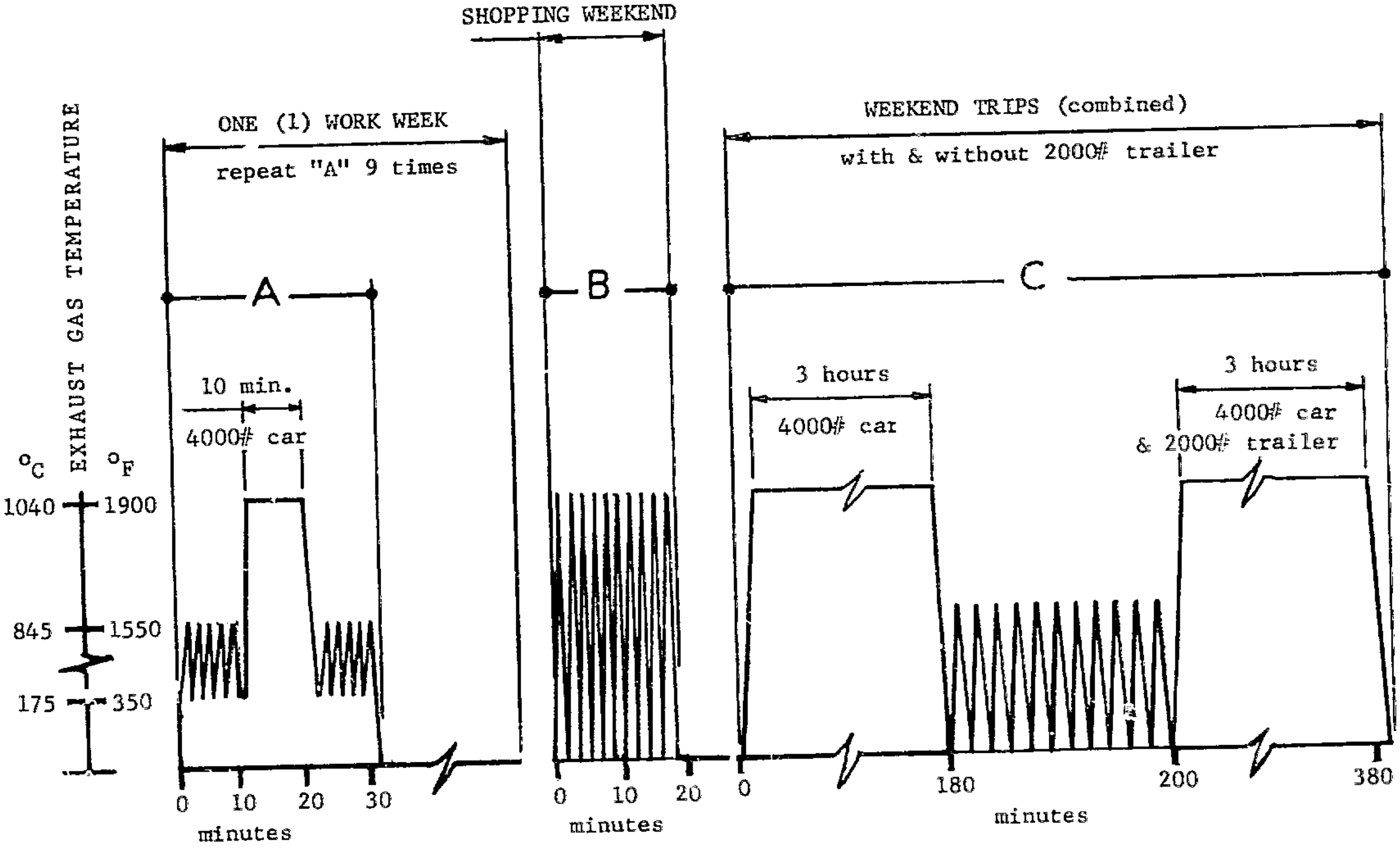


Figure 10 Thermal reactor installed in pickup truck



ENDURANCE TEST CYCLE = A+B+A+C+A+B+A+C = 32.5 hours (45% @ 70 mph)

Repeat to 600 hours

Figure 11 Reactor, thermal endurance test cycle

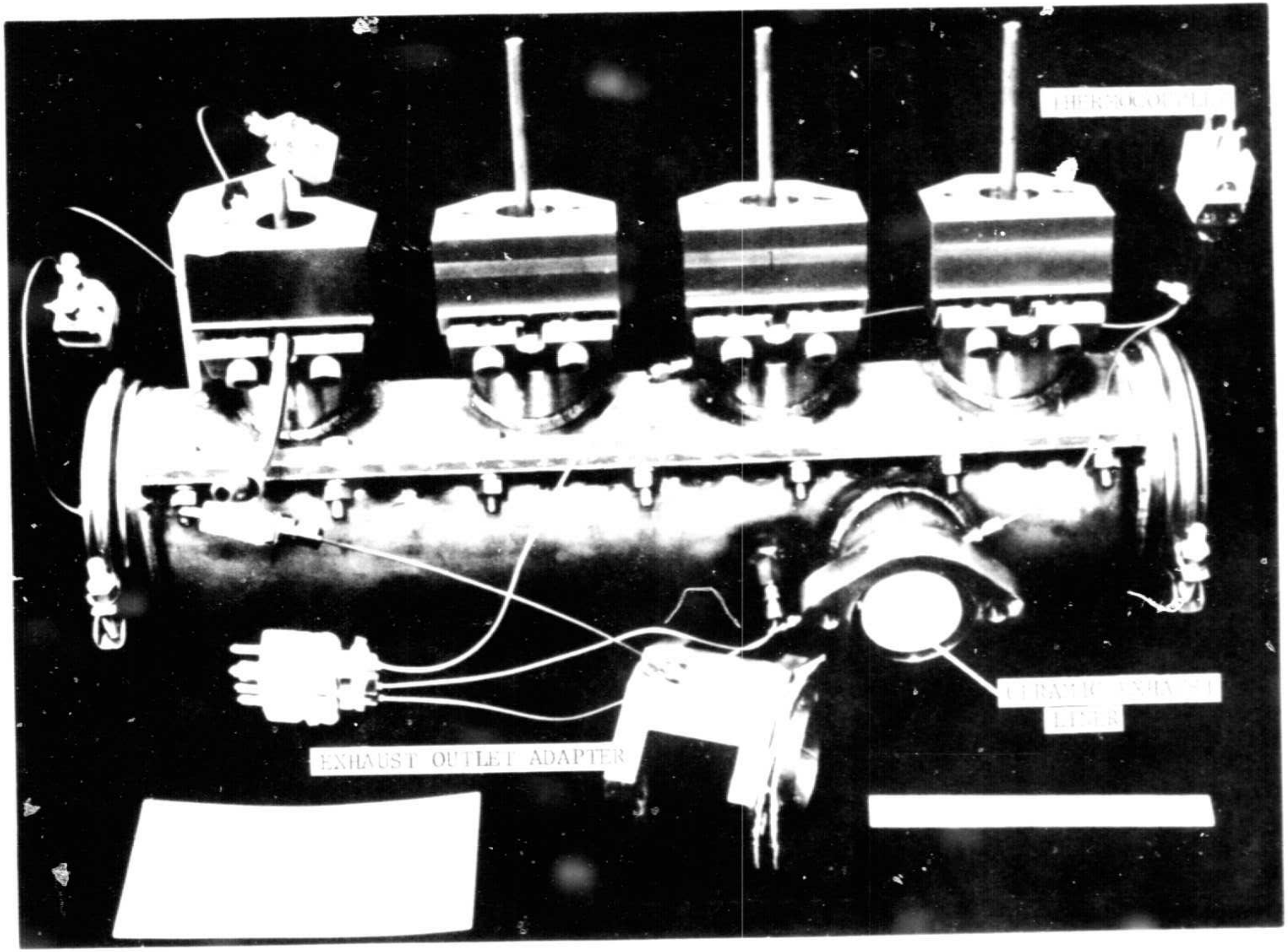


Figure 12 Thermal reactor as delivered to Teledyne Continental Motors

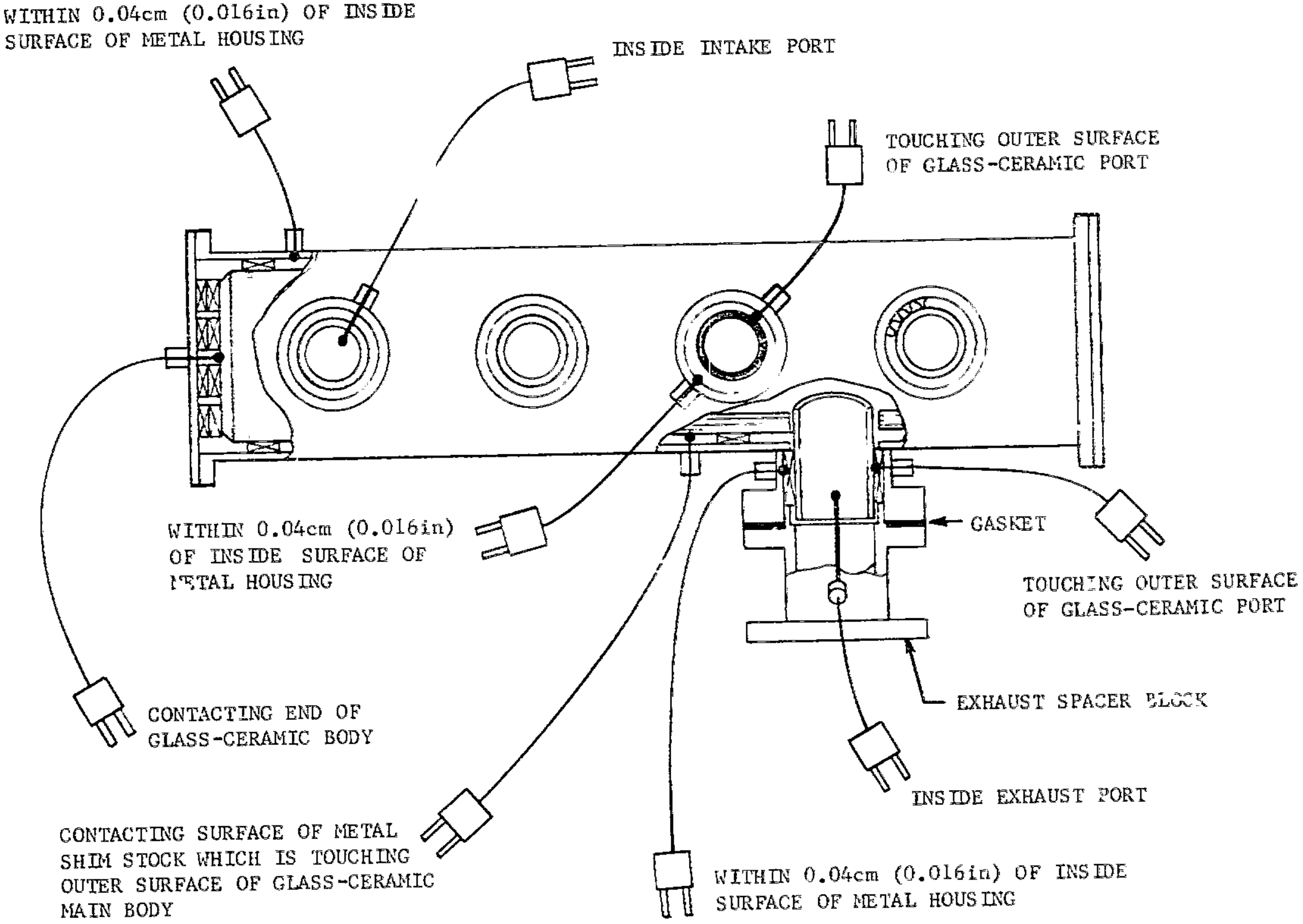


Figure 13 Location of thermocouples for reactor thermal endurance test

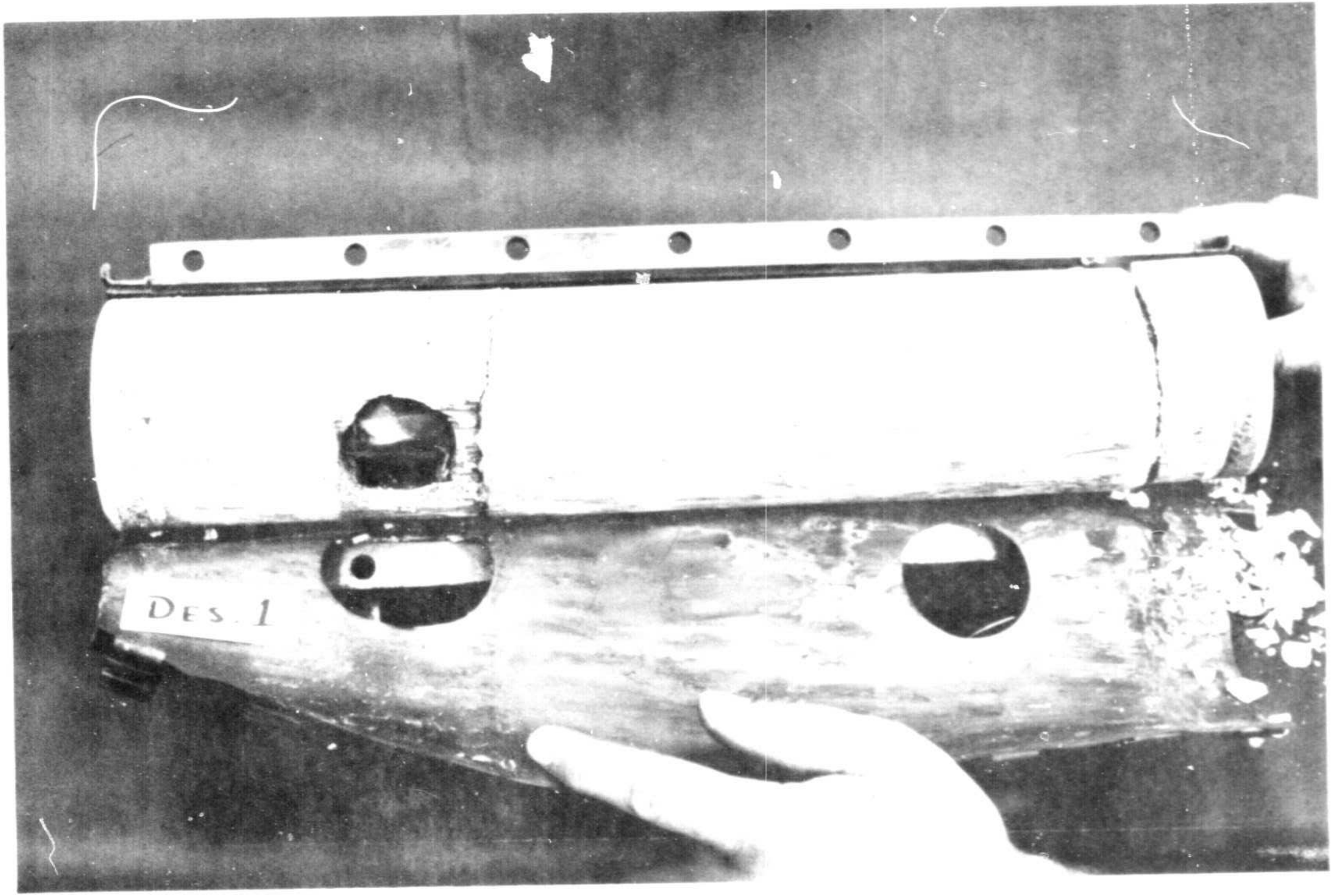


Figure 14 Breakage of glass-ceramic main body (REACTOR R-6)

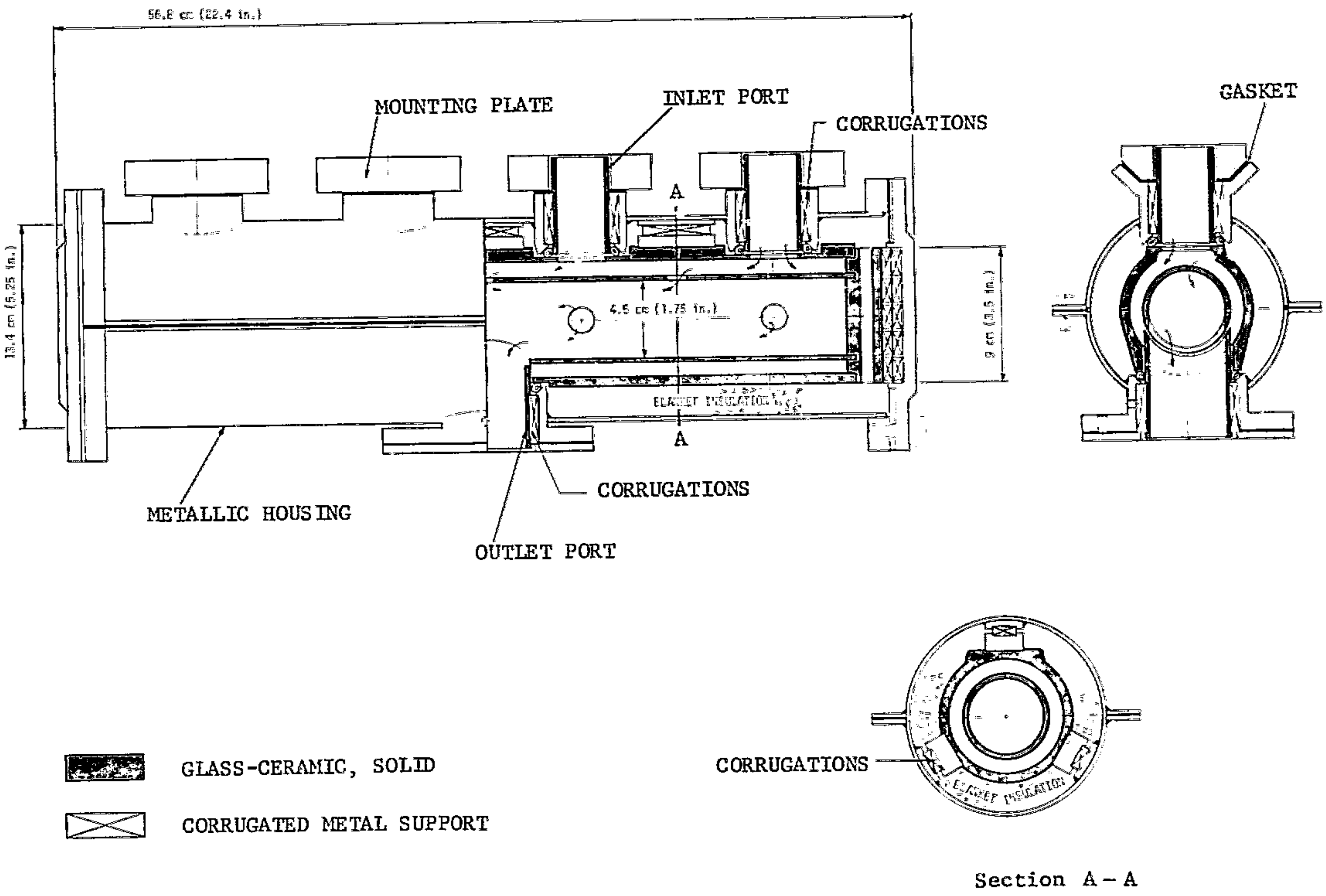


Figure 15 Glass-ceramic thermal reactor, Design IV

TABLE I.

LENGTH Cm.	LENGTH In.	WIDTH Cm.	WIDTH In.	HEIGHT Cm.	HEIGHT In.	LOAD Kilograms	LOAD Lbs.	COMPRESSIVE MOR KN/M²	COMPRESSIVE MOR Psi	TIME TO BREAK IN Secs.
GROUP A - 0.17 Cm. (0.067") PASSAGES PARALLEL TO APPLIED FORCE										
2.540	1.000	2.540	1.000	5.080	2.000	159 9	3525	24305	3525	27
2.537	0.999	2.537	0.999	5.077	1.999	125 9	2775	19240	2780	17
2.535	0.998	2.548	1.003	5.080	2.000	122 5	2700	18596	2697	20
2.540	1.000	2.543	1.001	5.083	2.001	111 1	2450	16813	2450	17
2.543	1.001	2.545	1.002	5.067	1.995	102 1	2250	15457	2243	19
2.550	1.004	2.545	1.002	5.077	1.999	134 9	2975	20513	2975	19
GROUP B - 0.17 Cm. (0.067") PASSAGES PERPENDICULAR TO APPLIED FORCE										
2.548	1.003	2.545	1.002	5.085	2.002	102.1	225	1544	224	8
2.548	1.003	2.545	1.003	5.083	2.001	113.4	250	1717	249	5
2.548	1.003	2.548	1.003	5.080	2.000	102.1	225	1544	224	3
2.527	0.995	2.530	0.996	5.085	2.002	68.0	150	1041	151	5
2.545	1.002	2.548	1.003	5.085	2.002	124.7	275	1889	274	6
2.530	0.996	2.545	1.002	5.085	2.002	102.1	225	1551	225	7
GROUP C - 0.10 Cm. (0.040") PASSAGE PARALLEL TO APPLIED FORCE										
2.545	1.002	2.545	1.002	5.083	2.001	1041	2295	15762	2286	15
2.545	1.002	2.548	1.003	5.077	1.999	1122	2475	16975	2462	18
2.543	1.001	2.545	1.002	5.083	2.001	1166	2575	17699	2567	18
2.548	1.003	2.548	1.003	5.083	2.001	987	2175	14907	2162	16
2.548	1.003	2.545	1.002	5.090	2.004	1134	2500	17133	2485	17
2.540	1.000	2.540	1.000	5.080	2.000	1111	2450	16893	2453	19
GROUP D - 0.10 Cm. (0.040") PASSAGES PERPENDICULAR TO APPLIED FORCE										
2.530	0.996	2.545	1.002	5.088	2.002	34.0	75	517	75	6
2.537	0.999	2.537	0.999	5.077	1.999	36.3	80	552	80	7
2.535	0.998	2.540	1.000	5.085	2.002	29.5	65	448	65	4
2.535	0.998	2.543	1.001	5.075	1.998	36.3	80	552	80	5
2.535	0.998	2.537	0.999	5.085	2.002	29.5	65	448	65	4
2.535	0.998	2.542	1.002	5.070	1.996	34.0	75	517	75	5

COMPRESSIVE STRENGTH RESULTS

Table 2 - Summary of Full-Size Reactor Endurance Tests on Engine Dynamometer

Reactor Number	Ceramic Material	Design Type	Time in Test, h	Results of Visual Examinations
R-6	Glass-Ceramic CER-VIT C-129	Type I	30	Inadequate corrugation support at temperature: thermal cycling and engine vibration led to cracked ceramic parts.
R-7	Same as R-6	Type II	35	Same as for R-6
R-10	Same as R-6	Type II	330	Same as for R-6
R-12	Same as R-6	Type II	255	Same as for R-6
R-13	Same as R-6	Type III	85	Same as for R-6

REFERENCES

1. Cantwell, E. N., Rosenlund, I. T., Barth, W. J., Kinner, F. L., and Ross, S. W., "A Progress Report on the Development of Exhaust Manifold Reactors." SAE Transactions, Vol. 78 (1969), Paper 690139.

2. Stone, P. L. and Blankenship, C. P., "Exploratory Evaluation of Ceramics for Automobile Thermal Reactors," SAE Paper 730224, Jan. 1973.

3. Dickson, A. C., and Petticrew, R. W., "CER VIT® Material for Emission Control Components," SAE Paper 730225, Jan. 1973.