2

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DESIGN AND EVALUATION OF EXPERIMENTAL CERAMIC AUTOMOBILE THERMAL REACTORS

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29

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16. Abstract

This report summarizes the results obtained in an exploratory evaluation of ceramics for automobile thermal reactors. Candidate ceramic materials were evaluated in several reactor designs by using both engine-dynamometer and vehicle road tests. Silicon carbide contained in a corrugated-metal support structure exhibited the best performance, lasting 1100 hr in engine-dynamometer tests and more than 38 600 km (24 000 miles) in vehicle road tests. Although reactors containing glass-ceramic components did not perform as well as those containing silicon carbide, the glass-ceramics still offer good potential for reactor use with improved reactor designs.

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CONTENTS

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SUMMARY

Several candidate ceramics were evaluated for use in automobile thermal reactors. Emphasis was placed on reactor designs to support the relatively brittle ceramic components. Ceramics included were silicon carbide, glass-ceramics, ALCET (aluminum and silicon nitride), and a graphite-fiber-reinforced silicon carbide. Primary support of the ceramic components in all designs was provided by a corrugated-metal structure. Full-size reactors were used in evaluating the performance of the ceramics and the reactor designs. The reactors were subjected to engine-dynamometer tests or vehicle road tests or both. In the cyclic engine-dynamometer tests, peak reactor gas temperatures ranged from 1040° to 1090° C (1900° to 2000° F) for about 60 percent of the test time. Vehicle road tests were conducted under normal driving conditions with a peak reactor gas temperature near 980° C (1800° F).

Silicon carbide exhibited the best performance, lasting up to 1100 hours in engine-dynamometer tests and 38 600 kilometers (24 000 miles) in vehicle road tests. The 1100-hour engine-dynamometer test was representative of the life of the test engine under the severe cyclic test conditions.

In the vehicle road test, a glass-ceramic reactor survived 33 800 kilometers (21 000 miles) and was still in good condition at the completion of the program. However, the glass-ceramic reactors failed in less than 330 hours of the more severe engine-dynamometer tests. Failure was attributed to reactor design deficiencies that prevented accommodation of the difference in thermal expansion between the glass-ceramic and metallic reactor components. None of the glass-ceramic components showed any evidence of chemical attack or erosion. With proper design, the glass-ceramics offer good potential for reactor use.

ALCET and graphite-fiber-reinforced silicon carbide reactors failed in less than 200 hours of engine-dynamometer tests. Both materials were unstable under the imposed test conditions and were severely degraded.

INTRODUCTION

Thermal reactors have been shown to be an effective means of reducing exhaust gas pollutants from automobile engines (refs. 1 to 3). A thermal reactor is essentially a closely coupled afterburner (installed in place of the cast-iron exhaust manifold) into which air is injected to oxidize unburned hydrocarbons and carbon monoxide. From the oxidation process, the core of the reactor reaches temperatures of approximately 870° to 1040° C (1600° to 1900° F) under normal driving conditions. This high-temperature oxidizing environment in combination with high-velocity corrosive constituents in the exhaust gas presents a severe environment for reactor materials. Of particular concern has been the inability of low-cost, abundantly available materials to survive the reactor environment (ref. 4).

Ceramics offer excellent potential for use in automobile thermal reactors because of their inherent resistance to oxidation and relatively low cost. In addition, some ceramics can be used to higher temperatures than conventional metallic materials. An exploratory evaluation of ceramics for thermal-reactor use was conducted by the NASA Lewis Research Center through both in-house and contracted studies. The primary objective of this exploratory program was to demonstrate the performance of ceramics in a thermal-reactor environment by achieving the following:

(1) A life of at least 600 hours in a cyclic, engine-dynamometer endurance test (reactor life comparable to some of the better metallic materials, ref. 5)

(2) A life of at least 32 200 kilometers (20 000 miles) in a vehicle road test

The program described in this report was part of an automotive thermal reactor technology program conducted in cooperation with the Environmental Protection Agency (ref. 5).

The major emphasis of our ceramic reactor studies was on development of reactor design concepts to support the relatively brittle ceramic components and prevent their failure by mechanical shock. Several reactor design concepts were considered. Full-size reactors of the most promising designs were subjected to engine-dynamometer tests or vehicle road tests or both. Ceramics for use in the experimental thermal reactor tests were selected primarily on the basis of resistance to thermal shock and relative ease of component manufacture. Reactor designs, candidate ceramic materials, and results from engine-dynamometer and vehicle road tests of full-size reactors are described in this report.

We want to emphasize that this experimental program was directed primarily toward contributing material performance data and design concepts that might be useful to the designers of emission control systems. Potential problems of meeting emission standards with ceramic thermal reactors (such as a thermal inertia higher than that of corresponding metal reactors) were recognized. Accordingly, qualitative measurements were made on some of the ceramic reactors to provide a reference point with respect to their warmup behavior and steady-state emission control. The detailed emission control aspects of the thermal reactors were beyond the scope of this program.

REACTOR MATERIALS, DESIGN, AND FABRICATION

Materials Selection

Selection of the candidate ceramics for this program was based primarily on their resistance to thermal shock, strength, maximum use temperature, fabricability, and low cost. The ceramics selected for consideration, their typical properties, and their respective sources are listed in table I. Silicon carbide was one of the prime candidates. It is quite strong and has good thermal shock resistance because of its high thermal conductivity. Also, fabrication technology was adequate to manufacture the reactor components. Three varieties of silicon carbide were included. Both KT_2 and CRYSTAR silicon carbide represent commercial grades made by ceramic powder techniques. Graphite-fiber-reinforced silicon carbide is an experimental ceramic composite with a potential high-temperature strength advantage over unreinforced silicon carbide.

Glass-ceramics have excellent resistance to thermal shock because of their low coefficient of thermal expansion. Two CER-VIT glass-ceramics were used in our evaluation on the basis of availability and ease of manufacturing reactor components. A different type of ceramic tested was ALCET, which is a refractory material containing silicon nitride and aluminum. This material was selected on the basis of its good thermal shock resistance, fabricability, and resistance to oxidation.

All the above materials were used in full-scale reactor tests. The other materials noted in table I were evaluated only in coupon screening tests. Fabrication technology for the latter materials was not developed sufficiently to assure manufacture of reactor components. However, with improved manufacturing techniques, these materials would warrant consideration on the basis of either lower cost or better resistance to the thermal reactor environment. They include silica/calcium aluminate, fused silica, mullites, and CPI (mullite and glass).

Reactor Design

The baseline reactor configuration used for most of the ceramic reactors is shown schematically in figure 1. Design and operation of this reactor configuration were similar to those for the Dupont Type-II circumferential flow reactor, which has been shown to be effective in emissions control (ref. 3). In the baseline reactor configuration, two concentric ceramic cylinders were used to form the combustion chamber. The inner cylinder was termed the reactor core, and the outer cylinder was termed the liner. In the baseline design, the ceramic components (including the inlet ports and exhaust port) were supported by thin-gage metal corrugations. The corrugated support structure acted like a spring to hold the ceramic components in place and absorb mechanical shock and vibration. Other forms of support were considered such as high-temperature, resilient insulation. But support systems of this type are more likely to be compacted by vibration and lose their ability to support the ceramic components.

The overall dimensions of the baseline reactor were a length of about 51 centimeters (20 in.) and a diameter of 14.0 centimeters (5.5 in.). Typical ceramic components were about 0.30 centimeter (0.12 in.) thick. Both the reactor core and the liner were about 44.5 centimeters (17.5 in.) long. The outside diameter of the core was 5.72 centimeters (2.25 in.), and that of the liner was 8.26 centimeters (3.25 in.). The corrugated-metal structure was made from 0.015-centimeter- (0.006-in.-) thick sheet. In the design shown in figure 1, the exhaust gas passed from the inner core through the slotted ends to the annulus and out the large exhaust port. A similar design also evaluated had 14 holes about 1.5 centimeters (0.6 in.) in diameter in the wall of the inner core. The holes were located between the inlet ports and provided for exhaust gas flow from the inner core to the annulus and out the exhaust port.

In addition to the baseline reactor design, several other reactor configurations were designed and evaluated by Owens-Illinois, Inc., under a NASA contract (ref. 6). Their proprietary glass-ceramics, CER-VIT C-126 and CER-VIT C-129, were used in this development study. Four reactor designs, designated A to D and shown in figures 2 to 5, were evaluated. Designs A, B, and C were about 51 centimeters (20 in.) long and 11.4 centimeters (4.5 in.) in diameter. Design D was about 61 centimeters (24 in.) long and 14.0 centimeters (5.5 in.) in diameter. Typical ceramic components were about 0.30 centimeter (0.12 in.) thick. In designs A and B, the core was 5.1 centimeters (2.0 in.) in outer diameter; the liner outer diameter was 7.6 centimeters (3.0 in.). The design C core inner diameter was 4.45 centimeters (1.75 in.). In design D, the core was 5.72 centimeters (2.25 in.) in outer diameter; the liner outer diameter was 8.9 centimeters (3.5 in.). The liner was 0.64 centimeter (0.25 in.) thick.

In designs A and B, the reactor combustion chamber was similar to that in the baseline reactor except for the gas flow passages. For designs A and B, the exhaust gas entered the outer annulus and passed to the reactor core through several holes in the core wall. Then the gas exhausted from the core through the outlet exhaust port. A closed-end honeycomb matrix provided thermal insulation and support of the internal reactor structure. The honeycomb matrix was about 1.2 centimeters (0.5 in.) thick and consisted of honeycomb cells that had a web thickness of about 0.025 centimeter

(0.010 in.) and a distance across the webs of about 0.170 centimeter (0.065 in.). The reactor core, liner, end pieces, and honeycomb matrix were cemented together to form a monolithic structure. A corrugated-metal structure was used to support the ceramic reactor components both radially and axially. Design B was a modification of design A with conical ends on the monolithic structure. Most of the support of this structure was provided by corrugations and metallic rings around the conical ends. Corrugations for radial support were reduced to about one-third those in design A.

In design C, figure 4, the exhaust gas entered the central chamber and then passed through the open honeycomb matrix (about 1.2 cm (0.5 in.) thick) to the exhaust outlet port. Insulation and support were provided by the closed honeycomb matrix. Design C was also a monolithic structure supported by metal corrugations.

Design D, shown in figure 5, used a different method of supporting the ceramic main body in the radial direction. Three longitudinal equally spaced ceramic ribs were cemented to the exterior of the outer liner. Two corrugated-metal strips and one insulating strip (Raybestos) were used to cushion and spring-load the ceramic main body as illustrated in figure 5. Batting insulation (Fiberfrax) was placed between the ceramic main body and the reactor housing. The primary purposes of this design were to reduce the temperature of the corrugated support structure by moving it farther away from the reactor combustion chamber and to provide for a lower reactor housing temperature by the added insulation. The housing diameter was made larger than the other designs to accommodate the ribs and insulation. Also, the reactor housing was longer since the reactor was tested on a larger automobile engine, as described in the section TEST PROCEDURE.

Reactor Fabrication

Full-size reactors were fabricated for engine-dynamometer and vehicle road tests. The ceramic components for the reactors were manufactured by the suppliers indicated in table I using existing manufacturing techniques. Final assembly of the reactors was performed at NASA. Most of the reactors fabricated contained 11 ceramic parts: four inlet ports, a large exhaust port, an inner core, an outer liner, and two caps and two rings for the reactor ends. The reactor end caps were loosely fitted to permit inspection during testing. A typical set of ceramic parts prior to assembly into a reactor housing is shown in figure 6. This particular set was made from a glass-ceramic, and several of the ceramic pieces were cemented together so that the basic number of parts was reduced from 11 to 7.

The corrugated metal used to support the ceramic components of most reactors was made from sheets of the nickel-base alloy Inconel 601, 0.015 centimeter (0.006 in.)

thick. This alloy offered the best combination of strength, oxidation resistance, and low cost of the alloy candidates considered. Relatively high temperatures (870° C (1600° F)) were anticipated at the ceramic - corrugated-metal interfaces. It was believed that these high temperatures would probably preclude the use of lower cost iron alloys except for the outer portions of the overall corrugated structure. In the reactors that were built first, however, a combination of the iron-base alloys Incoloy 800 and A-286 was used for the corrugated metal. The overall main corrugated structure consisted of two major components for radial support and two circular pieces for each end of the reactor to provide axial support. All parts were made by spot-welding roll-corrugated strips (about 2 cm (0.8 in.) wide) to 0.015-centimeter- (0.006-in.-) thick face sheets. Corrugation height was about 0.478 centimeter (0.190 in.). Spacing between the corrugated strips on the radial support components was about 5.5 centimeters (2 in.). Figure 7 shows the radial corrugated structure wrapped around a ceramic core and liner. As shown, three layers of corrugated metal were used in the baseline design to support the ceramic liner and core assembly. A single corrugated layer was used to support the reactor inlet and exhaust ports. Final assembly of a reactor with the circular end corrugated pieces is shown in figure 8. The reactor housing was made from low-carbon steel. During final assembly of the reactors, the spacing of the end corrugations was adjusted to provide a light preload on the ceramic components at operating temperatures. Thermocouples were installed in all the reactors to measure the core gas temperature and the temperatures at various locations within the corrugated-metal structures.

The ceramic reactor components for designs A, B, C, and D were fabricated by using existing glass-forming technology. Fabrication of the corrugated-metal supporting structure and assembly of the reactor components were similar to those for the baseline design. However, the corrugated support was reduced to one or two layers. As indicated in figure 5, longitudinal corrugated strips were used in design D.

A total of ten reactors of the baseline design and a total of six of designs A, B, C, or D were made for either engine-dynamometer tests or vehicle road tests, as described in the following section.

TEST PROCEDURES

Engine-Dynamometer Tests

Endurance tests. - Several full-size ceramic reactors were subjected to endurance tests under simulated driving conditions on engine-dynamometer test stands. These tests were conducted by Teledyne-Continental Motors, Inc. under NASA contract. The test facilities, including the reactor installation, operation of the V-8 engines, and the control systems, are described in reference 7. Figure 9(a) shows schematically the endurance test cycle used. Cycle part A simulated driving to work at about 56 kilometers per hour (35 mph) (840° C (1550° F) reactor core gas temperature) with several stops and starts and a 10-minute drive on a freeway at 113 kilometers per hour (70 mph) (1040° C (1900° F) reactor core gas temperature). Weekend shopping trips were simulated in cycle part B, and cycle part C simulated a weekend trip consisting mostly of freeway driving at 113 kilometers per hour (70 mph). The total cycle consisted of 32.5 hours of engine operation with the reactors at a peak core gas temperature of 1040° to 1090° C (1900° to 2000° F) for approximately 60 percent of the time. The cycle was repeated continuously in the endurance test.

The endurance test cycle provided extremely severe engine operation. For example, engine life was only about 1000 to 1200 hours under these test conditions. Our goal was to achieve at least a 600-hour life under these conditions with ceramic reactors. As previously noted, this would be comparable to the life achieved in some of the better metallic reactors using this test cycle (ref. 5).

Nonleaded gasoline was used in the test since it was believed that some of the reactor materials (e.g., glass-ceramics) might be subject to lead attack.

The ends of the baseline reactors had fittings installed to permit a relatively small amount of air cooling (~ 0.06 m^3/min (20 ft^3/min)). This was done to prevent overheating of the corrugated structure by exhaust gas that would leak by the loosely fitted ceramic end pieces. Air cooling of sealed reactors for use on an automobile should not be required. As stated previously, the end pieces were loosely fitted to permit inspection during testing. The test reactors were inspected by removing the ends and making a visual assessment of reactor condition. Normal inspections were made at approximately 200-hour intervals.

Warmup, emission, and steady-state tests. - Two ceramic baseline-design reactors, one of silicon carbide and one of glass-ceramic, were tested to provide a relative comparison of reactor warmup and emission characteristics. For this qualitative evaluation, each reactor was compared with a metallic reactor (of the Dupont Type-II circumferential flow configuration) mounted on the other bank of a V-8 test engine. Engine timing, carburetion, and other operating conditions were in accordance with factory specifications for the 1969 engine. No attempt was made to alter engine parameters to improve reactor warmup or emission performance. The tests were conducted in the NASA Lewis facility described in reference 8.

For the warmup test, the engine was set at an air/fuel ratio of about 11:1 and was programmed for a cold start, followed by a 15-second idle and a 15-second gradual speed increase to 1800 rpm with a manifold vacuum of 53 kilonewtons per square meter (15.5 in. Hg). This condition was held for about 6 minutes, and the cycle was repeated four times. The core gas temperature of each reactor and the temperature of each reactor material (ceramic or metal) were measured by thermocouples and recorded continuously on a strip-chart recorder.

Comparative emission data at several steady-state engine conditions were measured for each reactor. The conditions were 1400 rpm and a manifold pressure of 68 kilonewtons per square meter (20 in. Hg), 1800 rpm and 68 kilonewtons per square meter (20 in. Hg), and 1800 rpm and 61 kilonewtons per square meter (18 in. Hg). At each engine condition, emissions were measured at two air/fuel ratios, 11:1 and 12:1. Carbon monoxide and hydrocarbon emissions were measured by pumping exhaust gas samples to a nondispersive infrared analyzer and a flame ionization detector, respectively.

In addition to these tests, glass-ceramic reactors of both the baseline design and design D were evaluated at steady-state conditions to assess the influence of reactor design on reactor housing temperatures. For this evaluation, engine conditions were adjusted to provide a reactor core gas temperature of 1065° C (1950° F) in each reactor. Core gas temperatures were measured by shielded thermocouples inserted in the reactor core interior. After a core gas temperature of 1065° C (1950° F) was attained, each reactor was held at that internal temperature for about 1 hour to assure equilibration. The core gas temperatures and housing temperatures were again monitored and recorded continuously by means of thermocouples and strip-chart recorders.

Ceramic coupon tests. - Engine-dynamometer testing of the ceramic coupon samples also was performed on the NASA Lewis test engine. The coupons tested were about 0.32 to 0.48 centimeter (0.12 to 0.19 in.) thick, 2.54 centimeters (1 in.) wide, and 5 centimeters (2 in.) long. The ceramic coupons were placed on a test rack inside a metallic thermal reactor mounted on the engine. The test coupons were located in line with the exhaust inlet ports of the reactor. Figure 9(b) shows schematically the 17-minute test cycle used. This is similar to the coupon screening test cycle used to evaluate metallic materials (refs. 3 and 9). The test coupons were exposed to a minimum of 100 cycles at a peak material temperature of 1040° C (1900° F). Resistance to thermal shock, vibration, and oxidation was of primary concern in this brief screening test.

Vehicle Road Tests

Vehicle road tests were included in the program to provide a better measure of the capability of the reactor designs to prevent failure of the ceramic components from road shock and vibration. A NASA motor-pool station wagon was modified to permit attachment of a thermal reactor on each bank of the V-8 engine. The modification included installation of an air injection system. Engine timing, carburetion, and other operating conditions were in accordance with factory specifications for the 1968 vehicle used. No attempt was made to alter engine parameters to improve reactor performance.

Two reactors of the baseline design were mounted on the vehicle for road tests: one reactor of silicon carbide and one reactor of the glass-ceramic. Figure 10 shows the engine compartment of the test vehicle with the reactors attached to the engine. Reactor core temperature, corrugated-metal temperatures, and housing temperatures were continuously monitored and recorded during the road tests. Most of the road testing was accomplished by routine driving in and around the Cleveland area. Both city roads and freeways were used. Periodically the reactors were inspected visually by removing the reactor ends.

RESULTS AND DISCUSSION

Reactor Temperature Profiles

Typical reactor temperature profiles obtained under the most severe conditions in the engine-dynamometer endurance test cycle and typical reactor temperature profiles obtained in the vehicle road test at 113 kilometers per hour (70 mph) are shown in figure 11 for both silicon carbide and glass-ceramic reactors of the baseline design. Reactor temperature profiles for designs A, B, and C under similar test conditions are presented in figure 12.

In the engine-dynamometer endurance tests, peak reactor core gas temperatures of 1040° to 1090° C (1900° to 2000° F) resulted in temperatures ranging from 880° to 940° C (1625° to 1725° F) at the ceramic - corrugated-metal interface for both silicon carbide and glass-ceramic reactors of the baseline design. Reactor end temperatures were considerably lower because of the air cooling. Reactor housing temperatures ranged from about 480° to 540° C (900° to 1000° F). These housing temperatures were considered excessively high with respect to reactor performance on a vehicle. Lower housing temperatures would be expected in vehicle operation because of a greater flow of air around the outside of the reactors than was provided in the engine-dynamometer tests.

Endurance test temperature profiles for designs A, B, and C exhibited much lower temperatures at the ceramic - corrugated-metal interfaces than those for the baseline design. These lower temperatures resulted from the insulating characteristics of the honeycomb matrix and the greater distance of the corrugated metal from the hot sections of the reactor interior. However, the reactor housing temperatures of 440° to 500° C (825° to 925° F) were still considered to be excessively high compared to those expected during vehicle operation.

In the vehicle road tests, the maximum core gas temperatures observed for both the silicon carbide and glass-ceramic reactors were about 1000° C (1830° F). Most of the time, the reactor core gas temperatures ranged from 900° to 955° C (1650° to 1750° F). These lower reactor core gas temperatures (compared to those observed in the endurance test) produced correspondingly lower ceramic-metal interface temperatures. Reactor housing temperatures were also lower because of the lower core temperature and the greater air cooling provided by the engine fan and vehicle motion. If the reactor core gas temperature had reached 1040° to 1090° C (1900° to 2000° F) as in the case of the engine-dynamometer tests, the housing temperatures would probably have been between 260° and 370° C (500° and 700° F). The temperatures of the silicon carbide reactor were lower overall than those of the glass-ceramic because of metal ducting installed in the vehicle. This ducting channeled a greater amount of air over the silicon carbide reactor for better cooling. Since air cooling of the reactor ends was not used in the vehicle test reactors, the ceramic - corrugated-metal interface temperatures at the ends and along the reactor length were similar.

In the steady-state tests, the comparison of the reactor housing temperatures of the baseline design with those of design D showed that a significant reduction in housing temperature was achieved with design D. With the core gas temperature of 1065° C (1950° F), the design D housing temperature was about 260° C (500° F). Under the same conditions, the baseline design exhibited a housing temperature of 440° C (825° F). Therefore, in cases where lower reactor housing temperatures are desired or necessary, reactor designs such as design D could be considered.

Engine-Dynamometer Tests

Endurance tests. - Six baseline reactors and five reactors of design A, B, or C were endurance tested on the engine-dynamometer stands. The results are summarized in table II.

Silicon carbide reactors of the baseline design gave the best performance. Reactor 2, containing KT_2 silicon carbide, was tested successfully for 1100 hours, far longer than the 600-hour test goal. The periodic inspections of reactor 2 showed no signs of erosion or component degradation. However, upon disassembly after completion of the test, a hairline crack was observed around the central circumference of the liner. At this location, about 50 percent of the liner cross section was removed to accommodate the large exhaust port (fig. 6). Thus, the crack occurred in an area of potential weakness. Since the crack was not detected in the periodic inspections and since no hotspots were observed in the supporting corrugated metal, the crack in the liner probably occurred late in the 1100-hour test. The last inspection was completed after 900 hours of exposure, which indicates that the crack probably occurred during the last 200 hours of the endurance test.

Reactor 3 lasted nearly 600 hours even though the silicon carbide liner contained a hairline crack almost entirely around the central circumference of the liner at the start of the test. The component was cracked during manufacture. The test was terminated when the crack opened sufficiently to cause overheating of the corrugated support structure.

Overall, the ceramic parts from reactors 2 and 3 showed no evidence of erosion or chemical attack. The ceramic parts exhibited a slight weight gain of 0.2 to 0.7 percent for reactor 2 and 0.1 to 0.3 percent for reactor 3. Oxidation of some uncombined silicon and pickup of some exhaust gas particulates probably accounted for the weight gains. Metallographic examination of the silicon carbide components before and after the test exposure showed essentially no change in the structural characteristics of this material.

The similar failure locations in reactors 2 and 3 indicate that the design of the reactor exhaust outlet should be altered to increase the central area of the liner. This area could be increased by reducing the exhaust port diameter from the 7.4 centimeters (2.9 in.) used in the baseline design to about 5.1 centimeters (2 in.). The change could be made without altering the performance of the reactors. Another approach would be to add stiffening ribs on the outside diameter of the liner.

Performance of the corrugated structures in supporting the ceramic components of reactors 2 and 3 was judged to be excellent. Both reactors used Incoloy 800 for the corrugated layer and the face sheet adjacent to the ceramic components. The second and third corrugated layers were made of A-286. Metallographic examination of both materials after the 1100-hour exposure showed grain-boundary oxidation of the Incoloy 800 to a depth of about 0.005 centimeter (0.002 in.) on both surfaces. The A-286 exhibited only minor surface oxidation. The entire corrugated structure was integrally sound and could be flexed without failure.

The endurance test of the CRYSTAR silicon carbide reactor (11) was inconclusive. Excessive leakage of exhaust gas past the loose end caps caused overheating of the end corrugated metal and housing. None of the silicon carbide components failed, although the test was of short duration (~110 hr). Modification of the end-cap design or closer end-cap tolerance would have been required in order to obtain a better evaluation of this material. We believe the CRYSTAR material has the capability to perform as well as the KT_2 material because these materials are quite similar.

Reactor 4, containing graphite-fiber-reinforced silicon carbide, failed in about 190 hours of testing. The primary failure was located at the reactor ends, but all the components exhibited appreciable erosion and porosity. Most of the reactor components lost about 6 to 8 percent of their original weight. It appeared that the initial graphite-fiber shapes had not been adequately protected with silicon carbide during the final production steps. Thus, exposure to the exhaust gas environment resulted in oxidation of the graphite, which in turn led to the general degradation of the reactor components.

Therefore, we conclude that improved manufacturing techniques are required to assure protection of the graphite-fiber structure in order for this material to perform satisfactorily in a thermal-reactor application.

Reactor 1, containing the ALCET ceramic, failed in less than 15 hours of testing. Failure resulted from excessive loss of aluminum from the ceramic. The free aluminum severely degraded the corrugated structure and resulted in loss of support for the ceramic components. Improved heat-treating procedures to assure stabilization of the ALCET material or better control of the composition or both are required before this material can be considered for reactor use.

Glass-ceramic reactors of both the baseline design and designs A, B, and C failed in less than 330 hours. However, we believe that this relatively short life was attributable to reactor housing temperature problems rather than material limitations. From the analysis of all the failed reactors, we concluded that the primary problem was associated with the great difference in thermal expansion between the ceramic and metallic support components. With the nil thermal expansion of the glass-ceramic and the higher than anticipated reactor housing temperatures, contact between the ceramic and the expanding metal support structure could not be maintained at temperature. Preloading the support structure sufficiently to assure contact at temperature could not be accomplished without permanently deforming the corrugated metal. Under the cyclic test conditions, the unsupported glass-ceramics were not strong enough to withstand the mechanical vibration from the test engines, and thus they failed. None of the glass-ceramic components showed any evidence of chemical attack or erosion.

The design D glass-ceramic reactor, although not endurance tested, did show an appreciable reduction in housing temperature in the steady-state tests. With the lower housing temperature of this design, contact between the glass-ceramic and the metal support structure could probably be maintained under the endurance test conditions.

Warmup and emission tests. - In the warmup tests, reactor performance was based on the time for the reactor core gas temperature to reach 730° C (1350° F), which is the approximate minimum temperature required to reduce emissions effectively (ref. 10). The ceramic reactors used in these tests contained about the same weight of ceramic components, and similar components in the metallic reactor weighed about 10 percent more than the ceramics.

As expected, the core gas temperature of the metallic reactor reached 730° C (1350° F) faster than that of the ceramic reactors. The time for the metallic reactor to reach the designated core gas temperature was 2.0 to 2.5 minutes. The silicon carbide reactor took 3.0 to 3.5 minutes to reach a core gas temperature of 730° C (1350° F). The greater specific heat of the silicon carbide as compared to the metal reactor (about 40 percent greater at ambient temperature and 90 percent at about 705° C (1300° F)) accounts for its slower warmup. However, the silicon carbide reactor reached temperature reasonably fast and probably could perform as well as a metallic reactor if the thickness of the ceramic parts could be reduced without affecting their ability to withstand mechanical shock in a reactor application.

The glass-ceramic reactor took 5.5 to 6.0 minutes to reach a core gas temperature of 730° C (1350° F). This considerably longer warmup time for the glass-ceramic reactor compared with the silicon carbide reactor is probably related to the greater specific heat of the glass-ceramic (about 30 percent greater at ambient temperature and about 40 percent above 650° C (1200° F)).

These results should be considered only as a first approximation of relative warmup of ceramic reactors. Many factors such as reactor design and engine operating conditions influence warmup behavior. For example, the core gas temperature of a glass-ceramic reactor of a different design (ref. 11) reached 730° C (1350° F) in about 15 seconds from a cold start. This test was conducted on an automobile with the engine adjusted to improve reactor warmup characteristics. Thus, with proper reactor design and engine operating conditions, the high thermal inertia of ceramic reactors may not be a major deterrent to their use.

In the steady-state emissions tests, both the silicon carbide and glass-ceramic reactors performed almost identically to the metal reactor. This was true for all engine conditions and air/fuel ratios used. For most engine conditions, hydrocarbon emissions were in the range of 5 to 15 ppm and carbon monoxide emissions were in the range of 0.2 to 0.4 percent. These levels were considered to be well within the range for good thermal-reactor performance (ref. 1).

Ceramic coupon tests. - The results of the coupon testing program are given in table III. The variation in the number of test cycles is due to testing of the coupon specimens on one bank of the engine while reactors were being tested on the other. A one-to-one quantitative comparison of all materials is thus not possible, but clear trends are seen. The two silicon carbide specimens gained weight. This is consistent with the data obtained from the endurance tests of silicon carbide reactors. The graphite-fiber-reinforced silicon carbide material lost a significant amount of weight, a result which is also in agreement with the full-size-reactor test of this material. Most, if not all, of the glass-ceramic weight loss appeared to be due to chipping during disassembly from the test rack. The ALCET, the silica/calcium aluminate, and the CPI materials displayed mechanical strength problems, as shown by their inability to complete even a 100-cycle test. The fused silica and the two mullites appeared to have good potential for reactor use based on the screening tests.

Vehicle Road Tests

The station wagon was driven more than 38 600 kilometers (24 000 miles) with the silicon carbide reactor attached and approximately 33 800 kilometers (21 000 miles) with the glass-ceramic reactor attached. Operating confidence was obtained first with the silicon carbide reactor prior to installation of the glass-ceramic reactor. The reactors were inspected visually at approximately 3200-kilometer (2000-mile) intervals by removing the reactor ends. The reactors showed no signs of degradation or incipient failure. The maximum reactor housing temperature observed in these tests was 260° C (500° F) for the glass-ceramic reactor. This low reactor housing temperature probably explains, at least in part, why the glass-ceramic reactor survived the vehicle road tests while its close counterpart, reactor 5, failed the engine-dynamometer tests.

Overall, the vehicle road tests were successful in demonstrating the potential use of ceramic components in a thermal reactor. Ample support of the ceramic components was provided by the corrugated-metal structure. The reactors survived mechanical shock from both rough roads and engine vibration coupled with thermal cycling. Road shock and engine vibration in the vehicle road tests were considered to be representative of normal driving conditions since the tests included freeway driving at high speeds, city driving, and starting in subzero weather.

Although the engine-dynamometer tests were more severe in terms of rapid thermal cycling and peak reactor temperatures, the vehicle road tests provided a major test of the reactor design and support structure in terms of resistance to mechanical shock. From the design aspect, the reactor cores, 44.5 centimeters (17.5 in.) long and supported only at the ends, were considered to be the components most vulnerable to failure. But they performed well, and their end-tab supports showed no signs of chipping or abrasion.

CONCLUDING REMARKS

From the results of this study, several ceramic materials appear to be good candidates for use in thermal reactors. Silicon carbide exhibited the best performance of the ceramics evaluated. Excellent containment of the relatively brittle ceramic components was provided by the corrugated-metal support structure in both the engine-dynamometer and vehicle road tests.

We believe the glass-ceramics also offer good potential for reactor use, even though they did not perform as well as silicon carbide. Reactor design is more critical with the glass-ceramics in order to accommodate the greater differences in thermal expansion between the glass-ceramic and a metal support structure. A reactor design with a rib-type support structure (design D) is one approach that reduces the temperature of the metal support components and thereby reduces the expansion differential. This type of design might also be used with silicon carbide reactors to reduce the peak temperature at the ceramic-metal interface. Reducing the ceramic-metal interface temperature would be an important factor should reactor core gas temperatures exceed the nominal 1040° C (1900° F) peak temperature used in this evaluation program.

Compared to silicon carbide, the glass-ceramics have an advantage in the manufacture of complex reactor geometries since well-established glass manufacturing technology can be used. Also, glass-ceramics offer potential for lower costs. But silicon carbide is stronger at reactor operating temperatures, and it has a higher overtemperature capability (at least 200° C (360° F)) than glass-ceramics. Other ceramics that warrant consideration for reactor use include fused silica and high-temperature mullites. Their potential for lower cost and ease of component manufacture (compared to silicon carbide and glass-ceramics) should be considered in future ceramic reactor studies.

On a qualitative basis, the ceramic reactors performed as well as a metallic reactor in reducing emissions under steady-state conditions. From a cold start, the slower warmup of ceramic reactors was apparent. However, other work suggests that, with engine parameters adjusted to provide for faster warmup and possibly improved reactor designs, the thermal lag of ceramics may not be a major deterrent to their use.

SUMMARY OF RESULTS

Several candidate ceramics were evaluated for use in automobile thermal reactors. Emphasis was placed on reactor designs to support the relatively brittle ceramic components. Ceramics included were KT_2 and CRYSTAR silicon carbide, CER-VIT glass-ceramics, ALCET (aluminum and silicon nitride), and a graphite-fiber-reinforced silicon carbide. Primary support of the ceramic components in all designs was provided by a corrugated-metal structure. Full-size reactors were used in evaluating the performance of the ceramics and the reactor designs. The reactors were subjected to engine-dynamometer tests or vehicle road tests or both. In the cyclic engine-dynamometer tests, peak reactor core gas temperatures ranged from 1040° to 1090° C (1900° to 2000° F) for about 60 percent of the test time. Vehicle road tests were conducted under normal driving conditions with peak reactor core gas temperatures near 980° C (1800° F). The results are summarized as follows:

1. Silicon carbide exhibited the best performance, lasting up to 1100 hours in engine-dynamometer tests. This test time was representative of the life of the test engine under the severe cyclic test conditions.

2. Glass-ceramic reactors failed in less than 330 hours of engine-dynamometer tests. Failure was attributed to reactor design deficiencies that prevented accommodation of the difference in thermal expansion between the ceramic and metallic reactor components.

3. In vehicle road tests, silicon carbide and glass-ceramic reactors both successfully withstood road shock and vibration. No signs of degradation or incipient failure were evident in more than 33 800 kilometers (21 000 miles) of road testing. Reactor housing temperatures in the vehicle road tests were lower (about 260° C (470° F)) than the housing temperatures obtained in the more severe engine-dynamometer tests. This lower temperature permitted accommodation of the differences in expansion between the glass-ceramic and the metal support structure.

4. ALCET and graphite-fiber-reinforced silicon carbide reactors failed in less than 200 hours of engine-dynamometer tests. Both materials were unstable under the imposed test conditions and were severely degraded.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 19, 1974,
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TABLE I. - CANDIDATE CERAMICS FOR THERMAL REACTORS AND TYPICAL PROPERTIES

Ceramic	Coefficient of thermal expansion, cm/(cm/°C)	Coefficient of thermal expansion, in./(in./°F)	Thermal conductivity, W/(m)(K)	Thermal conductivity, (Btu)(in.)/(hr)(ft²)(°F)	Rupture test temperature, °C	Rupture test temperature, °F	Modulus of rupture, MN/m²	Modulus of rupture, ksi	Maximum use temperature, °C	Maximum use temperature, °F	Density, g/cm³	Material supplier
Silicon carbide												
KT_2[a]	5.0×10^{-6}	2.8×10^{-6}	31	215	1200	2200	124-145	18-21	1650	3000	2.8	Carborundum Company
CRYSTAR[a]	4.9	2.7	26	145	20	70	97-124	14-18	1760	3200	2.6	Norton Company
					1480	2700	124-152	18-22				
Graphite-fiber-reinforced[a]	--------	--------	-----	-----	20	70	97	14	1260	2300	2.3	Fansteel, Inc.
Glass-ceramic												
CER-VIT C-126[b]	0.7×10^{-6}	0.4×10^{-6}	2.1	11.6	20	70	207-242	30-35	1090	2000	2.5	Owens-Illinois, Inc.
					1040	1900	28-35	4-5				
CER-VIT C-129[a]	.2	.1	1.9	10.5	20	70	69-97	10-14	1200	2100	2.5	Owens-Illinois, Inc.
					1040	1900	69	10				
ALCET (Al and SiN)[a]	6.3×10^{-6}	3.5×10^{-6}	43.2	240	20	70	172	25	1650	3000	2.6	Remington Arms Company
					820	1500	24	3.5				
Silica/calcium aluminate[c]	0.81×10^{-6}	0.45×10^{-6}	0.36	2.0	----	----	-------	-----	1650	3000	1.8	Bell-Aerosystems, Inc.
Mullite												
R-21[c]	5.5×10^{-6}	3.1×10^{-6}	-----	-----	20	70	33	4.8	1450	2650	---	Electrical Refractories Company
B-47[c]	4.3	2.4	-----	-----	20	70	19	2.7	1230	2250	---	Electrical Refractories Company
CPI (mullite and glass)[c]	5.4	3.0	0.32	1.8	20	70	17	2.5	1090	2000	0.4	Grumman Aerospace Inc.
Fused silica[c]	1.3×10^{-6}	0.7×10^{-6}	0.22	1.2	----	----	-------	-----	1150	2100	2.2	Owens-Corning Fiberglas Company

[a]Full-size reactor and coupon tests.
[b]Reactor test only.
[c]Coupon test only.

TABLE II. - SUMMARY OF FULL-SIZE REACTOR ENDURANCE TESTS ON ENGINE DYNAMOMETER

Reactor	Ceramic material	Design	Test time, hr	Results
2	Silicon carbide - KT_2	Baseline	1100	Circumferential crack in ceramic liner at end of test; reactor integrity maintained
3	Silicon carbide - KT_2		570	Circumferential crack in ceramic outer liner (present from beginning) opened and caused housing overheating
11	Silicon carbide - CRYSTAR		110	Excessive exhaust gas leakage at reactor ends caused corrugation and housing overheating
4	Graphite-fiber-reinforced silicon carbide		190	Excessive graphite loss (6 to 8 wt. %) leading to part deterioration
1	ALCET (Al and SiN)		15	Excessive loss of aluminum leading to part and corrugated-metal deterioration
5	Glass-ceramic - CER-VIT C-126		165	Inadequate corrugated-metal support at temperature; thermal cycling and engine vibration led to cracking of ceramic parts
6	Glass-ceramic - CER-VIT C-129	C	30	
7		A	35	
10		A	330	
12		A	255	
13		B	85	

TABLE III. - SUMMARY OF CERAMIC COUPON TEST DATA

Ceramic	Number of test cycles	Weight change, percent	Results of visual examination
Silicon carbide			
KT_2	140	0.15	No cracks or chipping
CRYSTAR	100	.19	No cracks or chipping
Graphite-fiber-reinforced	140	-4.7	Minor chipping on edges
Glass-ceramic - C-129	100	-2.5	Chipping upon disassembly from test rack
ALCET	100	-----	Specimens cracked
Silica/calcium aluminate	100	-----	Specimens cracked
Fused silica	100	-0.11	No cracks or chipping
Mullite			
R-21	150	1.0	No cracks or chipping
B-47	150	1.0	No cracks or chipping
CPI	150	-----	Specimens cracked

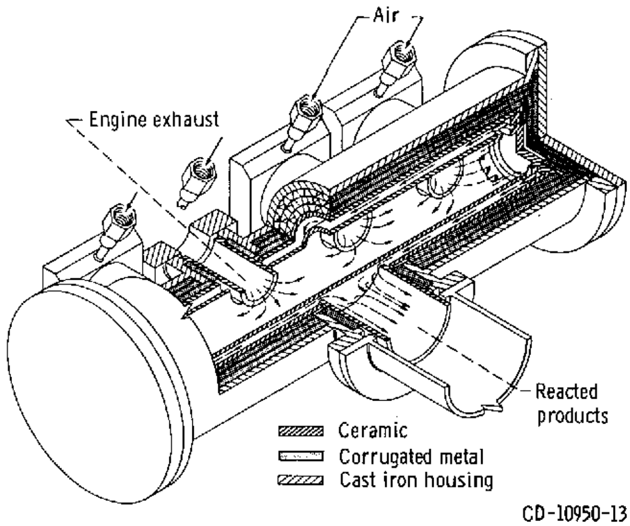


Figure 1. - Ceramic-lined automobile thermal reactor, baseline design.

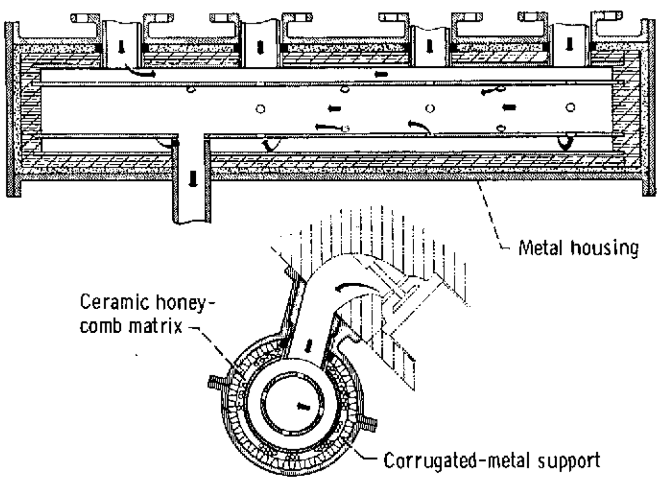


Figure 2. - Glass-ceramic thermal reactor, design A.

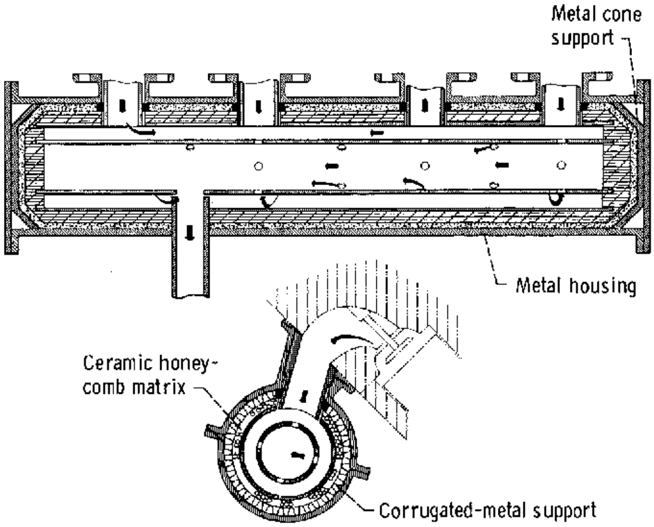


Figure 3. - Glass ceramic thermal reactor, design B.

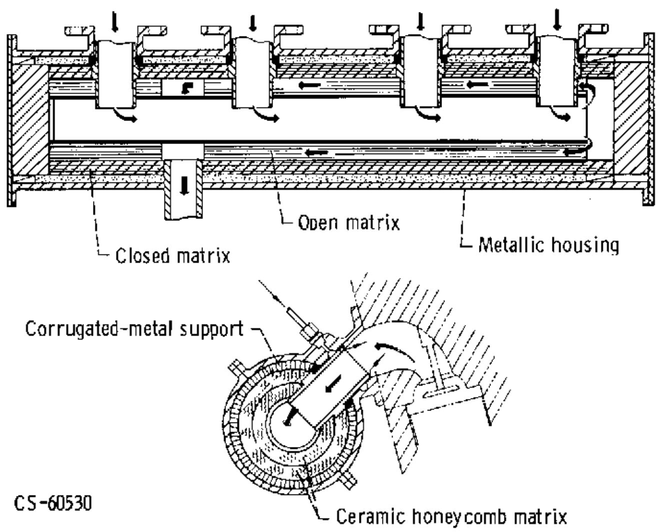


Figure 4. - Glass ceramic thermal reactor, design C.

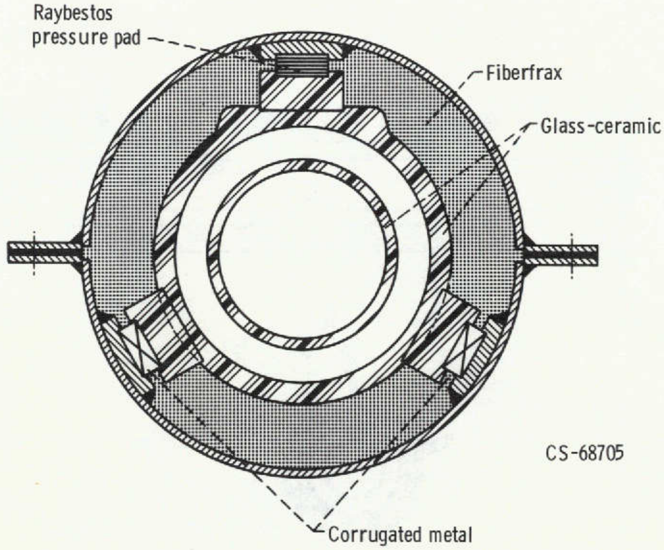


Figure 5. - Cross section of glass-ceramic thermal reactor, design D.

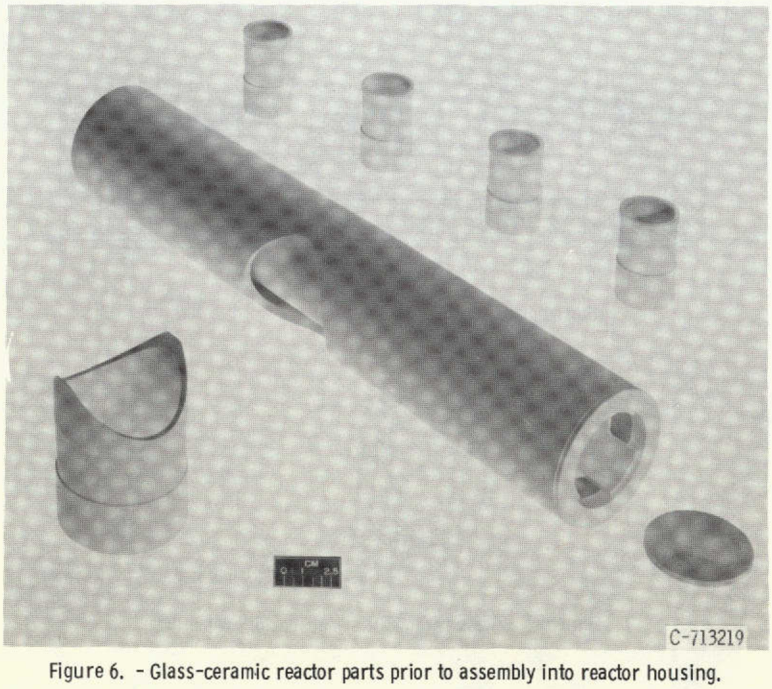


Figure 6. - Glass-ceramic reactor parts prior to assembly into reactor housing.

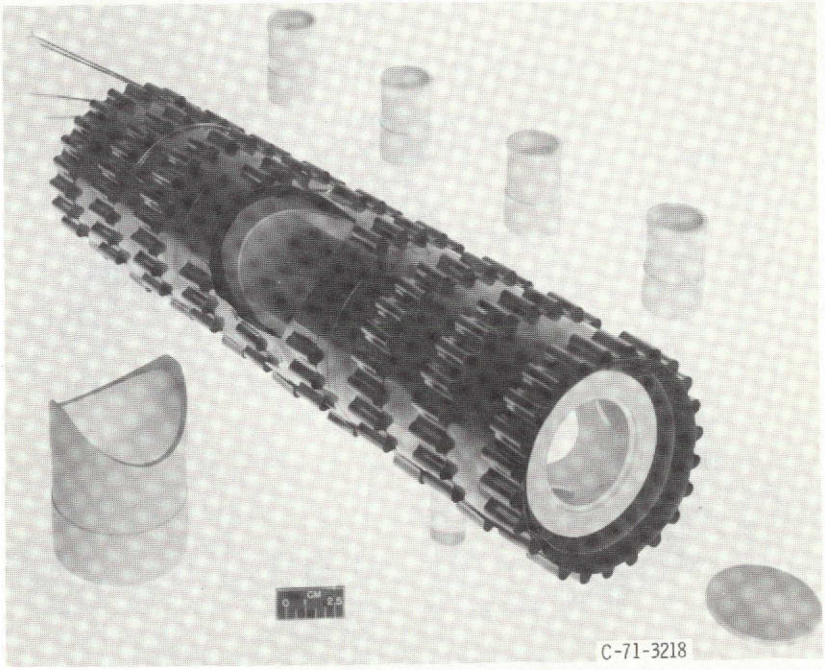


Figure 7. - Glass-ceramic reactor parts with corrugated-metal support structure.

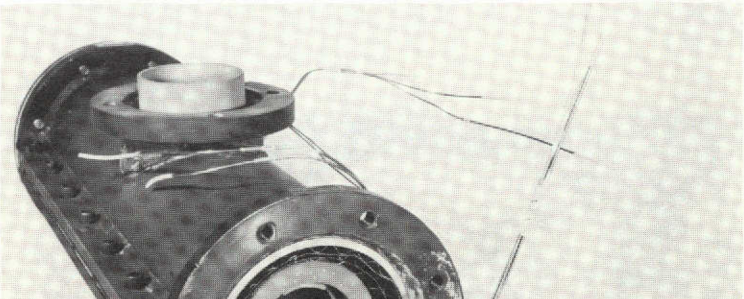
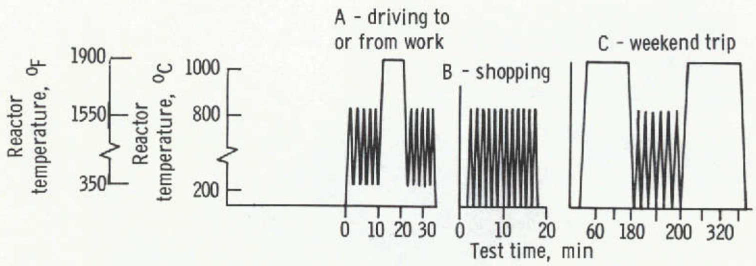
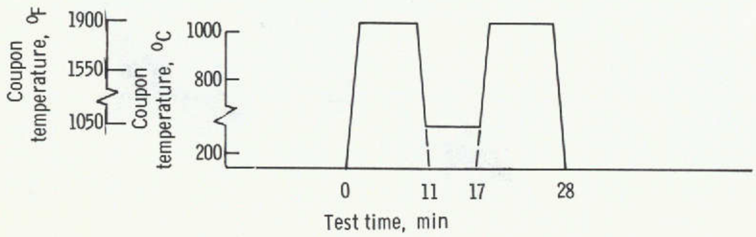


Figure 8. - Final assembly of ceramic thermal reactor, baseline design.



(a) Endurance test cycle, 10A + B + 10A + C + 10A + B + 10A + C.



(b) Screening test cycle.

Figure 9. - Engine-dynamometer test cycles.

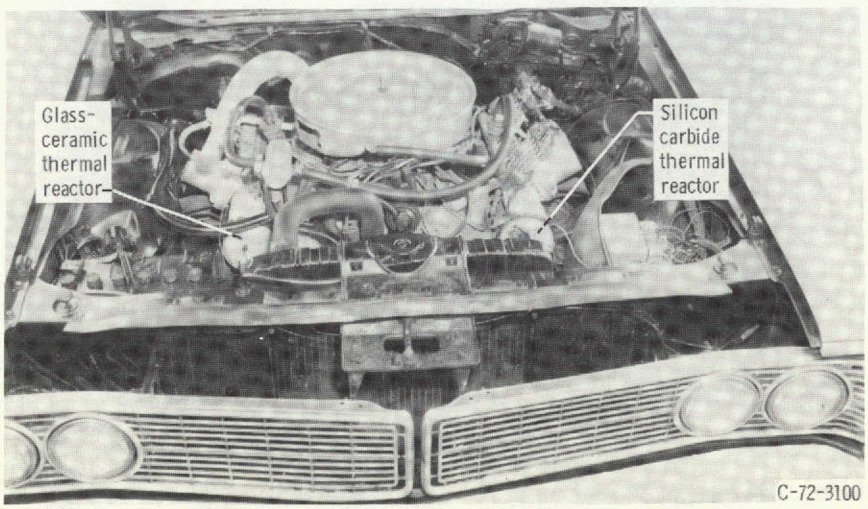
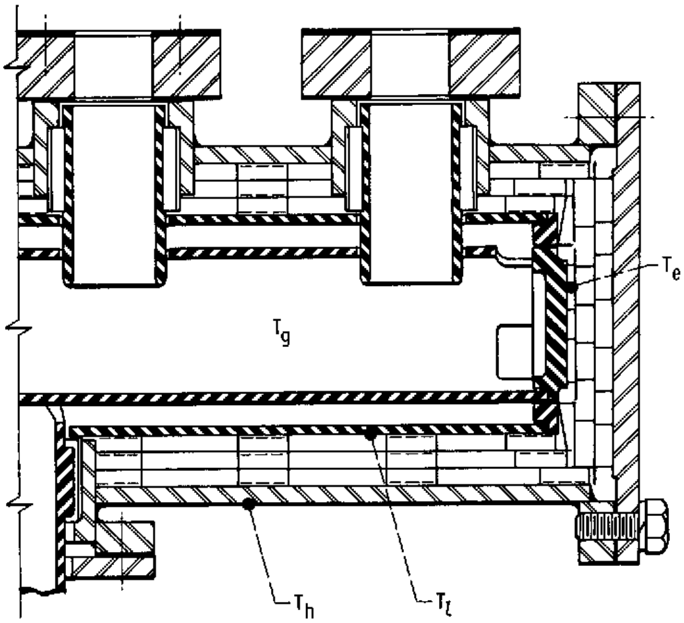
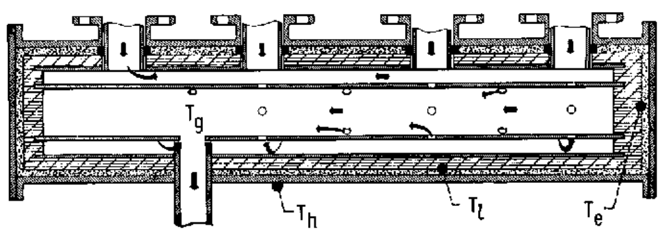


Figure 10. - Engine compartment of test vehicle showing thermal reactor installation.



Reactor material	Test method	Gas temperature, T_g		End temperature, T_e		Liner temperature, T_l		Housing temperature, T_h	
		^oC	^oF	^oC	^oF	^oC	^oF	^oC	^oF
Silicon carbide	Engine-dynamometer	1040 - 1090	1900 - 2000	650 - 760	1200 - 1400	880 - 940	1625 - 1725	480 - 540	900 - 1000
Glass ceramic	Engine-dynamometer	1040 - 1090	1900 - 2000	500 - 520	925 - 975	910 - 940	1675 - 1725	510 - 540	950 - 1000
Silicon carbide	Road vehicle	900 - 950	1650 - 1750	760 - 780	1400 - 1450	750 - 800	1375 - 1425	190 - 220	375 - 425
Glass ceramic	Road vehicle	900 - 950	1650 - 1750	800 - 830	1475 - 1525	800 - 830	1475 - 1525	230 - 260	450 - 500

Figure 11. - Typical reactor temperature profiles, baseline reactor design.



Gas temperature, T_g		End temperature, T_e		Liner temperature, T_l		Housing temperature, T_h	
^oC	^oF	^oC	^oF	^oC	^oF	^oC	^oF
1040 - 1090	1900 - 2000	205 - 260	400 - 500	510 - 570	950 - 1050	440 - 500	825 - 925

Figure 12. - Typical reactor temperature profiles, designs A, B, and C. Reactor material, glass-ceramic.