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A RESONANCE-TUBE IGNITER FOR HYDROGEN-OXYGEN ROCKET ENGINES

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SUMMARY

Resonance tube phenomena have been investigated and optimized with a stoichiometric mixture of gaseous hydrogen and gaseous oxygen. The data show the effect of geometric variables on the temperature attained at the resonance cavity bottom for the insulated and uninsulated cases. The maximum temperature attained ($>1100^{\circ}$ F (866° K)) was sufficient to ignite the gas mixture and thereby demonstrate the capability of a resonance tube as an igniter.

INTRODUCTION

Ignition in hydrogen-oxygen rocket engines has been commonly achieved by the use of high-energy spark igniters with controlled local mixture ratio around the spark plug, or by the use of a third chemical, such as fluorine, which is hypergolic with the fuel. Both systems have been demonstrated in full-size engines; however, both entail questions of complexity (reliability) and/or toxicity, as well as ground-handling complication. An ideal system would be passive, entailing no high-voltage electrical system, yet not burdened with the need for a separate fluid tankage system or with the hazards of toxicity characterizing most hypergolic liquids. A potential device offering these advantages was conceived based on the phenomenon exhibited by the resonance tube.

An impressive demonstration of the resonance-tube phenomenon may be had by the use of a simple block of wood and ordinary shop service (125 psia, or 862 kN/m^2 abs) air. When air from a simple (sonic) nozzle is directed into a dead-ended hole in the wood block, a distance between the nozzle and the block can easily be found wherein a resonance condition is established. At resonance, a sound of more than 170 decibels occurs, and in a few seconds smoke issues from the block which quickly becomes deeply charred around the bottom of the hole. To produce such charring (fig. 1), a temperature of over 300° F
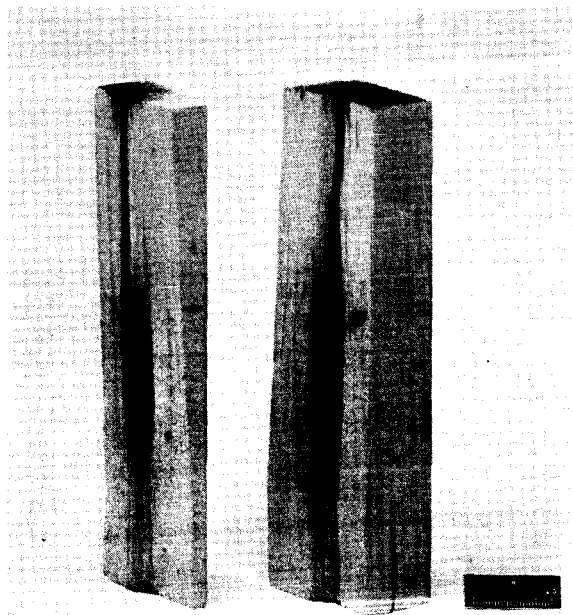
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Figure 1. - Wood char produced by resonance-tube phenomenon.
Working fluid, air at 125 psia (862 kN/m² abs) and 70° F (294° K).

(422° K) is required, which indicates clearly the creation of a temperature far in excess of the stagnation temperature ($\cong 70^O$ F (294° K)) of the service air. It was postulated that the temperature amplification might be optimized by geometry variations to yield values sufficient for self-ignition of a hydrogen-oxygen mixture ($\cong 1100^O$ F (866° K)).

The resonance tube is not new, having first been described by Hartmann in 1931 (ref. 1). Other studies are given in references 2 and 3. More recent schlieren studies and the analysis of reference 4 (1964) have provided further understanding by indicating that the heating is produced by the irreversibility of reflected shock waves which penetrate and reflect back toward the opening of the cavity repetitively at high frequency.

The results presented herein are based on data obtained in early 1964 with the objectives of simply optimizing the geometric variables involved to produce maximum temperature and determining whether ignition of hydrogen-oxygen mixtures could be achieved. Inasmuch as design-type data are not yet reported in the literature, these data are presented herein along with a discussion of efforts to obtain ignition using mixtures of hydrogen and oxygen. In the intervening time period, further references were obtained which show that very high temperatures have been achieved (1420° F (1044° K) ref. 5) and which mention the use for ignition (ref. 4).

The system conceived for spacecraft application would consist simply of the igniter unit and two valves communicating with the respective propellant tanks, as shown sche-
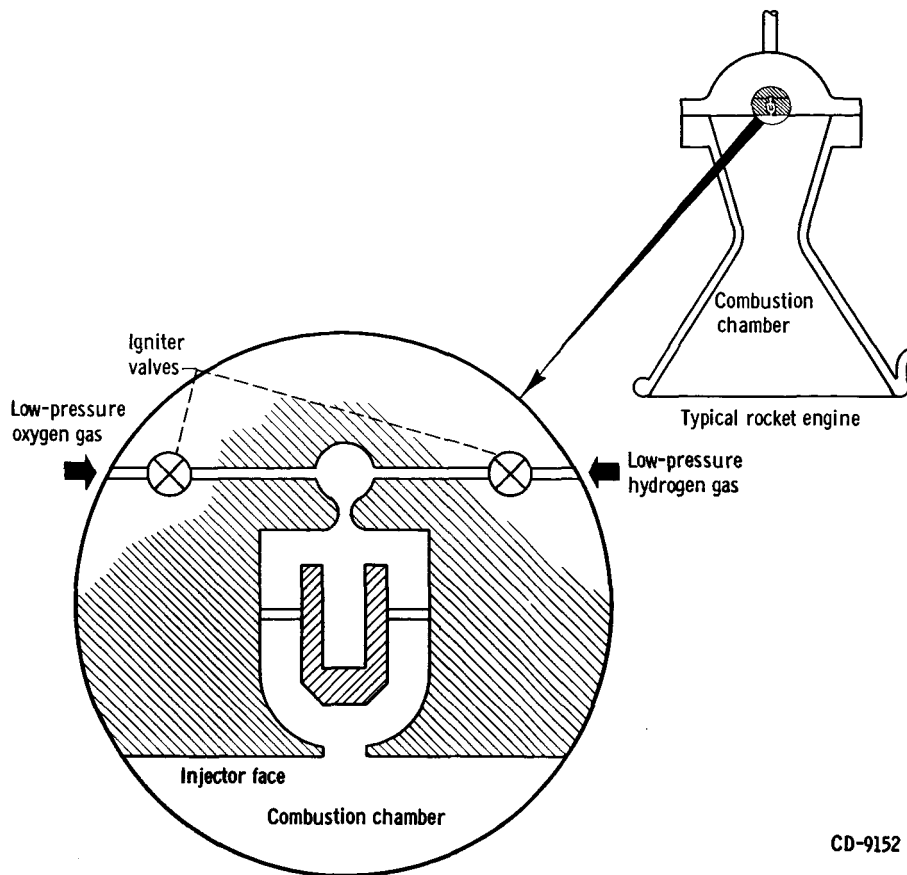
Figure 2. - Schematic drawing of resonance-tube-igniter concept in rocket-engine application.

matically in figure 2. The valves would be slaved to other activities in the starting sequence. Under space conditions, the normal tank pressures of 20 to 30 psia (137 to 207 kN/m^2 abs) provide almost infinite pressure ratio to drive the nozzle. The use of small-diameter supply lines virtually ensures that these cryogenic propellants will be in a gaseous state at the nozzle of the ignition unit.

APPARATUS

The test reported herein was performed in three phases, with the jet exhausting to normal atmospheric pressure in all cases. The experimental setup for the first phase (fig. 3) used air as the working fluid. This exploratory work was done with air to preclude any explosion hazard. The resonance tube was made of 3/4-inch-diameter (19-mm-diam) brass through which a 0.250-inch-diameter (6.35-mm-diam) hole was drilled to form the resonance cavity. An adjustable piston with an O-ring seal was fitted into the tube to allow variable cavity depth. Gas temperature at the bottom of the cavity
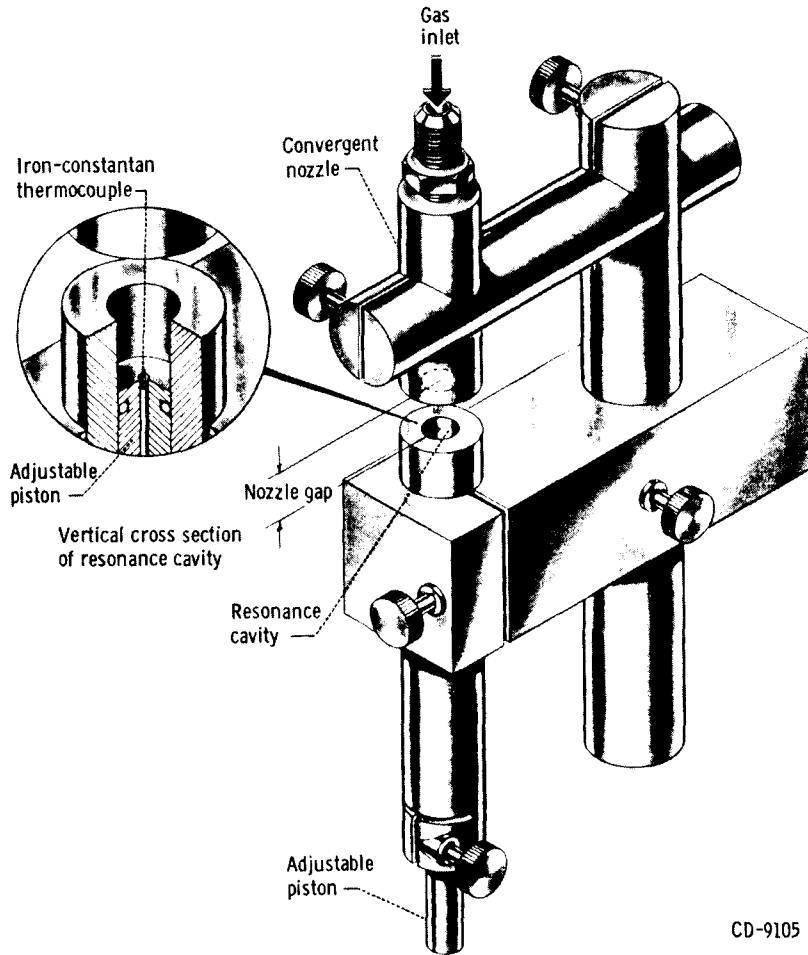
Figure 3. - Experimental setup for tests with brass resonance cavity.

was measured with an iron-constantan thermocouple that was routed through a hole in the piston (fig. 3). Besides variable cavity depth, provision was also made to allow changes in nozzle gap, jet angularity, and alinement of the nozzle with respect to the cavity.

The same apparatus was used in the second phase of testing, except that a stoichiometric mixture of gaseous hydrogen (H_2) and gaseous oxygen (O_2) was used as the working fluid. The gases were nominally at 70° F (294° K) and were supplied to the nozzle at a gage pressure of 65 psi (448 kN/m^2). It soon became apparent that heat loss to the massive brass resonance cavity was severely limiting the maximum temperature attainable. The third phase of testing was performed, to overcome this limitation, with the same apparatus but with the brass variable-depth cavity replaced with a well-insulated fixed-depth cavity of stainless steel (fig. 4). The most significant change from the earlier apparatus was the use of a very thin wall 0.010-inch-thick (0.254-mm-thick) stainless-steel resonator cavity surrounded by a highly polished vacuum chamber. This
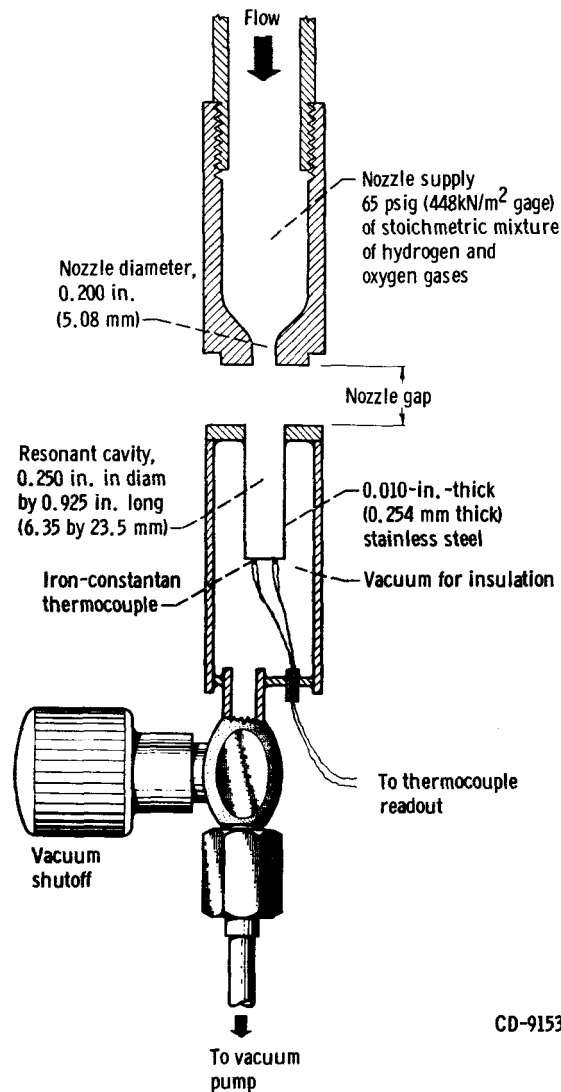
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Figure 4. - Insulated resonance cavity.

arrangement reduced drastically the heat loss by conduction, convection, and radiation from the cavity lower walls. A thermocouple was attached to the outside of the wall at the dead end of the cavity to measure metal temperature. The premixed stoichiometric room-temperature hydrogen-oxygen gas was supplied in the same manner as in the second phase. Provisions were made to allow variation in nozzle gap. This vacuum-jacketed resonance cavity failed structurally at a cavity-bottom temperature of approximately 760° F (677° K). A second vacuum-jacketed resonance cavity was built identical to the first, except that the joints were welded with an electron beam instead of being silver soldered. This cavity did not fail structurally but was consumed in the fire from the successful ignition.
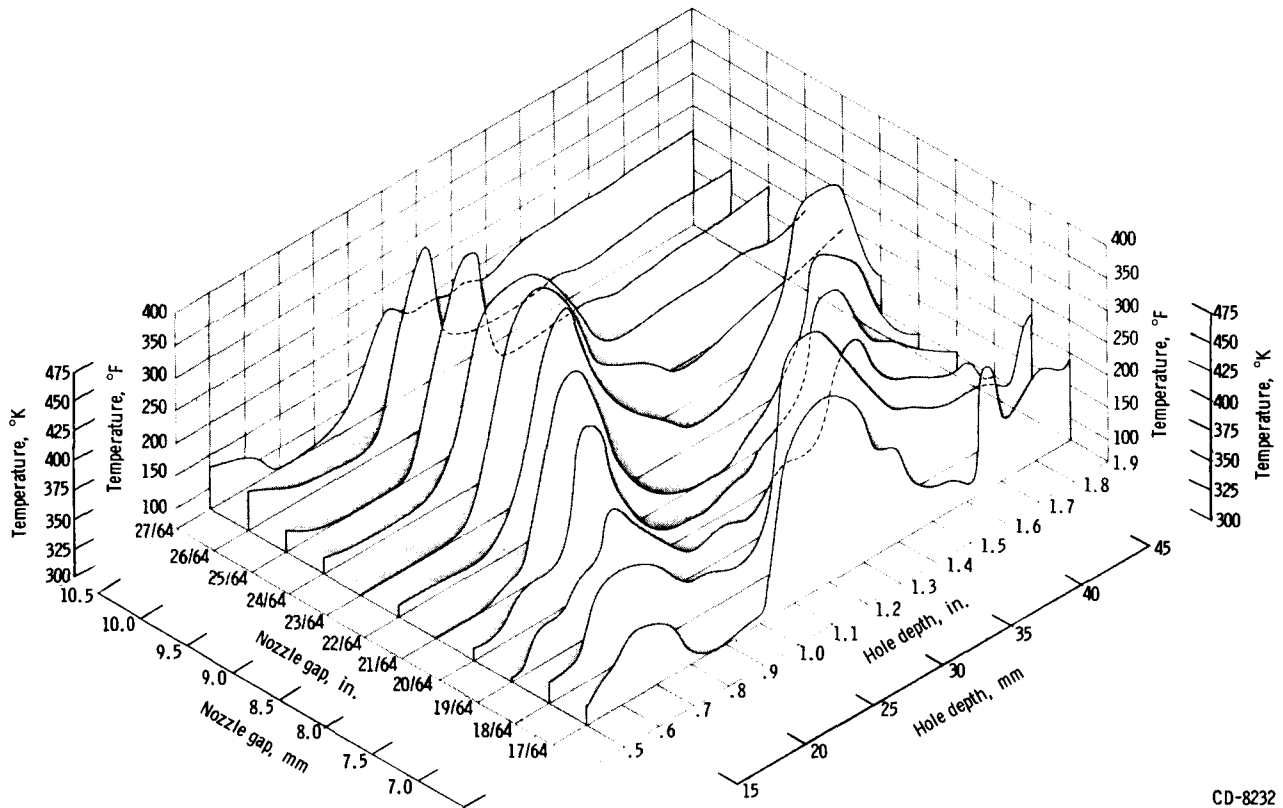
Figure 5. - Effect of nozzle gap and hole depth on gas temperature at bottom of resonator cavity. Working fluid, stoichiometric mixture of hydrogen and oxygen gases at 70° F (294° K).

PROCEDURE

In the first phase of testing, the brass resonance cavity was run with shop service air to optimize nozzle angularity and alinement in a qualitative manner. The nozzle alined directly over the cavity produced the highest temperature at the cavity bottom.

The gaseous hydrogen and gaseous oxygen mixture was then used in the second phase of testing, along with a remote actuator to position the piston. The purpose was to optimize nozzle gap and hole depth. The temperature response with the brass cavity seemed to have a time constant of 10 to 30 seconds, depending on hole depth and nozzle gap. Because of this time constant, the data were recorded after exactly 20 seconds of flow duration for all runs on the brass cavity. At this point, it became apparent that much of the energy at the cavity bottom was being dissipated into heating the massive brass cavity walls. Therefore, a hole-depth value of 0.925 inch (23.5 mm) (fig. 5) was selected as nearly optimum, and an insulated cavity was built, as shown in figure 4, for the third

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phase of testing. A series of runs was made at varying nozzle gaps. When the silver solder joints on the cavity failed, a second stainless-steel cavity was then built, using welded construction, and used to complete the third phase of testing.

RESULTS AND DISCUSSION

A cursory investigation of the effects of nozzle angle and nozzle alinement indicated the most promising configuration to be one with the axis of the sonic nozzle coincident with the axis of the resonance tube.

The variations made in hole depth at several nozzle-gap settings resulted in temperature curves of irregular shape containing several peaks probably associated with different resonance modes within the cavity. When these curves are superimposed, clear trends are not easily discerned. Accordingly, a three-dimensional plot containing the data obtained with the gaseous hydrogen - gaseous oxygen mixture is presented in figure 5. Two major ridges were produced with maximum temperatures of almost 400° F (477° K) for one and a little over 300° F (422° K) for the other. It must be emphasized that these values are gas temperatures measured at 20 seconds from the start of each run, and are strongly influenced by large conduction losses caused by the massive brass construction of the resonator tube. The gas temperature under adiabatic conditions should be much higher.

Examination of the larger ridge shows a relatively constant maximum temperature for nozzle gaps from 22/64 to 26/64 of an inch (8.7 to 10.3 mm). Further, this maximum occurs at an almost constant value of hole depth (near 1.0 in. (25.4 mm)). The shape of the contour map generated by these profiles is such that neither gap nor depth is likely to be affected seriously by machining tolerances or thermal expansion. The secondary ridge, at greater hole depth, is of less practical interest, being of somewhat lower amplitude and also skewed on the gap-depth plane.

Results obtained with the insulated tube and a stoichiometric mixture of hydrogen and oxygen are presented in figure 6. For comparison, the 0.925-inch (23.5-mm) hole-depth data from the "brass-hole" configuration are shown also. The two vacuum-jacketed configurations agreed well. Ignition was achieved with the second vacuum-jacketed configuration at a nozzle gap of 19/64 inch (7.52 mm). The end of the resonance tube was burned out after ignition. Data were obtained at high and low nozzle gaps by appropriate sequencing of the tests. It should be noted that the vacuum-jacketed configurations exhibited characteristics quite different from the brass-hole configuration. The highest temperature peak was quite sharp, requiring attention to dimensional control not apparent in the results with the brass tube. The nozzle gaps at which the maximum temperatures occurred did not coincide. The temperature of the hole bottom was recorded after the insulated tube reached thermal equilibrium, about 3 seconds after start of flow.
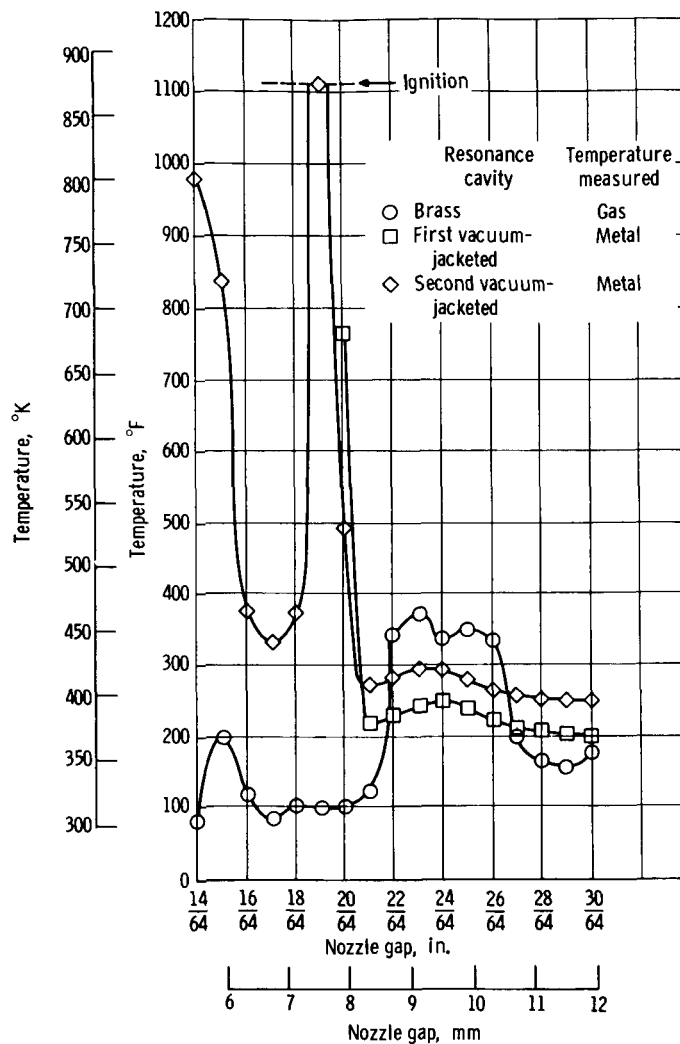
Figure 6. - Effect of nozzle gap on temperature using hydrogen-oxygen mixture. Hole depth, 0.925 inch (23.5 mm); nozzle gas supply, 65 psig (448 kN/m² gage) ratio of hydrogen to oxygen, 1 to 8.

The "tuning" (optimizing nozzle gap and hole depth) of a resonance tube is dependent on the acoustic velocity in the resonance cavity and, hence, is affected by the temperature of the gas in the cavity. A resonance cavity that is tuned while it has a substantial heat leak, will not be optimumly tuned when operating without this heat leak (insulated), and, therefore, resonance-tube tuning should be performed with the final insulation in place. Thus, the feasibility of the concept of resonance-tube ignition of a mixture of hydrogen and oxygen was demonstrated.

CONCLUDING REMARKS

It was demonstrated that ignition of a hydrogen-oxygen mixture can be achieved by

using the resonance-tube principle, with a driving pressure ratio of only $4\frac{1}{2}$. Further, it was shown that the temperature generated by resonance tubes is sensitive to heat leaks, and can be greatly enhanced by thermally insulating the resonance cavity.

This exploratory test of resonance ignition shows significant promise for application to rocket engines. Questions still to be answered are the effect of altitude and the effect of a different (colder) gas-supply temperature on the resonance phenomenon.

In an actual rocket-engine application, three avenues of improvement are obvious:

1. Careful tuning of the resonance tube at the operating temperatures (i.e., with a fully insulated configuration)

2. Fabricating the resonance cavity and associated hardware with a high-temperature-resistant material to avoid melting the igniter after ignition, and, hence, to provide a multiple start capability

3. Improvement of the resonance-cavity insulation and/or a decrease in the mass and specific heat of the cavity lining, perhaps using a pyrolytic graphite or ceramic lining

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, June 20, 1967,
            128-31-06-05-22.

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