# CATALYTIC IGNITION OF HYDROGEN/OXYGEN

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## ABSTRACT

An experimental program was conducted to evaluate the catalytic ignition of gaseous hydrogen and oxygen. Shell 405 granular catalyst and a unique monolithic sponge catalyst were tested. Mixture ratio, mass flow rate, propellant inlet temperature, and back pressure were varied parametrically in testing to determine the operational limits of a catalytic igniter. The test results showed that the gaseous hydrogen/oxygen propellant combination can be ignited catalytically using Shell 405 catalyst over a wide range of mixture ratios, mass flow rates, and propellant injection temperatures. These operating conditions must be optimized to ensure reliable ignition for an extended period of time. The results of the experimental program and the established operational limits for a catalytic igniter using both the granular and monolithic catalysts are presented. The capabilities of a facility constructed to conduct the igniter testing and the advantages of a catalytic igniter over other ignition systems for gaseous hydrogen and oxygen are also discussed.

## INTRODUCTION

The hydrogen/oxygen propellant combination is commonly used for space propulsion systems because of its high specific impulse, fast reaction rate, lack of toxicity and excellent regenerative cooling capability. However, this bipropellant combination is not hypergolic. Ignition of liquid propellant rocket engines fueled by hydrogen and oxygen must be accomplished by an igniter device which releases heat and initiates reaction of the main propellants. A number of ignition techniques have been investigated for liquid propellant rocket engines and combustion devices with varying degrees of success. These ignition techniques have included pyrotechnic, hypergolic, electric, hot-gas tapoff, ionic, passive thermal, dynamic thermal, and catalytic ignition (Ref. 1). Catalytic ignition is a promising concept, with several potential advantages compared with the other ignition techniques. This report presents the results of an experimental program conducted to investigate the operational characteristics of a catalytic igniter for the gaseous hydrogen and oxygen propellant combination.

Catalytic ignition is a very simple concept and has flown in space for periods over eight years, performing thousands of qualified cycles with monopropellant hydrazine. Catalytic igniters have a minimum component count which makes them simple, safe, lightweight and inexpensive. The

simplicity of the concept is demonstrated by the fact that it requires no external energy source. In addition, catalytic igniters are passive in operation and present no radio frequency interference problems. These attributes make catalytic ignition competitive with conventional igniters such as the spark torch and hypergolic system for use in liquid bipropellant rocket engines. A review and comparative evaluation of techniques applicable to ignition of the hydrogen/oxygen propellant combination are contained in Reference 2.

The feasibility of using catalysts to promote the reaction of hydrogen and oxygen was demonstrated in several research programs in the 1960's and early 1970's. Catalyst screening investigations by Rocketdyne (Ref. 3) and later by TRW (Ref. 4) identified several granular catalysts such as Shell 405 and Englehard MSFA that are reactive with hydrogen and oxygen. Shell 405 uses an iridium catalyst agent washcoated on a porous alumina substrate. Shell 405, which is very effective for the decomposition of monopropellant hydrazine (Ref. 5), became the preferred catalyst for the ignition of hydrogen and oxygen. TRW created an extensive experimental data base for catalytic ignition of hydrogen/oxygen propellants using Shell 405 catalyst. Shell 405 was selected for testing in the present program to compare experimental results with past efforts and to augment the existing experimental data base.

Granular catalysts have shortcomings for catalytic ignition of hydrogen/ oxygen propellants. These include the inherently high pressure drop of a tightly packed granular catalyst bed and the attrition due to thermal and mechanical loads on the catalyst particles. Monolithic catalysts are unitary structures which offer the potential advantages of extremely low pressure drop, attrition resistance for longer life, and design flexibility. A unique monolithic sponge catalyst was tested in the present program to explore these potential benefits. The monolithic catalyst consisted of a carbon sponge substrate coated with rhenium to give it structural integrity and iridium as the catalyst agent.

Despite substantial evolution of technology for catalytic ignition of hydrogen/oxygen propellants in past programs, the reliability and longevity required for use of catalytic igniters in space propulsion systems has not been demonstrated to date. An experimental program was, therefore, recently conducted at the NASA Lewis Research Center with an objective to develop the technology for a reliable, long-life catalytic igniter for gaseous hydrogen/oxygen propulsion systems. The focus of the research was on critical igniter components such as propellant injectors and catalyst beds. Catalytic igniter hardware was designed, drawing on generalized design guidelines and scaling criteria for catalytic igniters developed through analysis of experimental data from TRW's program (Ref. 4). A facility was constructed to test the catalytic igniter under space-simulated conditions. Finally, testing was conducted to establish the operational limits of the catalytic igniter over a wide range of operating conditions. This report describes the results of the experimental program. The catalytic igniter test hardware, test facility, and test procedures are first described. The igniter operational characteristics for both the granular Shell 405 catalyst and the monolithic sponge catalyst are then discussed. Finally, the results of tests to characterize the performance and pulse mode life of the catalytic igniter using the Shell 405 granular catalyst are presented.

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APPARATUS

Test Hardware

A schematic of the catalytic igniter assembly is shown in Figure 1. The hardware consists of an upstream injector, spool piece, downstream injector, and nozzle. Both of the injector units are made of type 304 stainless steel, while the spool piece and nozzle are made of hastelloy X. Hydrogen gas and the primary oxygen gas are introduced into the catalyst bed, which is contained in the spool piece, by means of a cross-drilled injection scheme in the upstream injector. The hydrogen gas flows axially from the fuel inlet into the catalyst bed through twelve 0.081 cm (0.032 in.) diameter injector holes. The oxygen gas flows from the oxidizer inlet in through the annulus of the injector into 0.159 cm (0.062 in.) diameter holes that intersect with the nine 0.053 cm (0.021 in.) oxygen orifices, and then flows axially into the catalyst bed. Figure 2 shows a schematic of both the upstream and downstream injectors. The oxygen inlet is isolated from the catalyst bed and from the outside using rubber O-ring seals. The upstream injector is connected to the spool piece with bolts that pass through compression springs. With these springs in place, the upper injection faceplate keeps the catalyst bed under constant compression so that the catalyst remains tightly packed, even if it deteriorates with use. The spool piece has a chamber diameter of 1.270 cm (0.500 in.) and a nominal length of 5.080 cm (2.000 in.).

The hydrogen and primary oxygen are injected into a diffusion bed to provide mixing of the gases, flow through the catalyst bed where they ignite, and then flow through the downstream injector into the nozzle. The nozzle has a throat diameter of 0.508 cm (0.200 in.) and an exit diameter of 1.270 cm (0.500 in.). This geometry yields a value of 6.25 for both the contraction and expansion ratios. The diffusion bed is 1.270 cm (0.500 in.) long and consists of an inert material separated from the catalyst bed by a stainless steel screen. The catalyst bed is 3.810 cm (1.500 in.) long. The downstream injector also uses a cross-drilled injection scheme, with the combustion gases from the catalyst bed passing axially through twelve 0.102 cm (0.040 in.) orifices and into the downstream chamber and the secondary oxygen entering from the annulus through nine 0.064 cm (0.25 in.) diameter orifices. The hardware can thus be operated with a low mixture ratio in the catalyst bed and a higher mixture ratio in the downstream chamber. Figure 3 shows an exploded view of the catalytic igniter hardware.

Two different catalyst materials were tested, along with a number of different diffusion bed materials. The majority of the testing was done with Shell 405 catalyst, which consisted of the active iridium catalyst deposited on an alumina substrate. A monolithic catalyst was also tested, which consisted of a carbon sponge substrate with rhenium deposited on the carbon for strength using chemical vapor deposition (CVD). The active metal, iridium, was then deposited on the sponge using CVD. The diffusion bed materials tested were silica sand, fused zirconia/silica, zirconia/magnesium, 0.238 cm (0.094 in.) diameter high carbon chrome steel balls, and 0.238 cm (0.094 in.) diameter 440 stainless steel balls. Figure 4 shows the Shell 405 catalyst and two of the diffusion bed materials tested. Figure 5 shows the monolithic sponge catalyst.

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Temperature measurements were taken inside the catalyst bed and on the backwall at the locations shown in Figure 1. Type K (chromel constantan) thermocouples were used for the temperature measurements. The bed thermocouples were labeled T1, T2, T3, and T4, with T1 located nearest the upstream injector in the diffusion bed, and T4 farthest downstream. These thermocouples were located at the inner radius of the reactor. Pressure measurements were taken inside the catalyst bed (IPC) and in the downstream injector (PC) using strain gauge type pressure transducers. The pressure transducers for these measurements were located just downstream of the primary and secondary injectors, respectively.

## Test Facility

Testing of the catalytic igniters was conducted in Cell 21 of the Combustion Research Laboratories (CRL21) at the NASA Lewis Research Center. CRL21 was designed and built for the testing of ignition systems and small gaseous hydrogen/oxygen rockets (up to fifty lbf thrust) and is capable of testing at sea level or space simulated altitude, with ambient or chilled propellants. Figure 6 shows a photograph of the test stand in CRL21.

A schematic of the propellant feed system for CRL21 is shown in Figure 7. The feed system consists of two gaseous oxygen feed lines and one gaseous hydrogen feed line. A second hydrogen line exists, but was not used for this program. Each oxygen line can deliver a maximum mass flow rate of 0.050 kg/sec (0.110 lb/sec), and the hydrogen line can deliver a maximum flow rate of 0.012 kg/sec (0.026 lb/sec). Sonic orifice meters are used to control the mass flow rates in all propellant lines. These orifice meters deliver a constant specified mass flow rate based on the upstream temperature and pressure of the propellant. The upstream pressure is regulated while the upstream temperature is ambient. Different diameter orifices can be installed in the feed lines to deliver the mass flow ranges necessary for testing. A gaseous nitrogen system purges all the propellant lines and the vacuum chamber. Propellants and gaseous nitrogen are delivered from remote 16.55 MN/m2 (2400 psig) trailers.

The altitude system consists of a 0.62 m (2.0 ft.) diameter, 1.22 m (4.0 ft.) long vacuum chamber driven by a two stage ejector system mounted on the roof of the test cell. The vacuum chamber is mounted on tracks for easy removal for hardware access or sea level testing. The ejectors consume 3.63 kg/sec (8.0 lb/sec) of combustion air to maintain a near perfect vacuum in the chamber.

The propellant temperature is controlled by passing the gaseous propellant through a liquid nitrogen heat exchanger. The propellant lines are coiled inside the heat exchanger to provide more surface area for heat transfer. A partition separates the fuel and oxidizer coils in the heat exchanger as a safety precaution. Liquid nitrogen is fed from a remotely located dewar into the compartments of the heat exchanger. The level of liquid nitrogen in the  heat exchanger is automatically controlled by level sensing devices that enable more liquid nitrogen to be added automatically when the level is too low.

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The control system in the cell consists of both manual and automatic control. A programmable control system is used to open and close valves during the run based on manually entered timing values. Automatic and manual aborts are available if a problem should occur during testing.

The test cell has both high speed and low speed data acquisition systems. The high speed data acquisition system records 100 readings per second, averages every ten readings, and outputs a data point every tenth of a second. A high speed data program on the mainframe computer performs calculations with the raw data. A minicomputer and a strip chart recorder are used to monitor the facility and obtain local, immediate data acquisition during testing.

## Test Procedure

Pulse mode testing was primarily conducted on the catalytic igniter because the igniter hardware was uncooled. Each hot fire pulse was two or three seconds in duration, preceded by a hydrogen lead to ensure smooth start-up and followed by a hydrogen lag to ensure smooth shut-down. The catalyst bed was then purged with nitrogen gas to remove all of the residual propellants. New catalyst beds were conditioned by flowing hydrogen through the bed for approximately one minute prior to the test. This hydrogen purge activated the catalyst bed by removing residual oxygen adsorbed on the surface.

Catalytic igniter tests were conducted over a wide range of operating conditions. The mixture ratio (ratio of oxidizer to fuel) in the catalyst bed was varied frm 0.3 to 1.2, with the nominal operating value being 1.0. The total mass flow rate through the bed was varied from 0.0009 kg/sec to 0.0027 kg/sec (0.002 lb/sec to 0.006 lb/sec), with 0.0018 kg/sec (0.004 lb/sec) being the nominal operating value. The catalyst bed was first characterized without downstream oxygen injection to avoid damage to the nozzle due to the high temperatures generated when downstream oxygen was used. When downstream oxygen injection was employed, the total mixture ratio was varied from 2.0 to 12.0 and the total mass flow rate was varied from 0.0027 kg/sec to 0.0215 kg/sec (0.006 lb/sec to 0.0473 lb/sec). The initial temperature of the catalyst bed was varied from ambient temperatures to -164.3 deg. C (-263.7 deg. F). Testing was done at ambient back pressure (sea-level) as well as under a vacuum.

## RESULTS AND DISCUSSION

### Igniter Operational Characteristics

Experimental testing was conducted to characterize the operational characteristics of the catalytic igniter with 14-18 mesh Shell 405 granular catalyst. Several operating parameters were varied in testing. The effects of each of these parameters on overall igniter performance are discussed below.

The igniter was initially characterized without downstream injection in order to protect the nozzle from the high temperatures resulting when downstream oxygen injection was employed. For these cases, the mixture ratio in the catalyst bed was:

$$(O/F)_b = W_{oa}/W_{fa}$$

where

$(O/F)_b$     Catalyst bed mixture ratio

$W_{oa}$     Primary oxygen mass flow rate, kg/sec

$W_{fa}$     Hydrogen mass flow rate, kg/sec

Several tests were initially conducted in the program with only Shell 405 catalyst in the reactor. The poor mixing efficiency of the primary injector resulted in damaging hot spots in the catalyst bed. The hot spots were due to axial injection of a non-uniform mixture of hydrogen and oxygen into the catalyst bed. It was determined, therefore, that a diffusion bed would be required upstream of the catalyst bed to enhance mixing of the propellants prior to injection into the catalyst bed.

Screening tests were conducted to evaluate various diffusion bed materials for use in the reactor. The materials tested were silica sand, fused zirconia/silica, fused zirconia/magnesium, high carbon chrome steel balls, and 440 stainless steel balls. Both types of steel balls were able to withstand the high pressure, high velocity gases and thermal shock inside the reactor, while the other materials physically deteriorated very quickly to varying degrees with use. This deterioration increased the pressure drop across the reactor with time and also adversely affected the flow characteristics and mixing efficiency of the diffusion bed. Flame flashback into the diffusion bed frequently occurred. The steel balls did not deteriorate with time as did the other materials, but they exhibited localized melting and fusion if a flashback occurred. This was more of a problem with the carbon steel balls than with the stainless steel ones. Consequently, 0.238 cm (0.094 in.) diameter 440 stainless steel balls were selected for use as a diffusion bed in the reactor.

Tests were next conducted to select a nominal mass flow rate through the catalyst bed. To do this, the pressure drop through the catalyst bed was measured as a function of reactor total mass flow rate for both cold and hot fire testing. The results of these tests are shown in Figure 8. A nominal mass flow rate of 0.0018 kg/sec (0.004 lb/sec) was chosen to maintain a reasonable pressure drop through the reactor.

Testing was then undertaken to determine the effect of mass flow rate on reactor temperature distribution and to characterize the flashback phenomenon. Flashback is defined as the sudden propagation of the flame in the upstream direction from the catalyst bed into the diffusion bed or to the injector. This phenomenon can be severely damaging to the diffusion bed and injector and adversely affects the performance of the igniter. Figure 9 shows the variation of the temperature distribution with mass flow rate at a mixture ratio of 1.0. Mass flow rate has little effect on the temperature distribution for mass flows between 0.0018 and 0.0027 kg/sec (0.004 and 0.006 lb/sec), the range at which most of the testing was performed. Figure 9 also shows no flashback on any of the firings. Early testing indicated that flashback may occur for mass flow rates lower than 0.0016 kg/sec (0.0035 lb/sec), but Figure 9 shows that after an initial flashback, the mass flow could be as low as 0.0009 kg/sec

(0.002 lb/sec) without flashback occurring. This can be attributed to the fact that the initial flashback causes some melting and fusing of the diffusion bed, which alters the flow characteristics of the reactor such that additional flashback would not occur. A diffusion bed material that could withstand high temperature flashbacks is needed to further characterize the flashback phenomenon.

Another component that is critical to igniter operation is the upstream injector. The existing hardware employed discrete axial injection of the fuel and oxidizer which led to regions of non-uniform mixture ratio in the reactor, and a diffusion bed was necessary to enhance mixing of the propellants. A more efficient injector (such as a platelet injector) that supplies a uniform propellant mixture to the catalyst bed would eliminate the need for a diffusion bed, making flashback in the reactor more predictable as a function of the flow conditions and reactor geometry. The occurrence of flashback in hydrogen/oxygen catalytic igniters as a function of mixture ratio and interstitial velocity in the reactor has been well characterized in past experimental programs (Ref. 4).

With a nominal mass flow rate of 0.0018 kg/sec (0.004 lb/sec) selected, testing was next conducted to determine a nominal mixture ratio for the reactor. This optimum mixture ratio should be high enough to ensure reliable ignition in the catalyst bed, while remaining low to keep the catalyst bed cool for longer life. Figure 10 shows the effect of mixture ratio on the temperature distribution at the end of a three second firing. Based on this data, a nominal mixture ratio of 1.0 was chosen. T1, which was located in the diffusion bed, remained at ambient temperature, indicating that flashback did not occur. T2 increased only slightly due to axial conduction, while T3 and T4 increased linearly with mixture ratio. The temperature distribution for this series of tests indicated that the flame front was located near T4, since T4 was the hottest temperature for all cases.

Throughout the course of testing, it was observed that the location of the flame front changed due to a variety of factors. The flow characteristics of the diffusion and catalyst beds may have changed over time due to channeling of the flow, localized hot spots, or flashback, and the activity of the catalyst bed may have degraded with time. Figure 11 shows a transient temperature distribution for a hot fire test at nominal flow conditions. The large magnitude of T2 for this firing, which was the first firing of a fresh catalyst bed, indicates that the flame front was located near T2 and, therefore, the catalyst was much more active than the firing at a mixture ratio of 1.0 in Figure 10. This emphasizes the fact that the temperature distribution depends on the nature and amount of previous testing.

One factor that had a major impact on the temperature distribution and the location of the flame front was the propellant inlet temperature. Figure 12 shows the results of testing conducted to determine the effect of inlet temperature on the transient temperature distribution. For this firing, chilled propellants were used, and the catalyst bed was pre-chilled to -97.7 deg. C (-143.9 deg. F). The flame front was located at T4, which was the only temperature that reached a value higher than -17.78 deg. C (0 deg. F). Testing was next conducted to determine the overall effect of

initial bed temperature on ignition of hydrogen and oxygen using Shell 405 catalyst. An ignition boundary for the Shell 405 catalyst was defined by varying the initial bed temperature and mixture ratio in the reactor. The results are shown in Figure 13. It was observed that as temperature decreases, mixture ratio must be increased to achieve ignition of the hydrogen and oxygen propellants. This phenomena can be explained by the chemical kinetics of the reaction between hydrogen and oxygen. The following model has been proposed for the reaction at the surface of the catalyst particle (Ref. 6):

$$-d(O2,s)/dt = A(O2,s)^a \exp(-E/RT_s)$$

where

| | |
|---|---|
| $-d(O2,s)/dt$ | Chemical reaction rate, kg O2 reacted/$m^3$–sec |
| $(O2,s)$ | Concentration of oxygen on the catalyst surface, kg/$m^3$ |
| $T_s$ | Surface temperature of catalyst, K |
| $E$ | Activation energy, cal/g–mol |
| $R$ | Universal gas constant, 1.9872 cal/g–mol-K |
| $a$ | Empirical exponent |
| $A$ | Arrhenius factor, kg/$m^3$–sec |

This model suggests that the rate of reaction of hydrogen and oxygen at the surface of the catalyst will increase with oxygen concentration (mixture ratio) or catalyst temperature. This agrees with the experimental results.

To characterize the overall operation of the igniter, testing was conducted using downstream oxygen injection. For these cases, the total mixture ratio for the igniter was:

$$(O/F)_t = (W_{oa} + W_{ob})/W_{fa}$$

where

| | |
|---|---|
| $(O/F)_t$ | Total mixture ratio |
| $W_{oa}$ | Primary oxygen mass flow rate, kg/sec |
| $W_{ob}$ | Secondary oxygen mass flow rate, kg/sec |
| $W_{fa}$ | Hydrogen mass flow rate, kg/sec |

For optimum igniter operation, the total mixture ratio should be near stoichiometric in order to release the maximum amount of energy for main propellant ignition, while the reactor mixture ratio remains low to increase the life of the igniter. To determine the optimum operating conditions for the igniter, the catalyst bed and total mixture ratios were varied, while holding the mass flow rate through the reactor constant at 0.0027 kg/sec (0.006 lb/sec). The results of this testing, plotted in Figure 14, show that a boundary exists between ignition and no ignition in the downstream chamber. Fuel rich mixtures in the downstream chamber were difficult to ignite. Ignition in the downstream chamber could not be achieved at total mixture ratios less than 5.0. Oxidizer rich mixtures in the downstream chamber were easily ignited, even at catalyst bed mixture ratios as low as 0.4.

The igniter was tested without downstream injection at sea level (ambient

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pressure) and at a near perfect vacuum. Nozzle back pressure was found to have no effect on the ignition characteristics in the reactor because the flow through the downstream injector was choked for the range of reactor flows tested. Back pressure would have an effect on ignition characteristics when downstream injection is employed, but testing was not performed to characterize this effect.

## Monolithic Sponge Catalyst Tests

Igniter tests were conducted in which a monolithic sponge catalyst replaced the Shell 405 granular catalyst. The monolithic catalyst consisted of a carbon sponge substrate coated with rhenium for strength and iridium as the active catalyst agent. The unique feature of this monolithic catalyst was that the geometric surface area of the catalyst was used for dispersion of the catalyst agent rather than using a high surface area washcoat. Washcoats are typically used with noble metal catalysts to increase the surface area for dispersion of the catalyst agent. However, washcoats can be life-limiting to the catalyst since they typically have a different coefficient of thermal expansion than that of the substrate.

The monolithic sponge catalyst was not successful for ignition of the gaseous hydrogen and oxygen propellant combination. At nominal igniter operating conditions, the monolithic catalyst bed was only able to elevate the temperature in the reactor slightly. This inability to ignite the propellants was due to the low available active surface area of the monolith. The porous Shell 405 granular catalyst with a high surface area washcoat possessed a much larger active surface area per unit volume than the monolithic sponge catalyst, which had only its geometric surface area available for catalyst dispersion.

The performance of the monolithic sponge catalyst at nominal igniter operating conditions is shown in Figures 15 and 16. Figure 15 shows the effect of mass flow rate on exit temperature for a mixture ratio of 1.0. It was observed that reducing the mass flow rate and, hence, the velocity of gases through the monolithic sponge catalyst bed increased the exit temperature. The temperatures in the reactor rise as mass flow rate is decreased because the energy generated by chemical catalysis is not transported from the reactor as quickly by convective flow. Figure 16 shows the effect of mixture ratio on the exit temperature for a mass flow rate of 0.0018 kg/sec (0.004 lb/sec). As expected, the exit temperature increased with increasing mixture ratio. Ignition could not be achieved for mixture ratios below 3.0 in the monolithic catalyst bed. At a mixture ratio of 3.0, ignition was achieved which destroyed the monolith due to the extreme temperature. The poor performance of the monolithic sponge catalyst in these tests can be attributed to two factors. First, the low active surface area of the catalyst prevented ignition at a nominal reactor mixture ratio of 1.0, and second, the catalyst lacked structural integrity due to the use of the carbon substrate. Upon ignition, the monolithic sponge catalyst was immediately destroyed.

## Igniter Performance

In order to obtain a measure of the overall performance of the catalytic
igniter using Shell 405 catalyst, the C* efficiency was calculated for the
runs with downstream oxygen injection. The following relation was used to
estimate C* efficiency:

$$C^*_{eff} = (P_c A_t g / W_{tot}) / C^*_{th} \times 100$$

where

| | |
|---|---|
| $C^*_{eff}$ | Experimental C* efficiency of the igniter |
| $P_c$ | Pressure in the downstream chamber, $MN/m^2$ |
| $A_t$ | Cross-sectional throat area, $m^2$ |
| $W_{tot}$ | Total mass flow rate, $W_{oa} + W_{fa} + W_{ob}$, kg/sec |
| $g$ | Gravitational constant, 9.81 $m/sec^2$ |
| $C^*_{th}$ | Theoretical characteristic velocity for igniter, m/sec |

Figure 17 shows the variation in C* efficiency with the total mixture
ratio of the catalytic igniter. The C* efficiency reaches a peak value of
79.2% at the stoichiometric mixture ratio for hydrogen/oxygen, 8.0. The
low value for C* efficiency can be attributed to losses due to heat
transfer by conduction in the long spool piece, losses due to the pressure
drop in the catalyst bed, and most importantly, losses due to the
inefficient mixing of the propellants in both injectors. Redesigning the
downstream injector or enlarging the downstream chamber to eliminate
streaking and obtain better propellant mixing could result in a much
higher value of C* efficiency.

## Pulse Mode Life Tests

Testing was also conducted, without downstream injection, to determine the
life of the Shell 405 catalyst bed. The testing consisted of two second
pulses followed by a fifteen second cooldown period. After the first 1100
pulses, an attempt was made to shorten the cooldown period between runs by
convectively cooling the exterior surface of the reactor with water, as
opposed to the normal cooldown by forced convection of air over the
exterior surface of the igniter. The decreased time between runs was not
sufficient to allow the catalyst bed to be purged of all the reacted gases
between runs, and flashback occurred. This flashback altered the flow
characteristics of the diffusion bed, which in turn altered the ignition
characteristics of the igniter. Because of the adverse effects it caused,
the water cooling was stopped after ten pulses. Testing then resumed as
before, with the catalyst bed sustaining ignition for a total of 1980
pulses.

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Figures 18 and 19 show the characteristics of the igniter during the pulse mode life tests. Only data from the first 1100 pulses are reported here because of the change in performance after water cooling was attempted. Figure 18 shows the variation in pressure drop across the catalyst bed and downstream injector as the number of pulses increase. The pressure drop increase throughout the testing can be attributed to deterioration of the catalyst and diffusion beds and to small catalyst particles clogging the downstream injector orifices. Figure 19 shows the variation in the temperature distribution in the bed as the number of pulses increase. After approximately 500 pulses, the temperature distribution reached a steady operating limit, after which T3 and T4 decreased only slightly as the number of pulses increased.

## CONCLUSIONS

An experimental program was conducted at the NASA Lewis Research Center to develop the technology for catalytic ignition of gaseous hydrogen and oxygen propellants. The feasibility of catalytic ignition for hydrogen/oxygen propellants was demonstrated in the program. The following are the major findings and conclusions from the program.

1.  The shortcomings of the axial flow injectors used in the catalytic igniter emphasize the criticality of this component to the operation of the igniter. A high efficiency primary injector which can deliver a uniform mixture of hydrogen and oxygen to the catalyst bed is essential to extended, reliable operation of a catalytic igniter.

2.  Reliable and repeatable operation of a catalytic igniter using Shell 405 granular catalyst is possible only within prescribed operating limits. The operating limits cover a wide range of mixture ratios, mass flow rates and propellant injection temperatures. These operating limits were experimentally established and are presented in this report.

3.  The following were demonstrated for the catalytic igniter with Shell 405 catalyst.
    a.      A cyclic life of nearly 2000 two-second pulses at nominal operating conditions.
    b.      $C^*$ efficiency near 80%.
    c.      Ignition with initial catalyst bed temperatures as low as -112.8 deg C (-171.1 deg F).

4.  A monolithic sponge catalyst composed of a carbon substrate with rhenium and iridium coatings performed poorly in the catalytic igniter due to low active surface area and lack of structural integrity.

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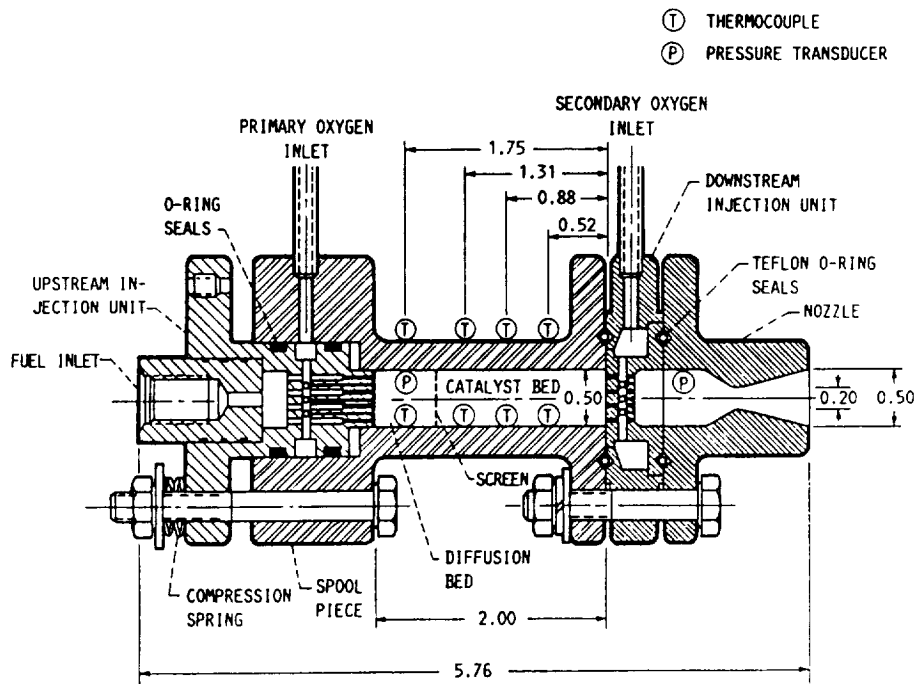
FIGURE 1. - SCHEMATIC OF CATALYTIC IGNITER HARDWARE. [ALL DIMENSIONS IN INCHES.]
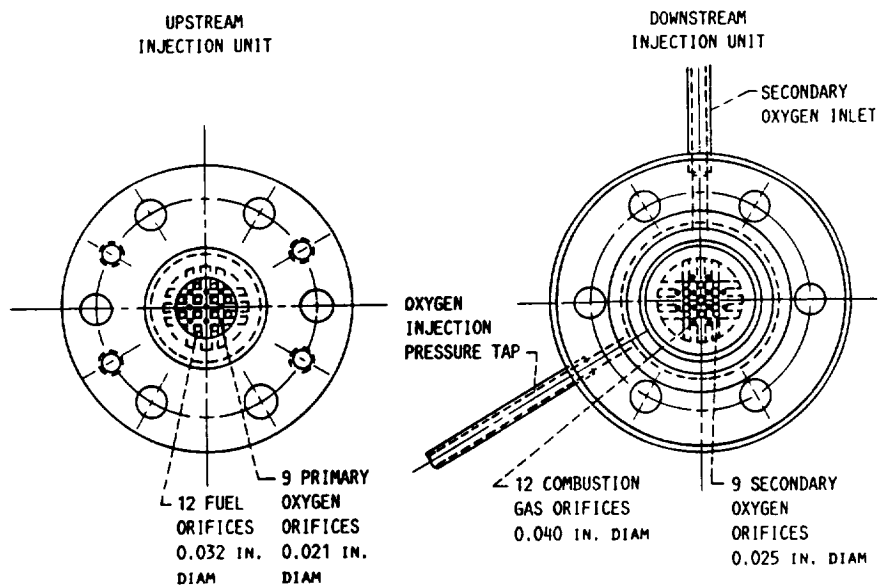


FIGURE 2. - SCHEMATIC OF INJECTOR UNITS.

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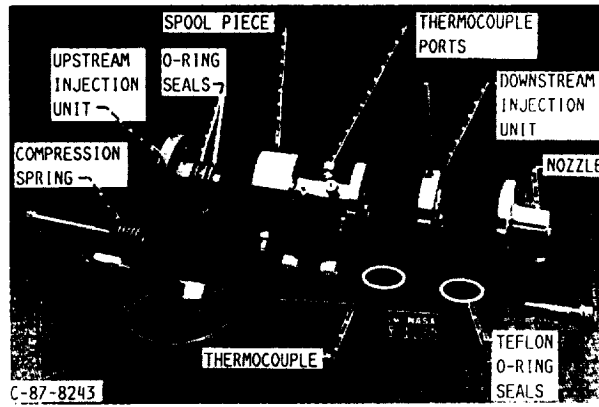
FIGURE 3. - EXPLODED VIEW OF CATALYTIC IGNITER HARDWARE.
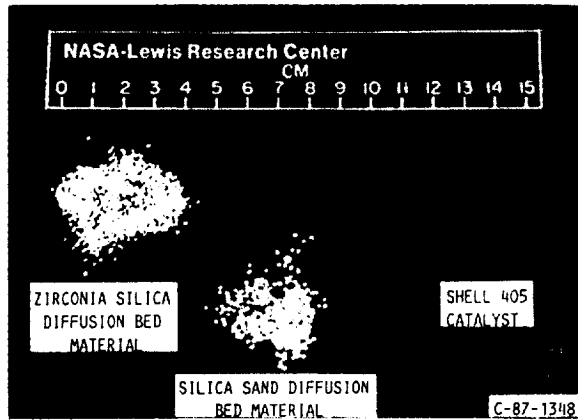


FIGURE 4. - CATALYST AND DIFFUSION BED MATERIAL.
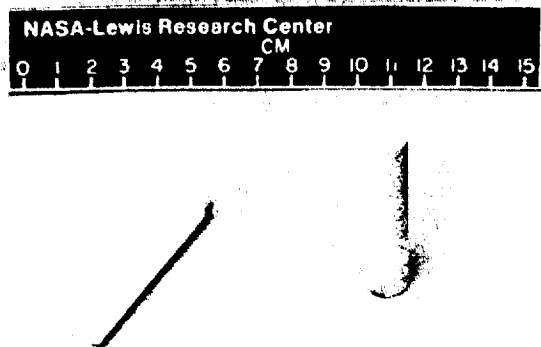


FIGURE 5. - MONOLITHIC SPONGE CATALYST.

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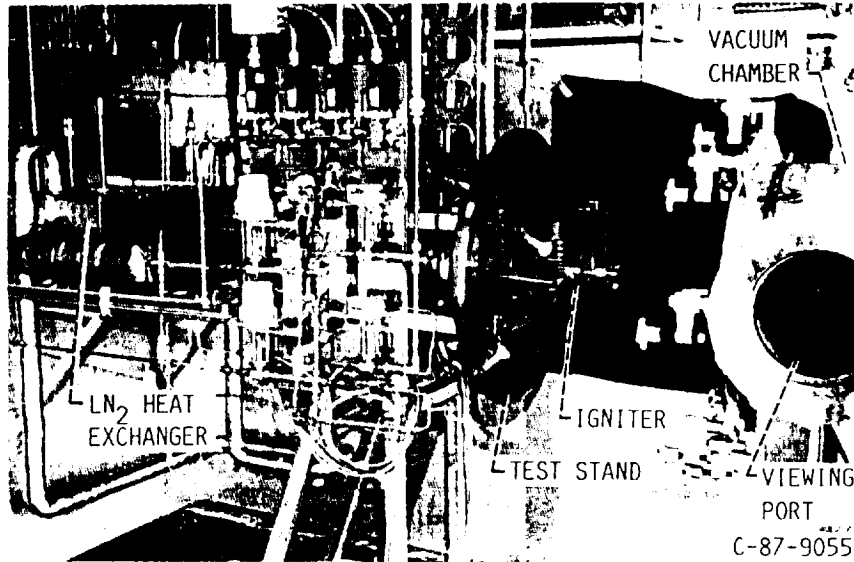
FIGURE 6. - TEST STAND.
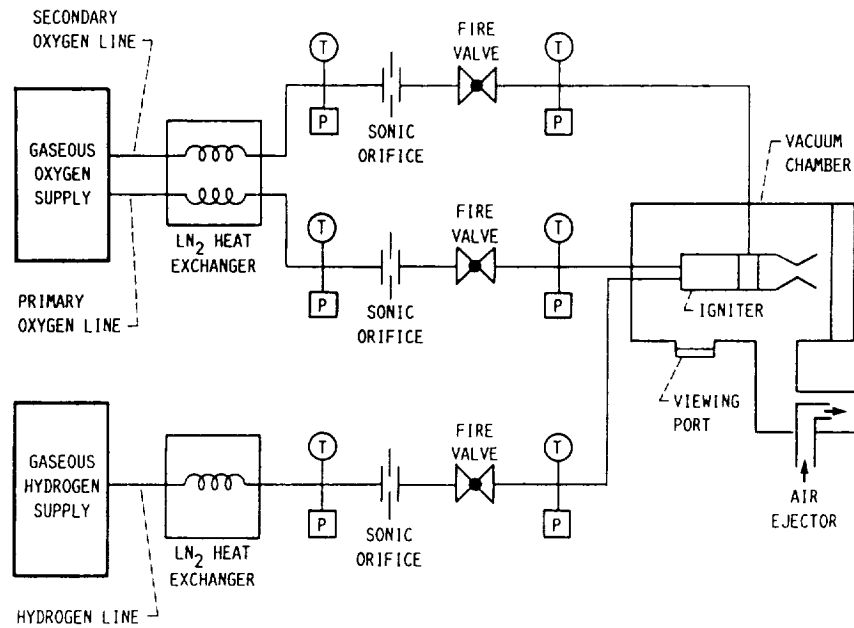


FIGURE 7. - PROPELLANT FEED SYSTEM SCHEMATIC.
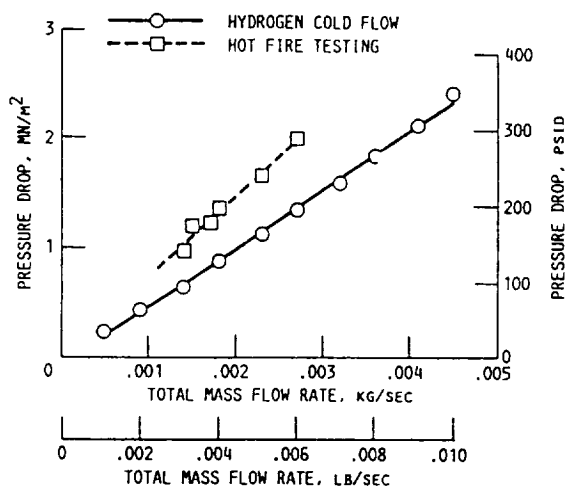
FIGURE 8. - EFFECT OF MASS FLOW RATE ON REACTOR
PRESSURE DROP. [MIXTURE RATIO = 1.0; 3 SEC
RUN DURATION FOR HOT FIRE TESTS.]
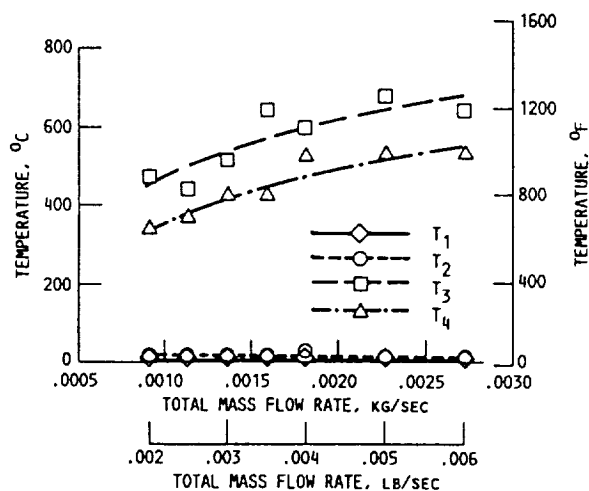


FIGURE 9. - EFFECT OF MASS FLOW RATE ON REACTOR
TEMPERATURE DISTRIBUTION. [MIXTURE RATIO =
1.0; 3 SEC RUN DURATION.]
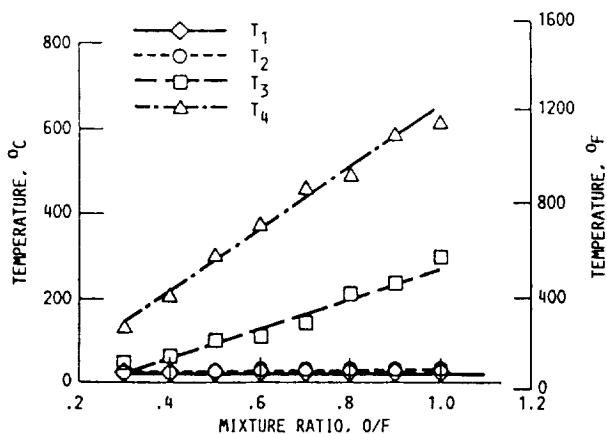


FIGURE 10. - EFFECT OF MIXTURE RATIO ON REACTOR
TEMPERATURE DISTRIBUTION. [TOTAL MASS FLOW
RATE = 0.0018 KG/SEC (0.004 LB/SEC); 3 SEC
RUN DURATION.]
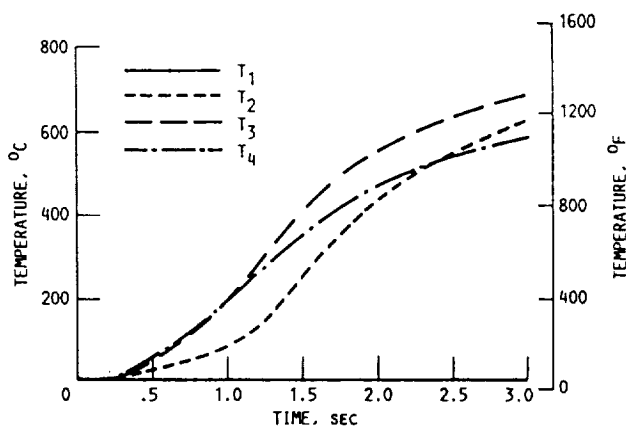


FIGURE 11. - REACTOR TEMPERATURE TRANSIENT FOR NOM-
INAL FLOW CONDITIONS. [TOTAL MASS FLOW RATE =
0.0018 KG/SEC (0.004 LB/SEC); MIXTURE RATIO = 1.0;
3 SEC RUN DURATION.]

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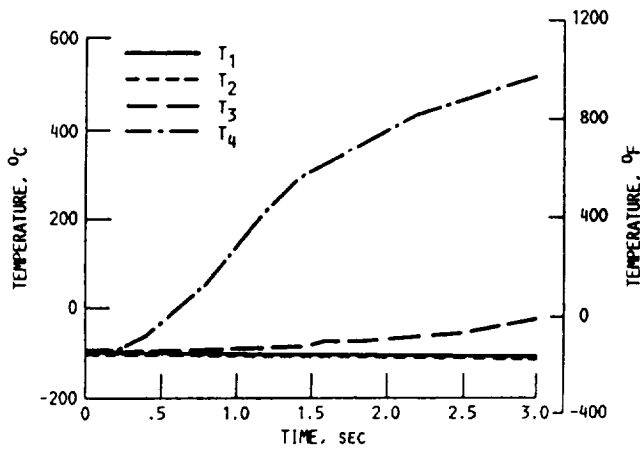
FIGURE 12. - EFFECT OF INLET TEMPERTURE ON REACTOR TEMPERATURE TRANSIENT. [TOTAL MASS FLOW RATE = 0.0018 KG/SEC (0.004 LB/SEC); MIXTURE RATIO = 1.0; 3 SEC RUN DURATION.]
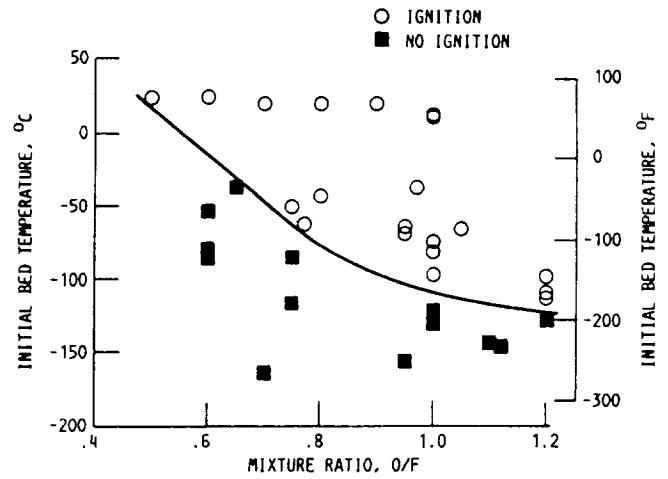


FIGURE 13. - EFFECT OF INITIAL BED TEMPERATURE AND MIXTURE RATIO ON IGNITION. [TOTAL MASS FLOW RATE = 0.0018 KG/SEC (0.004 LB/SEC); 3 SEC RUN DURATION.]
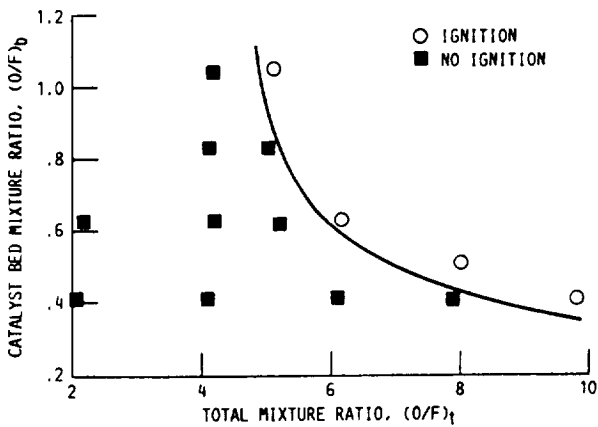


FIGURE 14. - EFFECT OF MIXTURE RATIO ON DOWNSTREAM IGNITION. [TOTAL MASS FLOW RATE = 0.0027 KG/SEC (0.006 LB/SEC); 2 SEC RUN DURATION.]
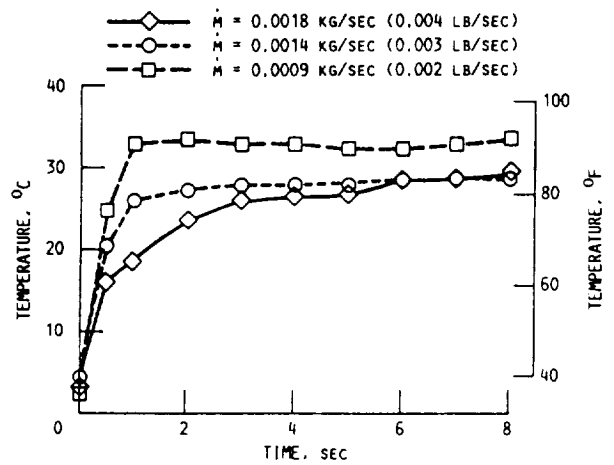


FIGURE 15. - EFFECT OF MASS FLOW RATE ON REACTOR TEMPERATURE FOR THE MONOLITHIC SPONGE CATALYST. [MIXTURE RATIO = 1.0.]
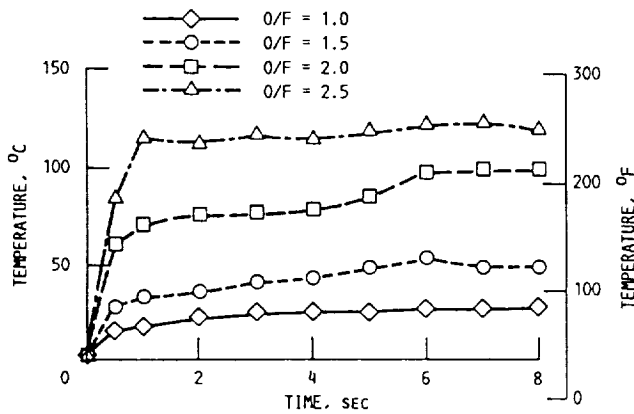
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FIGURE 16. - EFFECT OF MIXTURE RATIO ON REACTOR TEM-
PERATURE FOR THE MONOLITHIC SPONGE CATALYST.
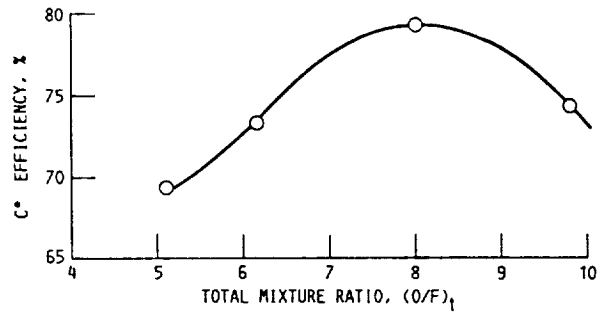[TOTAL MASS FLOW RATE = 0.0018 KG/SEC (0.004
LB/SEC).]



FIGURE 17. - EFFECT OF TOTAL MIXTURE RATIO ON IGNITER
C* EFFICIENCY. [REACTOR MASS FLOW RATE = 0.0027
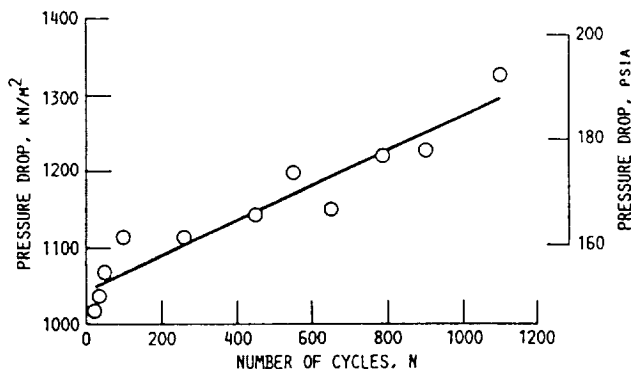KG/SEC (0.006 LB/SEC); 2 SEC RUN DURATION.]



FIGURE 18. - VARIATION OF REACTOR PRESSURE DROP
FOR CYCLIC LIFE TESTING. [TOTAL MASS FLOW RATE =
0.0018 KG/SEC (0.004 LB/SEC); MIXTURE RATIO = 1.0;
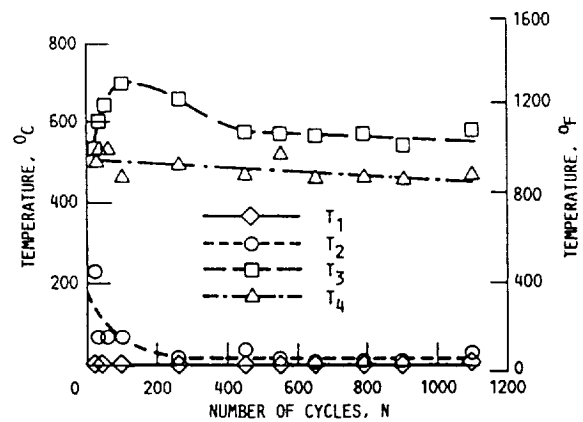2 SEC RUN DURATION.]



FIGURE 19. - VARIATION OF REACTOR TEMPERATURE
DISTRIBUTION FOR CYCLIC LIFE TESTING. [TOTAL
MASS FLOW RATE = 0.0018 KG/SEC (0.004 LB/SEC);
MIXTURE RATIO = 1.0; 2 SEC RUN DURATION.]

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