

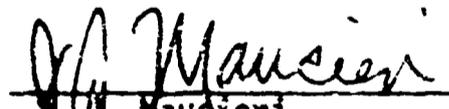
11602-6040-RO-00

SUMMARY REPORT
CONTRACT ARTICLE VI (e)

24 December 1969

Prepared for
NASA-MSC PRIMARY PROPULSION BRANCH
PROPULSION AND POWER DIVISION
UNDER CONTRACT NO. NAS 9-8229

Approved


J. M. Mauderi
Program Manager

TRW Systems Group
One Space Park, Redondo Beach, California

I. INTRODUCTION

Under contract NAS9-8229 with the NASA Manned Spacecraft Center, TRW Systems has conducted an 18-month analytical and experimental technology program to investigate and demonstrate material and design improvements that would reduce the ablative chamber throat erosion in the LM descent engine with: a) a resultant improvement in effective performance, and b) the ability to accommodate longer burn times with an increased margin of durability and reliability. The ultimate goal was to advance the capabilities of the LM engine should the need arise for some future mission.

At the time of contract award, there was no known future requirement. The LMDE had been qualified and was in production. Toward the end of the program, however, longer LM descent stage propellant tanks were proposed, effective with Apollo 16, and with the increased propellant came a new LMDE requirement called an extended G mission duty cycle. It was demonstrated that the qualified LMDE chamber could survive the increased firing time, but that throat erosion would increase by 50-to-100 percent over that experienced during the Qualification B Program. Such erosion was considered to be unacceptable for the mission.

When the new need arose, the improved prototype chamber that was the fruition of this program was being fabricated. The improvements were incorporated concurrently into a Qualification B chamber version and both chambers were test fired successfully to the new extended G mission duty cycle, with less than half the erosion exhibited in a qualified chamber fired similarly. All three tests were conducted with the same head end assembly. The improved LMDE chamber is now undergoing Design Verification Testing.

The results of the program demonstrate the desirability of low level technology programs, even on production components. Such programs serve the twofold purpose of maintaining: a) the technical proficiency of a developmental staff, and b) the ability to incorporate developed improvements rapidly into the production item should more stringent requirements arise.

II. STUDY OBJECTIVES

The primary objective of the study was to determine and demonstrate material and design improvements that would reduce the ablative chamber erosion in the Lunar Module Descent Engine. This study effort was to be separated into three phases. The objective of Phase I was to define and characterize the internal combustion chamber environment and to determine methods to minimize the severity of the environment to which the ablative chamber is subjected. The objective of Phase II was to determine and evaluate improved ablative chamber materials and chamber designs. Phase III was to encompass the design, fabrication, and test of an improved LMDE thrust chamber.

III. RELATIONSHIP TO OTHER NASA EFFORTS

In the literature and industry survey of Phase II, it appeared that the data most applicable to the LMDE chamber was that accumulated at NASA Lewis Research Center during the years 1966-1968. In these tests, LMDE-size throats were test fired with LMDE propellants, at comparable mixture ratios and chamber pressures. From the Lewis test data, it appeared that quartz-fabric/phenolic had better erosion resistance than the silica-fabric/phenolic of the qualified LMDE chamber. Torch testing and reactive testing in this program confirmed the superiority of quartz. Finally, a significant reduction in LMDE throat erosion was effected when quartz was incorporated in the liner in place of silica.

It is unknown whether the results of this program have any direct relationship to other NASA efforts now in progress. They might be applied beneficially to the other Apollo engines should erosion become a problem, even though environmental conditions at the chamber wall of those fixed-thrust units are different from those of the throttleable LMDE.

Of course, the results of the program were directly applicable to the mainline LMDE and the improved chamber will be incorporated in Apollo 16 and subsequent missions if the DVT and Qualification Test programs are concluded successfully.

IV. METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

As required by the contract, the program was conducted in three phases, the first two concurrently, consisting of the following:

Phase I - Define/Characterize the Internal Combustion Chamber Environment.

Experimental heat transfer studies were conducted with available qualification-design head end assemblies to evaluate the thermal environment to which the ablative thrust chamber was subjected. Specially designed and instrumented thrust chamber hardware was utilized for measurement of heat transfer to local areas of the chamber wall. These measurements were taken during firings at various thrust levels to characterize the chamber thermal profile, both axially and circumferentially. The basic heat-sink chamber hardware was employed for short duration firings at selected engine operating conditions. The local wall heat transfer data were obtained utilizing transient surface temperature techniques and data reduction procedures described in detail in the final report. The water-cooled chamber design provided local wall heat flux data during long duration, variable thrust level, engine operation. The heat flux was readily determined from the measured water flow rates and temperature rise under chamber equilibrium operating conditions.

Low cost fiberglass/phenolic streak chambers were tested at selected fixed thrust settings to obtain throat erosion patterns. These throat erosion data were compared and correlated with the thermal environment data from the heat-sink and water-cooled chamber tests to arrive at the variation of erosion with heat flux. In addition, ablative silica-fabric/phenolic chambers were duty-cycle tested to provide throat erosion patterns. These data were also compared with the heat flux data to provide erosion/thermal environment correlation.

Phase II - Evaluation of Improved Ablative Chamber Materials and Designs

A literature and industry survey was made to determine candidate ablative materials for an advanced ablative chamber design. A laboratory investigation showed that by proper balance of carbon and silica in an ablative structure, favorable endothermic reactions could be induced, resulting in the formation of stable refractory SiC instead of the volatile

SiO product. The reaction mechanism was duplicated in specimens exposed in an inexpensive torch simulation of the LMDE combustion products. Other candidate ablative and hard throat materials were evaluated similarly. The most promising advanced ablative materials were fabricated into a composite ablative throat and test fired at sea level in a chamber contour (Contour C) that promised improved engine performance. As a result of this firing, quartz-fabric/phenolic was chosen as the material to be used in a subsequent flightweight chamber test firing. A standard laminated LMDE silica-fabric/phenolic chamber was built to the configuration (Contour A) that exhibited the least heat flux and gas recovery temperatures at FTP and test fired at sea level with the qualification configured injector. From these tests, an advanced chamber design was recommended for NASA/MSO approval and subsequent fabrication of a flightweight unit in Phase III.

A hard throat design concept was analyzed thermally and presented to NASA/MSO. Cost and schedule considerations did not permit fabrication and testing of the design concept.

Phase III - Design, Fabrication, and Test of an Improved Descent Engine Thrust Chamber

A flightweight chamber was fabricated by production procedures. The improved chamber design (Contour C) was verified in an extended G mission duty cycle altitude test, using a qualification-type head end assembly of defined ablative chamber compatibility characteristics. The head end assembly for this test was typical, from a chamber erosion standpoint, of the Qual B descent engine configuration.

While the improved chamber was being fabricated, a new requirement, called an extended G mission duty cycle, was placed upon LMDE for Apollo 16 and subsequent missions. An improved flightweight LMDE chamber with the Qual B internal contour was then fabricated and tested at altitude with the same head end assembly described above. It incorporated the design improvements and the quartz-fabric/phenolic material developed under this program.

V. BASIC DATA GENERATED AND SIGNIFICANT RESULTS

- The heat sink tests showed that throat recovery temperatures varied from 4000°F to 4650°F over the LMDE thrust range.
- Convective heat transfer coefficients in the cylindrical section in the Qual B chamber were shown to be as much as 5.5 times theoretical values, whereas the throat heat transfer coefficients appeared to vary from 1.0 to 1.1 times theoretical values.
- At low thrust levels the cylindrical section heat flux was greater than that at the throat.
- A correlation of the erosion and thermal environment was accomplished with a fiberglass/phenolic streak chamber and a silica-fabric/phenolic ablative chamber at 25% thrust. The data showed the erosion to vary directly with heat flux changes.
- At thrust levels of 50%, 65%, and FTP, heat flux changes generally produced proportionate changes in erosion depth.
- A throat heat flux reduction at FTP of 40% was accomplished in going from a Qual B contour to a Contour A with a heat sink throat at a wall temperature of 1000°F. Fiberglass streak chamber tests at FTP for both chambers showed a reduction in erosion for Contour A, substantiating the heat flux reduction at the fixed thrust point. Duty cycle tests of the same two configurations with ablative silica throats substantiated the fact that Contour A eroded much less than Qual B at full thrust. When the engine was throttled down, however, Contour A erosion was greatly accelerated, so that its overall erosion exceeded that of the Qual B contour. Since the heat sink tests were conducted only at FTP, the effects of the duty cycle erosion sequence could not have been predicted. Nevertheless, should the need arise for a mission duty-cycle conducted primarily at full-thrust, a Contour A chamber would certainly offer a distinct advance in greatly reduced erosion and the concomitant overall performance gain.

- The effects of heat flux on LMDE throat erosion was deduced to be only part of a more complex problem. Erosion is caused by several mechanisms, including temperature, shear forces, oxidation, melt viscosity, and other properties. But perhaps the most serious mechanism is one of thermochemical reactions occurring at the wall.
- The Phase III Prototype Chamber and the improved Qualification B chamber that incorporated the quartz-fabric/phenolic developed under this program were both successfully test fired to the new extended G mission duty cycle, with less than half the erosion exhibited in a qualified silica chamber fired similarly. All three tests were conducted with the same head end assembly.

VI. LIMITATIONS

The interaction of a complex two-zone combustion flow field, in which the primary and secondary oxidizer streams react with the fuel sheet and the barrier coolant, points up the fact that the zone nearest the wall at the throat is significantly detrimental to the integrity of ablative material during the present LMDE duty cycle firing sequence.

VII. IMPLICATIONS OF RESEARCH

The results of the program demonstrate the desirability of low-level technology programs, even on production components. Such programs serve a two-fold purpose of maintaining: a) the technical proficiency of a developmental staff, and b) the ability to incorporate developed improvements rapidly into the production item should more stringent requirements arise.

VIII. SUGGESTED ADDITIONAL EFFORT

Despite the significant reduction in erosion experienced when silica fabric was replaced with quartz fabric in the LMDE chamber and throat, further potential ablative material advances for the nitrogen tetroxide and hydrazine type of fuel appear to be limited. One potential that should be

investigated further is that of in situ formation of silicon carbide by endothermic reactions in the ablative structure. The phenomenon was explored initially in this program but additional evaluation of the variations in the silica/carbon ratio and methods of increasing the proximity (and reactivity) of the two could prove fruitful.

Although bordering on the hard-throat category, the metal-infiltrated precharred graphitic laminates warrant further investigation. Although these have apparently overcome the poor thermal shock resistance of the refractories while exhibiting good erosion resistance, their high thermal conductivity requires a sophisticated design approach to accommodate thermal gradients and maintain the pressure vessel structure at reasonable temperatures.

Wall environmental control can reduce erosion. In this program it was accomplished successfully by reduction of the turbulator diameter. The turbulator improves the flow uniformity in the LMDE oxidizer jets and decreases the amount of oxidizer penetration to the chamber wall. Unfortunately the reduced erosion was accompanied by a reduction in specific impulse.

Other methods of wall environmental control that warrant investigation include:

- Changing the oxidizer-to-fuel pressure drop ratio by adjustments in the fuel-metering ramp on the injector control sleeve.
- Varying the fuel barrier coolant flow with throttle setting.