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TRW
SYSTEMS GROUP
ONE SPACE PARK • REDONDO BEACH, CALIFORNIA

FIRST MONTHLY PROGRESS REPORT

"EXTEND THE DESIGN CRITERIA FOR THE
COAXIAL PINTLE INJECTOR TO HIGHER CHAMBER
PRESSURES AND TO GASEOUS FUEL"

Reporting Period
2 July 1969 through 25 July 1969

Contract NAS3-13307

Prepared For
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
Cleveland, Ohio 44135

Prepared By
W. A. Carter, Program Manager

TRW SYSTEMS
One Space Park
Redondo Beach, California

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Contract No. NAS3-13307 — 25 August 1969

Prepared by: W. A. Carter
W. A. Carter
Program Manager

Approved by: S. J. Van Grouw
S. J. Van Grouw, Head
Combustion Technology
Section

Approved by: H. L. Burge
H. L. Burge, Manager
Applied Technology
Department

TRW SYSTEMS GROUP
One Space Park
Redondo Beach, California

"EXTEND THE DESIGN CRITERIA FOR THE COAXIAL PINTLE INJECTOR TO HIGHER CHAMBER PRESSURES AND TO GASEOUS FUEL"

1. INTRODUCTION

This report summarizes the activities during the first reporting period of the contract to "Extend the Design Criteria for the Coaxial Pintle Injector to Higher Chamber Pressures and to Gaseous Fuel" being performed by TRW Systems under NASA/LeRC Contract NAS3-13307. The reporting period covered is from contract award, 2 July 1969, through the end of accounting month, 25 July 1969.

The program to "Extend the Design Criteria for the Coaxial Injector to Higher Chamber Pressures and to Higher Chamber Pressures and to Gaseous Fuel" is an eight-month technical effort consisting of analytical and design effort, culminating in an experimental evaluation of the coaxial injector using FLOX and gaseous methane as propellants. The main program objectives are summarized below:

- Conduct a design analysis of a coaxial pintle injector for use with gaseous methane-liquid FLOX. Design operating conditions shall be a sea-level thrust of 3000 lb_f and a chamber pressure of 500 psia at a mixture ratio of 5.75. A passively cooled thrust chamber for use with the above injector shall also be designed.

- Perform an experimental program to establish the performance, heat transfer and erosion characteristics of the injector with a maximum of four oxidizer elements. The goal of this effort is the selection of an element which combines high performance, low heat flux and no streaking.

- With the selected oxidizer configuration, conduct an experimental program to determine the effect of L* variation on performance over a mixture ratio range of 80% to 110% of the optimum mixture ratio (5.75).

- Demonstrate hardware durability by conducting a single long-duration test.

- Demonstrate dynamic stability by conducting a single stability rating test using an induced explosive excitation.

To accomplish these goals, a five-task program will be conducted which will include the following:

- Design analysis of a coaxial pintle injector and passively cooled thrust chamber.
- Fabrication of injector and thrust chamber hardware.
- Cold flow evaluation of the candidate injector configurations
- Experimental determination of injector streaking characteristics with the subject design configurations
- Experimental evaluation of injector performance, chamber heat flux profiles and engine dynamic stability characteristics employing the selected injector design configuration
- Evaluation of the experimental data to provide design criteria.

2. PROGRESS DURING THE REPORTING PERIOD

During the July accounting month, the program work plan was prepared and submitted to the NASA/LeRC Project Manager for review and approval.

Design and analysis of the injector and thrust chamber were initiated during this period (Task I).

Facility planning was initiated for the streak tests and performance evaluation tests (Tasks III and IV).

2.1 Task I - Injector and Thrust Chamber Design

The Task I effort is a design analysis of the coaxial pintle injector for use with the FLOX (82.6%) - gaseous methane propellant combination. The design analysis includes an evaluation of data obtained for liquid-liquid, coaxial pintle injectors and its application to the gas-liquid injector.

2.1.1 Task I-1 - Injector Design

During the initial month of the program, the analysis and design of the coaxial injector were begun. The analysis of the injector includes the effects of geometry, momentum ratios, velocities, impingement angles and pressure drops. For gas/liquid injector designs (in the absence of gross propellant maldistribution), propellant atomization, by its control of vaporization rate, is the controlling process in determining the degree of combustion efficiency.

A combustion analysis was conducted based upon the model outlined by Priem and Heidmann (Reference 1). This model, derived in Reference 1, is a vaporization-limited combustion model in which the combustion efficiency is a function of the percent of the liquid which is vaporized. Figure 1 is the theoretical relationship (Reference 1) between combustion efficiency and the percent of FLOX vaporized. The percent of liquid vaporized is related to the initial drop size as shown in Figure 2. As combustion chamber length (the length downstream of the initial drop size) is decreased from 3 inches to 1 inch at a chamber pressure of 500 psia, the percent of FLOX which is vaporized is predicted to decrease from 100 to approximately 25 percent for an initial drop diameter of 250 microns. For drop diameters below approximately 65 microns, all of the liquid is vaporized within chamber lengths of 1 inch or longer.

Therefore, if combustion performance is limited by vaporization of the FLOX, a unique relat'onship should exist between characteristic velocity efficiency and some measure of drop size (volume mean, mass mean, etc.) at some distance from the injector face for a particular chamber configuration and propellant combination.

An analysis of the atomization of the liquid (FLOX) stream by a cross-current gas (CH_4) stream is also being conducted. Ingebo (Reference 2) and Clark (Reference 3) have conducted experiments to determine drop size distribution for cross-current breakup of jets. The volume number mean drop diameter estimated from Ingebo's studies is shown to be approximately

$$\frac{D_{30}}{D_o} = 3.9 \left(\frac{We}{Re}\right)^{.25} \tag{1}$$

where

D_{30} = volume-median droplet diameter

D_o = injector orifice diameter

We = Weber number, $\sigma/\rho_g V_g^2 D_o$

Re = Reynolds number based on orifice diameter, $D_o V_g/\nu$

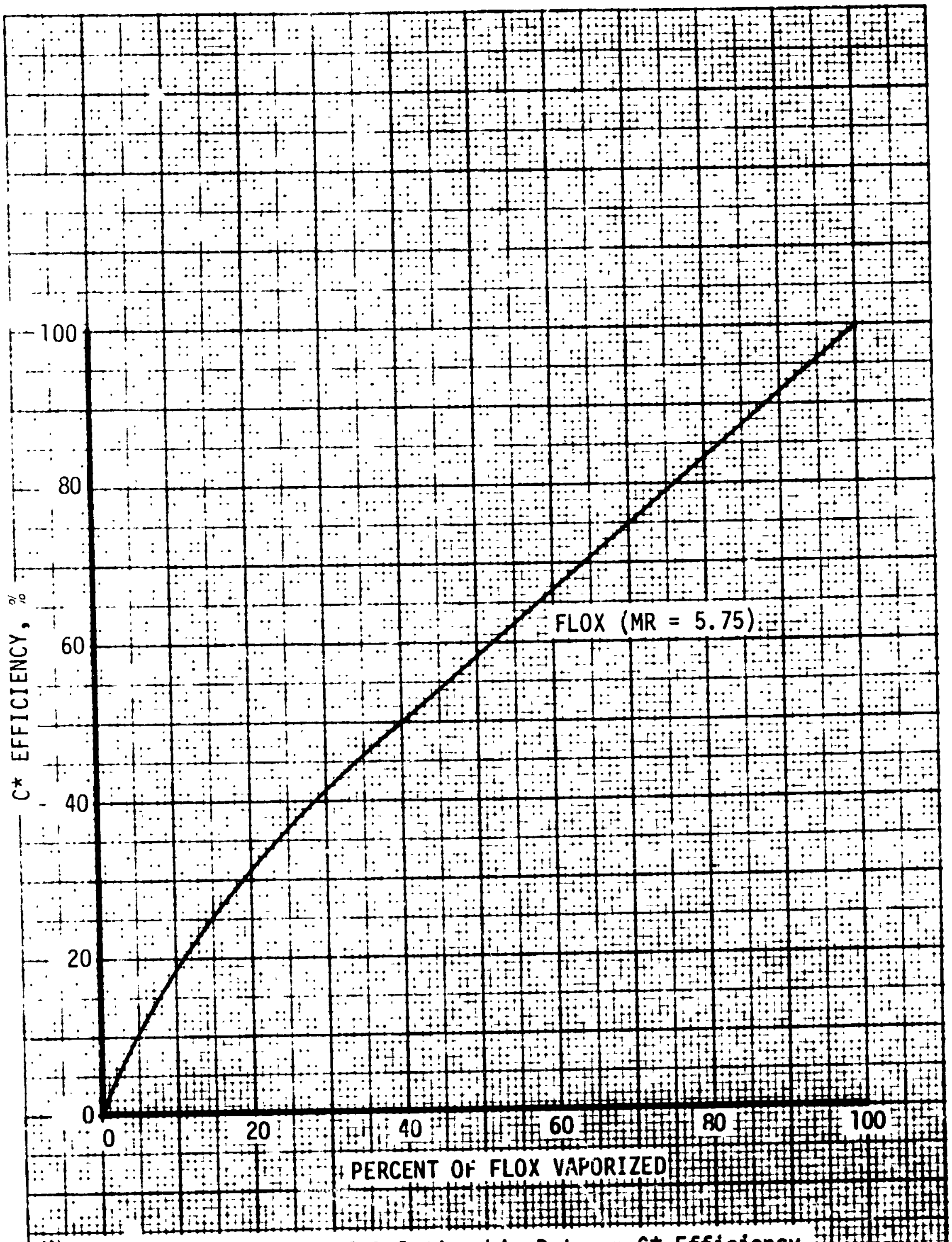

Figure 1. Theoretical Relationship Between C* Efficiency and Percent of FLOX Vaporized for FLOX/CH_4

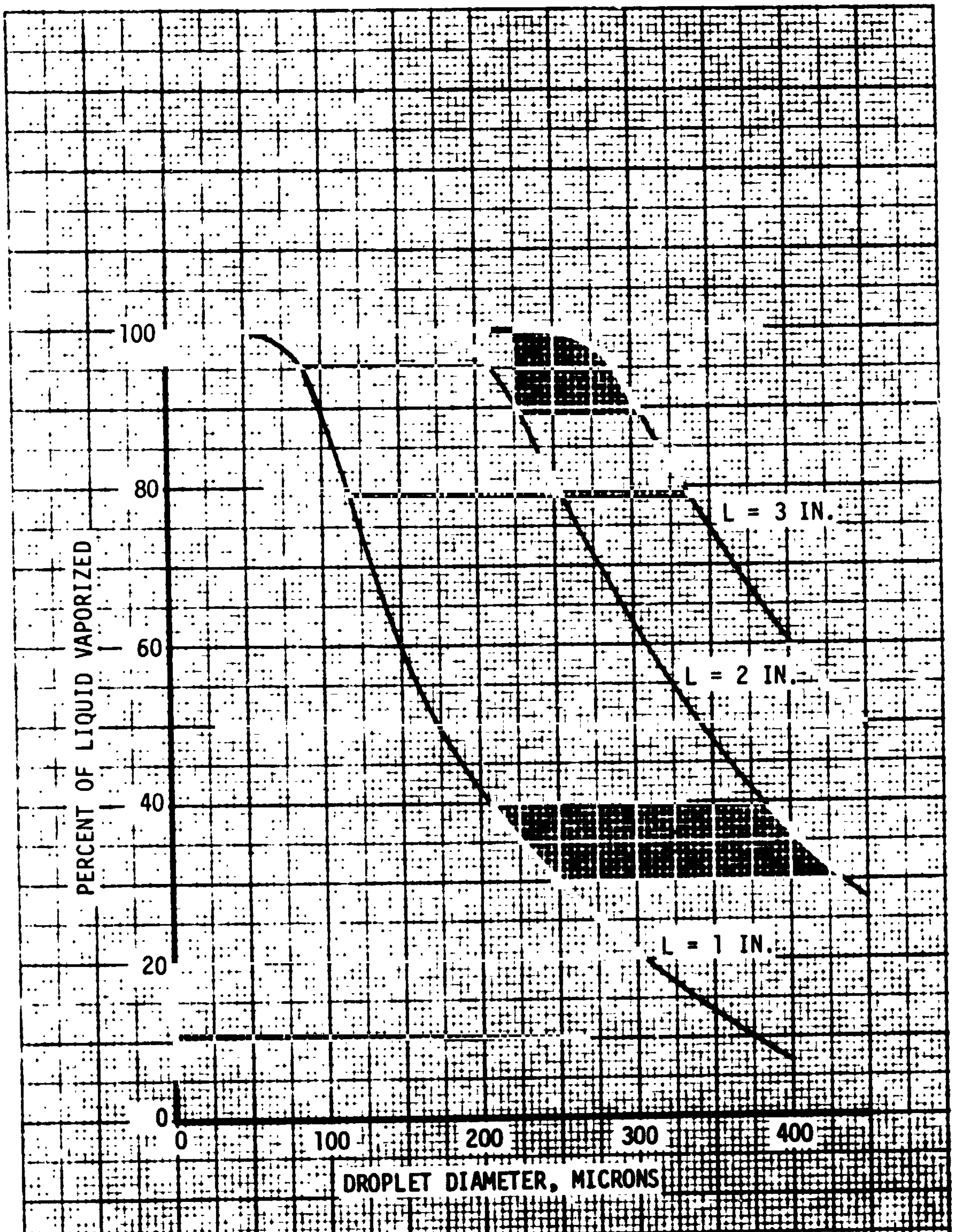

Figure 2. Effect of FLOX Droplet Size and Combustion Chamber Length on Percent of FLOX Vaporized; FLOX/CH_4 Combustion at Chamber Pressure of 500 psia, Initial Droplet Velocity of 100 ft/sec.

The above equation represents the volume number mean drop diameter which should occur in a uniform gaseous CH_4 velocity duct with no chemical reactions. This equation represents the smallest mean drop size which could be obtained with the given velocity and enough gas flow to complete atomization without depletion of gas stream momentum.

Figure 3 is a plot of volume median droplet diameter as a function of gas Mach number and oxidizer orifice diameter for the FLOX-gaseous methane at 500 psia.

Use of Equation 1 to estimate the volume number mean droplet diameter results in estimates of D_{30} which are less than approximately 25 microns for the oxidizer orifice diameter and injection Mach numbers of interest. Figure 3 shows the effect of methane injection Mach number on the volume number mean droplet diameter. The effect of the attenuation of the free jet velocity downstream of the injection orifice is also illustrated in this figure.

The fuel injection orifice is an annular orifice and therefore approximated by a two-dimensional or plane jet. It has been shown in Reference (4) that the jet velocity is attenuated in proportion to the inverse of the square root of the distance from orifice. As is evident from this figure, increasing the injection Mach number above about 0.4 does not appreciably decrease the oxidizer droplet diameter.

The mean droplet diameter predicted by Equation 1 and shown in Figure 3 results in estimates of D_{30} which are less than approximately 40 microns at gaseous CH_4 Mach numbers of 0.1 or higher. However, if a liquid-vaporization-limited combustion model is assumed, and if maximum drop diameter is 65 microns or less, then a combustion efficiency approaching 100 percent would be obtained if a combustion length of at least 1 inch downstream of this initial drop diameter were available.

Under this assumption, these estimates indicate that:

1. If sufficiently small (less than about 65 microns) maximum drop diameters can be obtained using CH_4 gas to atomize the liquid, then C* efficiencies approaching 100 percent (neglecting friction and heat transfer loss to the walls) can be achieved in combustion chamber lengths of a few inches.

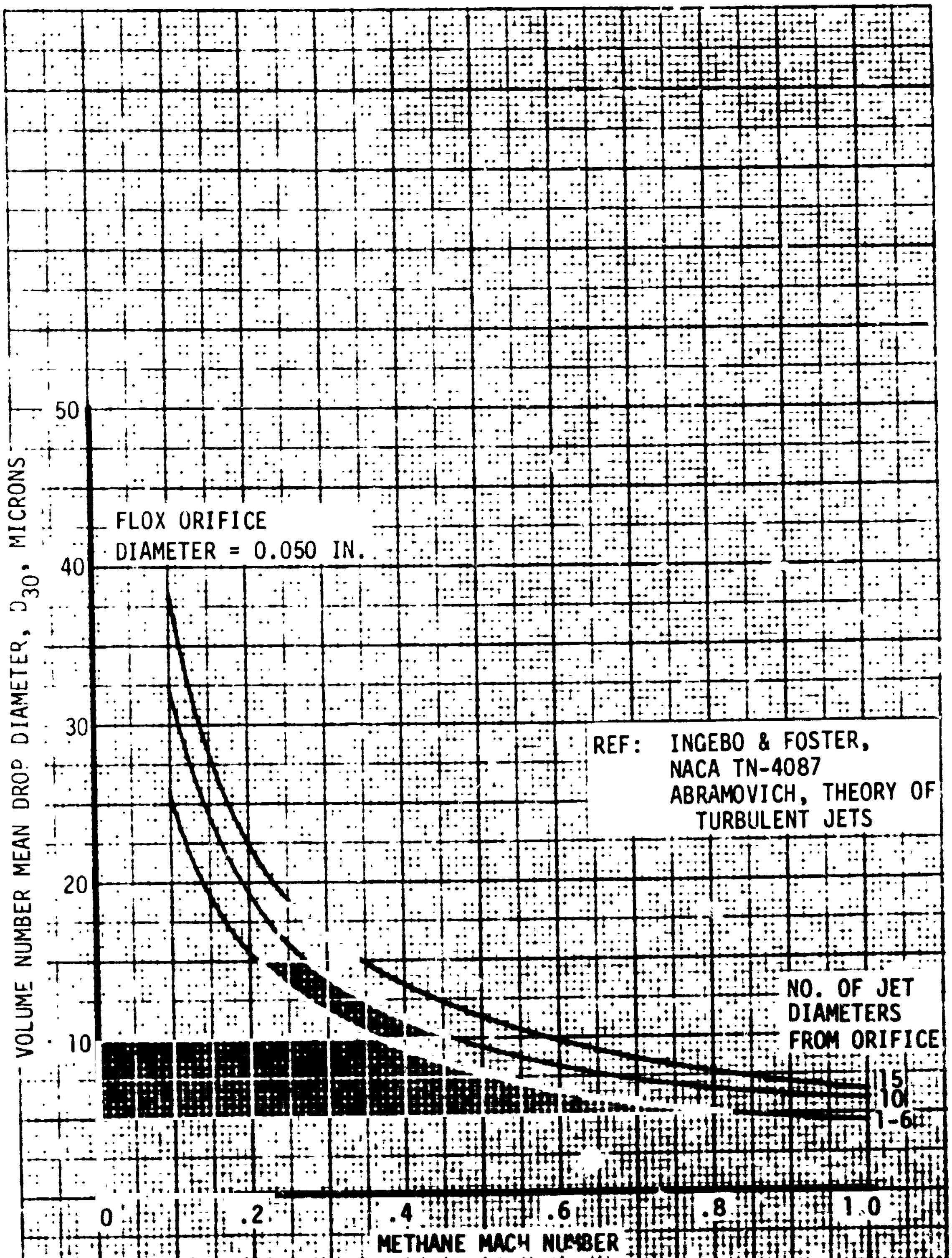

Figure 3. The Effect of Methane Injection Mach Number and Distance from Injection Orifice on FLOX Droplet Size at a Chamber Pressure of 500 psia.

2. The current gas-liquid injector design will provide for maximum liquid atomization.

3. Primary factors which will contribute to losses in C* efficiency are mass and mixture ratio maldistribution. The mass and mixture ratio distribution will be determined during Task III cold flow testing.

Thermal analyses of the injector design were initiated to determine the severity of the pintle tip heating and to determine whether condensation of the gaseous methane on the outside of the oxidizer element might occur. Detailed results of the thermal analyses will be inlcuded in the second monthly progress report.

2.1.2 Task I-2 - Thrust Chamber Design

During the first month of the program, the design and analysis of the thrust chambers for the streak tests and the performance evaluation tests were begun.

The program will utilize a multi-section heat sink thrust chamber for the streak tests and the performance evaluation tests. The chamber is being designed so that characteristic length (L*) variations can be achieved by interchanging the cylindrical sections with a common nozzle section. The streak tests are also accomplished by replacing the nominal 30-inch L* heat sink section with an ablative section.

The heat sink cylindrical chamber sections will be fabricated from OFHC copper and the nozzle section will be G-90 graphite. The streak chambers will be a silica phenolic ablative material contained within a steel shell.

An additional thrust chamber fabricated entirely of G-90 graphite is being designed to accomplish the long-duration run. This chamber will not contain all the instrumentation which the performance evaluation chambers contain.

Thermal analyses of the thrust chambers are being conducted to determine theoretical heat flux as a function of operating conditions. The thermal analyses will define duration limits for operation with the copper cylindrical sections and graphite nozzle.

The nominal design specifications for the thrust chamber are as follows:

Chamber pressure	-	500 psia
Thrust (sea-level)	-	3000 lb/sec
Total propellant flow rate at O/F = 5.75	-	9.3 lb/sec
Contraction ratio	-	4
Expansion ratio	-	5
Nozzle configuration	-	Conical - 15° half angle

Instrumentation on each chamber section will include two ports for measuring chamber pressure at the start of nozzle convergence, a dynamic chamber pressure measurement using a Photocon transducer, and multiple thermocouple plugs for measuring axial and circumferential heat flux profiles. The thermocouple plugs are similar in design to those used on contract NAS3-11200.

2.2 Task III-1 - Facility Preparation

Overall facility planning was initiated for the Injector Characterization and Performance Evaluation Tests. Effort was expended on preparation of system schematics, selection of test equipment required, and investigation of flow measurement and propellant conditioning requirements. All long lead time test facility items were determined and request for quotations have been placed.

3. CURRENT PROBLEMS

No major problems exist at this time that may impede performance of the program.

4. WORK TO BE PERFORMED DURING THE NEXT REPORTING PERIOD

The following program activities are planned for the August reporting period:

Task I-1 - Injection Design

- Complete injector detailed drawings
- Complete injector thermal analysis
- Complete injector hydraulic/combustion analysis

Task I-2 - Thrust Chamber Design

- Complete detailed fabrication drawings of the streak test, performance evaluation and long duration thrust chambers
- Complete thrust chamber thermal analysis

Task II-1 - Injector Fabrication

- Initiate procurement of material for injector fabrication

Task II-2 - Thrust Chamber Fabrication

- Initiate procurement of material for fabrication of thrust chambers

Injector and Thrust Chamber Design Review

The injector and thrust chamber analyses and designs will be presented to the NASA LeRC Project Manager at a design review on 26 August 1969 at TRW Systems.

5. NEW TECHNOLOGY DISCLOSURE

No new technology disclosures were reported during this period.

REFERENCES

1. Priem, R. J. and Heidmann, M. F., Propellant Vaporization as a Design Criteria for Rocket Engine Combustion Chambers, NACA TR R-67, 1960.

2. Ingebo, R. D. and Foster, H. H., Drop-size Distribution for Cross-current Breakup of Liquid Jets in Airstreams, NACA TN 4087, October 1957.

3. Clark, J. B., Breakup of a Liquid Jet in a Transverse Flow of Gas, NASA TN D-2424, August 1964.

4. Abramovich, "The Theory of Turbulent Jets" M.I.T. Press.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
CLEVELAND, OHIO 44135

CONTRACT PROGRESS SCHEDULE

REPORT FOR MONTH ENDING: 25 July 1969

9. NASA Use Only
a. NASA CODE
b. PROJECT MGR
c. EVALUATION DATE
d. EXCEPTION CATEGORY

1. CONTRACT TITLE: EXTEND THE DESIGN CRITERIA FOR THE COAXIAL PINTLE INJECTOR TO HIGHER CHAMBER PRESSURES AND TO GASEOUS FUEL

2. CONTRACTOR (Name and address): TRW INC., TRW SYSTEMS GROUP
One Space Park, Redondo Beach, California 90278

3. CONTRACT NO.: NAS3-13307

4. APPROVED (Contractor's Project Manager): W. A. Carter (signature)

PREPARATION DATE: 8-20-69

5. NASA APPROVED SCHEDULE DATE: 7-15-69

6. REPORTING CATEGORY	7. 1969 J	A	S	O	N	D	1970 J	F	M	A	8. TECH. OBJECTIVE a. WEIGHT FACTOR	b. % COMP.	c. % CONTR. COMP.	e.	f.	g.
Task I-1 Injector Design											10	90	9			
Task I-2 Chamber Design											7	85	6			
Task II-1 Injector Fabrication											13	0	0			
Task II-2 Chamber Fabrication											10	0	0			
Task III-1 Facility Preparation											20	2	4			
Task III-2 Injector Characterization Study											11	0	0			
Task IV Performance Evaluation											20	0	0			
Task V Data Analysis											6	0	0			
Reporting (a) Work Plan (b) Monthly Reports (c) Final Reports	(a)	(b)						(b)	(c)		3*	0	0			

NASA-C-63 (6-67)

NASA APPROVED SCHEDULE

CONTRACTOR'S WORKING SCHEDULE

* Final Report only.

SHEET 1 OF 2 SHEETS

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACTOR FINANCIAL MANAGEMENT REPORT - CONTRACTS UNDER $500,000

(Refer to NASA Handbook 9501.2 for expanded instructional procedures)

REPORT FOR MONTH ENDING AND NUMBER OF WORK DAYS: 7-25-69 / 17 W.D.

Budget Bureau No. 104-R011.2
Approval Expires December 31, 1970

TO: NASA LEWIS RESEARCH CENTER
21000 Brookpark Road
Cleveland, Ohio 44135

FROM: TRW, INC.
One Space Park
Redondo Beach, California 90278

2. CONTRACT VALUE: $ 157.6

3. FUND LIMITATION: $ 157.6

4. INVOICE AMOUNTS BILLED: $ -0-

5. TOTAL PAYMENTS RECEIVED: $ -0-

1. DESCRIPTION OF CONTRACT

a. TYPE: COST PLUS FIXED FEE (CPFF)

b. NO.: NAS3-13307

c. SCOPE OF WORK: COAXIAL PINTLE INJECTOR

d. AUTH. CONTRACT REPRESENTATIVE (Signature): W. A. Carter

PREPARATION DATE: 8-21-69

6. REPORTING CATEGORY		7. COSTS INCURRED/HOURS WORKED: CUM. ACTUAL END OF PRIOR MONTH (July) a.	DURING MONTH (August): EST. ACTUAL b.	DURING MONTH: PLANNED c.	CUM. TO DATE: ESTIMATED* d.	CUM. TO DATE: PLANNED e.	8. ESTIMATED COSTS/HOURS TO COMPLETE: SUBSEQUENT MONTH (Sept.) a.	BALANCE OF FISCAL YEAR b.	BALANCE OF CONTRACT c.	9. ESTIMATED FINAL COSTS
Task I	Injector & Thrust Chamber Design Engineering Labor	3.1 / 161	9.8 / 604	13.6 / 646	12.9 / 765	22.2 / 1054	9.3 / 289	0 / 0	0 / 0	22.2 / 1054
Task I	Injector & Thrust Chamber Design - Other Costs	.4 / 28	.6 / 50	1.7 / 64	1.0 / 78	2.7 / 128	1.7 / 50	0 / 0	0 / 0	2.7 / 128
Task I	Total Expenditures	3.5 / 189	10.4 / 654	15.3 / 710	13.9 / 843	24.9 / 1182	11.0 / 339	0 / 0	0 / 0	24.9 / 1182
Task II	Injector & Thrust Chamber Fabrication - Engrg. Labor	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	4.2 / 184	8.2 / 368	0 / 0	12.4 / 552
Task II	Injector & Thrust Chamber Fabrication - Mfg. Labor	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	3.0 / 256	5.2 / 432	0 / 0	8.2 / 688
Task II	Injector & Thrust Chamber Fabrication - Other Costs	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	11.7 / 76	2.0 / 152	0 / 0	13.7 / 228
Task II	Total Expenditures	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	18.9 / 516	15.4 / 952	0 / 0	34.3 / 1468
Task III	Cold Flow & Streak Tests Engineering Labor	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	4.2 / 184	0 / 0	4.2 / 184
Task III	Cold Flow & Streak Tests Test Labor	.1 / 8	.7 / 60	.7 / 60	.8 / 68	.8 / 68	.4 / 32	21.7 / 1533	0 / 0	22.9 / 1633
Task III	Cold Flow & Streak Tests Other Costs	0 / 0	1.3 / 0	12.6 / 0	1.3 / 0	12.6 / 0	11.3 / 0	6.8 / 56	0 / 0	19.4 / 56
Task III	Total Expenditures	.1 / 8	2.0 / 60	13.3 / 60	2.1 / 68	13.4 / 68	11.7 / 32	32.7 / 1773	0 / 0	46.5 / 1873

PLAN IDENT. ☐ UPDATED PLAN TO (Date) ☐ PRIOR SUBMISSION, NASA FORM 533b (Date) ☐ NONE

* *The actuals will be reported on the next month's report.*

NASA FORM 533b FEB 67

SHEET 2 OF 2 SHEETS

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACTOR FINANCIAL MANAGEMENT REPORT - CONTRACTS UNDER $500,000

(Refer to NASA Handbook 9501.2 for expanded instructional procedures)

REPORT FOR MONTH ENDING AND NUMBER OF WORK DAYS: 7-25-69 / 17 W.D.

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2. CONTRACT VALUE $ 157.6

3. FUND LIMITATION $ 157.6

4. INVOICE AMOUNTS BILLED $ -0-

5. TOTAL PAYMENTS RECEIVED $ -0-

1. DESCRIPTION OF CONTRACT
a. TYPE: COST PLUS FIXED FEE (CPFF)
b. NO.: NAS3-13307
c. SCOPE OF WORK: COAXIAL PINTLE INJECTOR
d. AUTH. CONTRACT REPRESENTATIVE (Signature): W. A. Carter
PREPARATION DATE: 8-21-69

6. REPORTING CATEGORY	7. COSTS INCURRED/HOURS WORKED					8. ESTIMATED COSTS/HOURS TO COMPLETE			9. ESTIMATED FINAL COSTS
	CUM. ACTUAL END OF PRIOR MONTH a.	DURING MONTH EST. ACTUAL b.	DURING MONTH PLANNED c.	CUM. TO DATE ESTIMATED* d.	CUM. TO DATE PLANNED e.	SUBSEQUENT MONTH a.	BALANCE OF FISCAL YEAR b.	BALANCE OF CONTRACT c.	
Task IV Performance Evaluation Engineering Labor	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	4.2 / 184	0 / 0	4.2 / 184
Task IV Performance Evaluation Test Labor	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	18.2 / 1276	0 / 0	18.2 / 1276
Task IV Performance Evaluation Other Costs	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	6.5 / 56	0 / 0	6.5 / 56
Task IV Total Expenditures	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	28.9 / 1516	0 / 0	28.9 / 1516
Task V Data Analysis & Reporting Engineering Labor	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	8.3 / 368	0 / 0	8.3 / 368
Task V Data Analysis & Reporting Other Costs	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	4.5 / 192	0 / 0	4.5 / 192
Task V Total Expenditures	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	12.8 / 560	0 / 0	12.8 / 560
Subtotal	3.6 / 197	12.4 / 714	28.6 / 770	16.0 / 911	38.3 / 1250	41.6 / 887	89.8 / 4801	0 / 0	147.4 / 6599
Fixed Fee	.3	.9	2.0	1.1	2.6	2.9	6.2	0	10.2
Unfilled Orders	0	0	0	0	0	0	0	0	0
Reserves	0	0	0	0	0	0	0	0	0
Total Contract Requirements	3.9 / 197	13.3 / 714	30.6 / 770	17.1 / 911	40.9 / 1250	44,5 / 887	96.0 / 4801	0 / 0	157.6 / 6599

PLAN IDENT. ☐ UPDATED PLAN TO (Date) ______ ☐ PRIOR SUBMISSION, NASA FORM 533b (Date) ______ ☐ NONE

** The actuals will be reported on the next month's report.*

NASA FORM 533b FEB 67