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SACRAMENTO PLANT

REPORT NO. RN-64010

TO

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

EXPERIMENTAL AND ANALYTICAL STUDIES OF NUCLEAR EXHAUST SYSTEMS

CONTRACT SNP-1 AUGUST 1964 NERVA PROGRAM

AEROJET
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AEROJET-GENERAL CORPORATION

SACRAMENTO, CALIFORNIA

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(48)

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AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

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I. INTRODUCTION

A. SECONDARY EJECTOR

Scale model testing and analysis of ejector systems undertaken concurrently with the development of a diffuser system for ETS-1 have yielded information about specific systems only. Whereas this information is valuable, it is limited in extent. It has been determined, for example, that the operation of a diffuser-ejector system is directly affected by some function of the velocity of the fluid exiting from the diffuser and the velocity and mass flow of the fluid coming from the ejector nozzles. Currently, only a relationship that is proportional to velocity has been investigated. No individual effects of velocity or mass variation by changes in molecular weight, geometry, temperature, or chamber pressure have been obtained, nor have actual velocity measurements or degree of mixing of the two fluids in the regions of interest been taken. However, the data have indicated that these parameters have a significant effect.

Currently, Drs. Jerry Grey and J. P. Layton are undertaking a study to help define the pumping phenomenon. This study is based on the mixing of coaxial streams and will develop a series of equations for prediction of ejector performance. Specifically, when completed the operational performance of a proposed ejector system can be determined over a wide range of variables. The equations and computer program will be completed by the end of NERVA Contract Year 1964. The program described herein will provide not only data for the checkout of the analysis but will indicate any modifications necessary in the analysis when describing real systems.

Diffuser-ejector performance is affected by slight changes in the system. Therefore it is necessary that all parameters be systematically investigated and their effects analyzed. This is necessary in any system but more so in nuclear systems. In nuclear systems, the "cut and try" or "fire and repair" methods cannot be used because of the inaccessability of the diffuser-ejector after a firing.

B. PRIMARY EJECTOR

As engines grow in size, and nozzle area ratios increase, the diameter of the diffuser system must be similarly increased. One governing parameter in diffuser operation is the length-to-diameter ratio. As the diameter is increased, the length must also be increased. Prohibitive test stand heights are soon required.

One method whereby test stand heights can be maintained at a reasonable value is by the use of a centerbody in the diffuser to accomplish the shocking process in a shorter overall length. A preliminary investigation at this time will yield much valuable information as to heat transfer to the centerbody, centerbody geometry and the feasibility of using centerbodies in nuclear systems.

This preliminary study will lay the ground work for sizing future test stands, and determining diffuser-ejector configurations required for testing future flight versions of the NERVA engine. A minimum amount of work and time will then be required to size the test stands and to design the diffuser-ejector systems that will be required in the near future.

By uprating the NERVA, either in nozzle area ratio, power level or both, the NES currently planned for ETS-1 will not be satisfactory. It is generally recognized that test stands are the pacing items in an engine development program and are usually the source of program delay.

It is also recognized that there is a possibility that the design demonstration tests for NES at ETS-1 could result in the necessity of a few scale model tests and analyses. These scale tests can be performed, quickly analyzed and corrective action determined only if the scale test facility and personnel are maintained. It would therefore be more economical in time and money if the above two programs were initiated in Contract Year 1965. (See proposed milestones on page 4.)

C. PROGRAM

To determine the exhaust system's design considerations for future test stands the following program steps are proposed.

1. Conduct generalized analytical and experimental secondary ejector investigations to determine the significant design parameters.

2. Investigate the feasibility of cooling centerbody ejectors.

3. Investigate the effects of flow leakage on primary ejector performance.

SECTION II

TECHNICAL DISCUSSION OF SECONDARY EJECTOR SYSTEM

II. TECHNICAL DISCUSSION OF SECONDARY EJECTOR SYSTEM

It has been found in previous test programs 1,2,3 that when an injector system is used in conjunction with a diffuser system, shown in Figure 1, that the operation and performance of the diffuser-ejector system is a function of the velocity of the diffuser and ejector fluids and the mass flow of the diffuser and ejector fluids, or:

$$\text{Performance} = f\,(V_P,\ V_S,\ \dot{w}_P,\ \dot{w}_S,\ L/D)$$

Mass and velocity are the parameters making up the momentum factor but all previous work has been unsuccessful in correlating test data on a purely momentum basis. The most successful attempt to date[2] has been with the use of the Ω *factor. Ω is however only proportional to velocity and therefore does not show the effects of specific methods of velocity variation.

For example in the above equation

$$V_P = f(A_d,\ T_P,\ m_p) \qquad (1)$$

$$V_s = f(A_{sd},\ Ad,\ A*_s,\ Ts,\ ms) \qquad (2)$$

There are two general ways in which the velocity of the primary and secondary streams can be varied; first, by changing the properties of the fluids (temperature and molecular weight), and, second, by geometric changes (areas and area ratio). These are described in detail in Tables I and II and Figure 2. It is desirable to find the effects of both methods of velocity variation. It is also desirable to keep constant as many parameters as possible while varying and finding the effects of one parameter. When changing the velocity of the fluids by geometric changes, many side

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1.) Analytical and experimental evaluation of Ejectors with 90° turn for use in Engine Test Stand No. 1. Aerojet Report #2403 Nov. 1962

2.) Experimental Evaluation of Secondary Pumping Systems for ETS-2 Aerojet Report #2680 Dec. 1963

3.) Performance Characteristics of ETS-1 Altitude Nuclear Exhaust System Aerojet Report RN-S-0101. June 1964

* $$\Omega = \frac{(T/m)_p^{1/2}}{(T/m)_s^{1/2}}$$

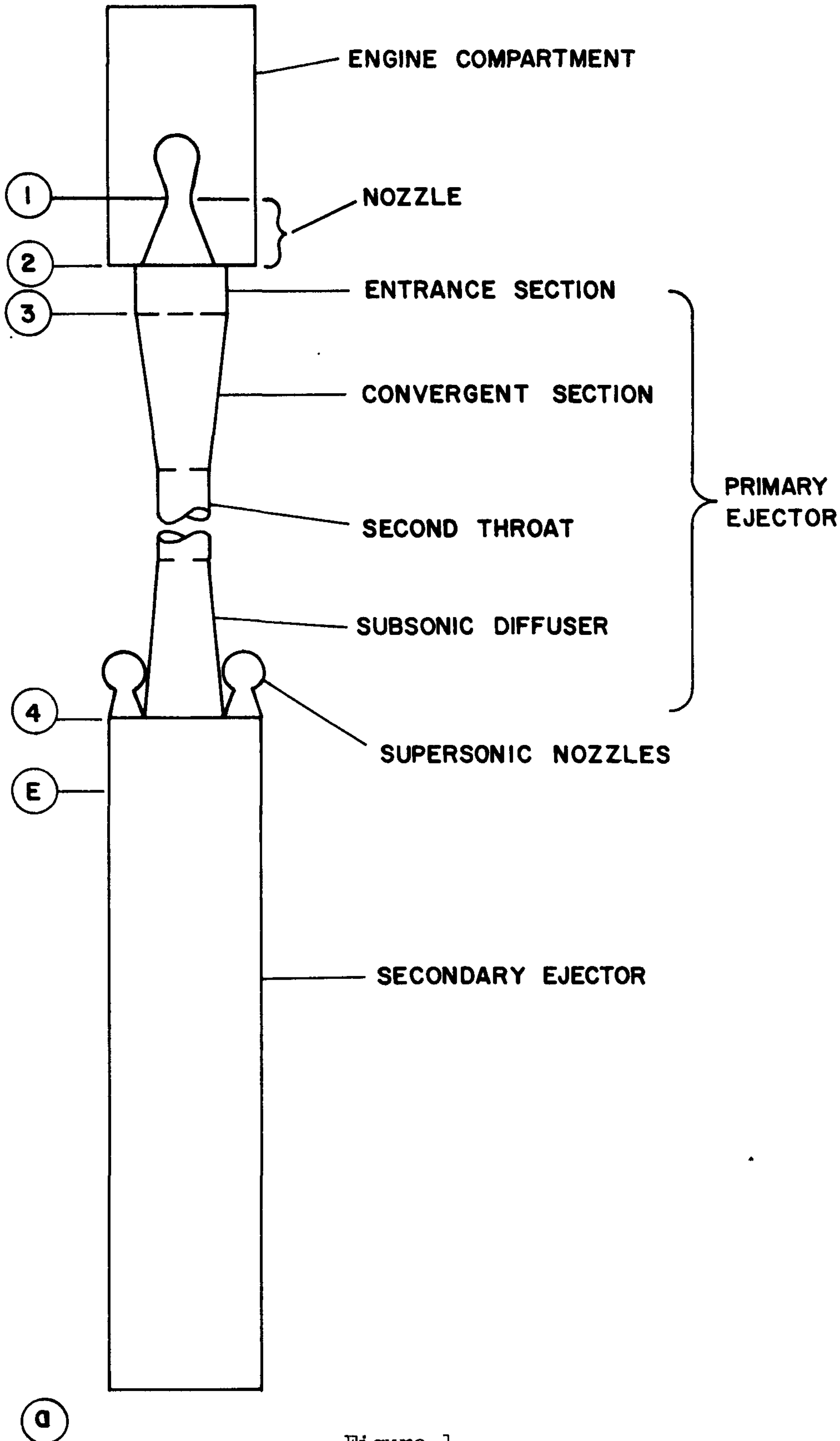


Figure 1

Typical Diffuser Ejector System

VARIATION OF PRIMARY FLUID VELOCITY

TABLE I

Methods	Results
I. VARY A_D	
A. Increase A_D	1. The primary velocity and Mach number are decreased.
	2. The static pressure at the primary duct exit is decreased.
	3. A flow restriction or aerodynamic blockage between primary and secondary fluid will occur once a certain upper limit has been reached.
	4. Secondary nozzle exit area is decreased thereby increasing the secondary nozzle exit pressure which in turn will decrease the secondary velocity and momentum.
	5. The primary starting pressure is decreased.
B. Decrease A_D	1. The primary velocity and Mach number are increased.
	2. The static pressure at the primary duct exit is increased which may cause separation in the S.E. nozzle.
	3. Higher values of primary starting pressure will result and the primary ejector will not start once a certain lower limit of A_D has been reached.

VARIATION OF PRIMARY FLUID VELOCITY (cont.)

TABLE I

Methods	Results
I, B, (cont.)	4. Secondary nozzle exit area is increased thereby decreasing the secondary nozzle exit pressure which increases the secondary velocity and momentum.
II. VARY A_D, A_{SD} KEEPING $A_{SE}/A^* = C$ & $A_{SD}/AD = C$	
A. Increase A_D and A_{SD}	1. The velocity and Mach number at the primary exit are decreased.
	2. By increasing A_{SD} a larger secondary flow will be required to start the secondary ejector system. Therefore, if $A_{SE}/A^* = C$ the secondary velocity will remain the same but the momentum will increase because of the increase in the secondary fluid mass flow.
	3. The primary starting pressure is decreased.
B. Decrease A_D & A_{SD}	1. The velocity and Mach number at the primary exit are increased.
	2. By decreasing A_{SD} a smaller secondary flow will be required to start the secondary ejector system. Therefore, if $A_{SE}/A^* = C$ the secondary velocity will remain the same but the momentum will decrease because of the decrease in the secondary fluid mass flow.

VARIATION OF PRIMARY FLUID VELOCITY (cont.)

TABLE I

Methods	Results
II, B, (cont.)	3. The primary starting pressure is increased.
III. VARY T_p	
A. Increase T_p	1. The mach number at the primary exit will remain constant but the velocity will increase.
B. Decrease T_p	1. The Mach number at the primary exit will remain constant but the velocity will decrease.
IV. VARY m_p	
A. Increase m_p	1. The Mach number at the primary exit will remain constant but the velocity will decrease.
B. Decrease m_p	1. The Mach number at the primary exit will remain constant but the velocity will increase.

VARIATION OF SECONDARY FLUID VELOCITY

TABLE II

Methods	Results
I. VARY A_{SD}	
A. Increase A_{SD}	1. Secondary nozzle area ratio will increase which will lower the pressure at the secondary nozzle exit. Lowering the secondary nozzle exit pressure will increase the secondary velocity and momentum.
	2. Flow separation could be induced in the secondary nozzle.
	3. A larger secondary flow rate would be required to start the secondary ejector system.
B. Decrease A_{SD}	1. Secondary nozzle area ratio will decrease which will increase the pressure at the secondary nozzle exit. Increasing the secondary nozzle exit pressure will decrease the secondary velocity and momentum.
	2. A flow restriction or aerodynamic blockage will occur once a certain lower limit has been reached.
	3. A smaller secondary flow rate will be required to start the secondary ejector system.

VARIATION OF SECONDARY FLUID VELOCITY (cont.)

TABLE II

Methods		Results
II. VARY A_D		
A. Increase A_D	1.	Secondary nozzle exit area is decreased thereby increasing the secondary nozzle exit pressure which in turn will decrease the secondary velocity and momentum.
	2.	A flow restriction or aerodynamic blockage will occur once a certain upper limit has been reached.
	3.	The primary velocity and Mach number are decreased.
	4.	The static pressure at the primary duct exit is decreased.
	5.	The primary starting pressure is decreased.
B. Decrease A_D	1.	Secondary nozzle exit area is increased thereby decreasing the secondary nozzle exit pressure which will increase the secondary velocity and momentum.
	2.	The primary velocity and Mach number are increased.
	3.	Higher values of primary starting pressure will result and the primary ejector will not start once a certain lower limit of A_D has been reached.

VARIATION OF SECONDARY FLUID VELOCITY (cont.)

TABLE II

Methods	Results
II, B, (cont.)	4. The static pressure at the primary duct exit is increased which may cause separation in the S. E. nozzle.
III. VARY A*	
A. Increase A*	1. A lower P_{sc} will be required to achieve a S.E. start condition. $\dot{W}_s$ remains constant.
	2. The secondary nozzle area ratio will decrease which will decrease the exit velocity and hence the momentum of the secondary fluid.
B. Decrease A*	1. A higher P_{sc} will be required to achieve a S.E. start condition. $\dot{W}_s$ remains constant.
	2. The secondary nozzle area ratio will increase which will increase the exit velocity and hence momentum of the secondary fluid.
IV. VARY T_s	
A. Increase T_s	1. The Mach number at the secondary duct exit will remain unchanged. The velocity will be increased and the flow rate will decrease.
B. Decrease T_s	1. The Mach number at the secondary duct exit will remain unchanged. The velocity will be decreased and the flow rate will increase.

VARIATION OF SECONDARY FLUID VELOCITY (cont.)

TABLE II

Methods	Results
V. VARY m_s	
A. Increase m_s	1. The Mach number at the secondary duct exit will remain unchanged. The velocity will be decreased and the flow rate will increase.
B. Decrease m_s	1. The Mach number at the secondary duct exit will remain unchanged. The velocity will be increased.

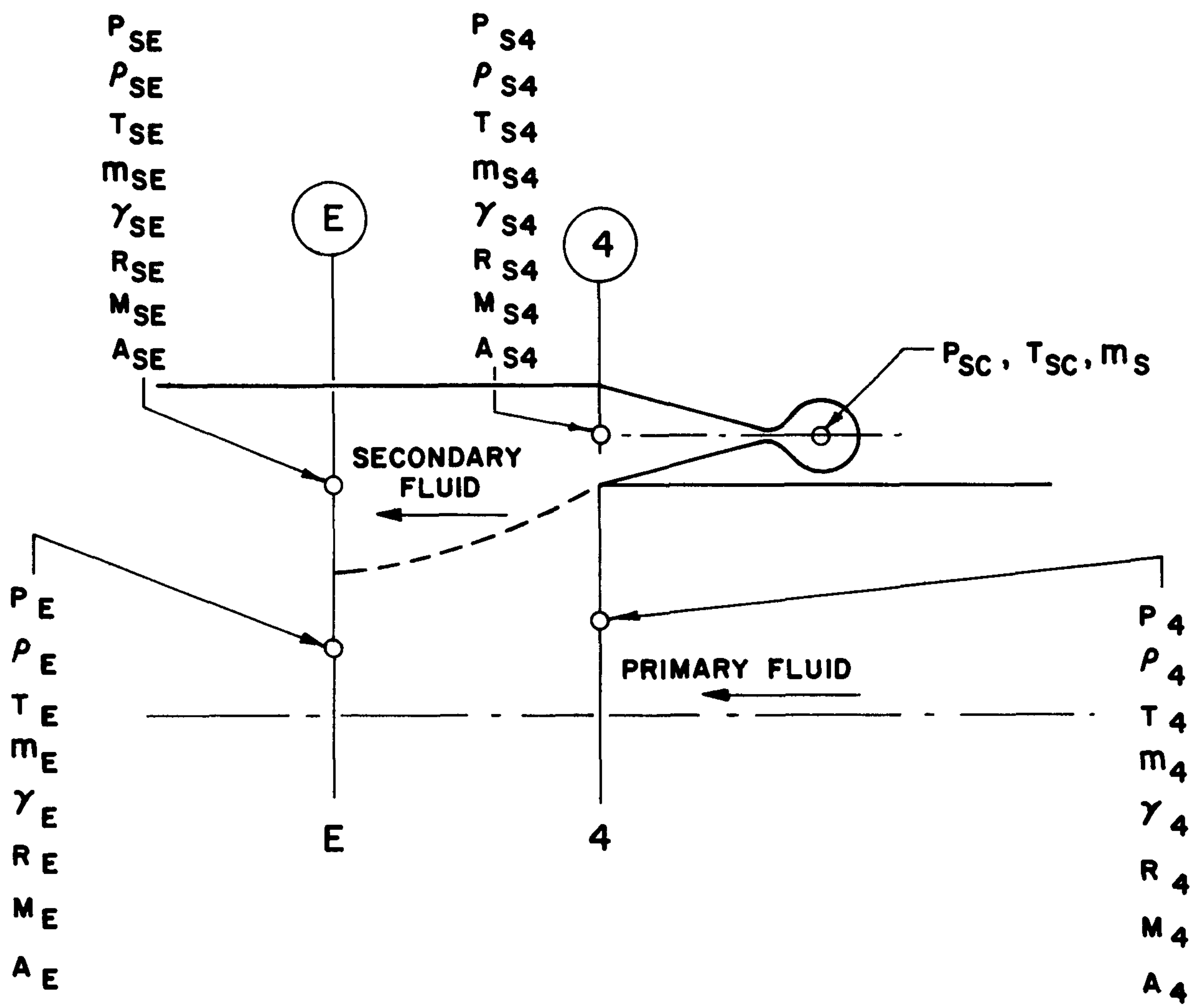


Figure 2

Analysis Flow Parameters

effects, not readily apparent, influence the behavior of the ejector system. These side effects, unless recognized and allowed for, could lead to erroneous conclusions. For instance, the early data indicated that only low molecular weight gases would pump. However, recent data indicate that under some conditions steam may be used as the pumping gas.

It has been shown in REON Report 2680 that the secondary ejector chamber pressure for a fixed system, plays an important role in the pumping ability of the ejector system. Figure 3 shows the effect of various values of Ω on the optimum secondary ejector chamber pressure.

The reason that the secondary ejector chamber pressure must be increased to provide optimum pumping as Ω is increased is not known at this time but is important from both the design and analysis viewpoint.

Two possible reasons for this necessary increase in secondary ejector chamber pressure are:

A. To provide additional momentum by increasing the mass of the secondary fluid.

B. To prevent flow separation which will increase the velocity in the secondary nozzle.

Expanding on the above explanations:

With regard to reason "A", test results have shown that as Ω is increased, for a given system, the primary engine chamber pressure required to start the ejector increases. As a result of this increase in primary engine pressure, the velocity of the primary fluid when it contacts the secondary fluid, is greater than for a lower value of Ω . In order that the secondary fluid be able efficiently to pump out this

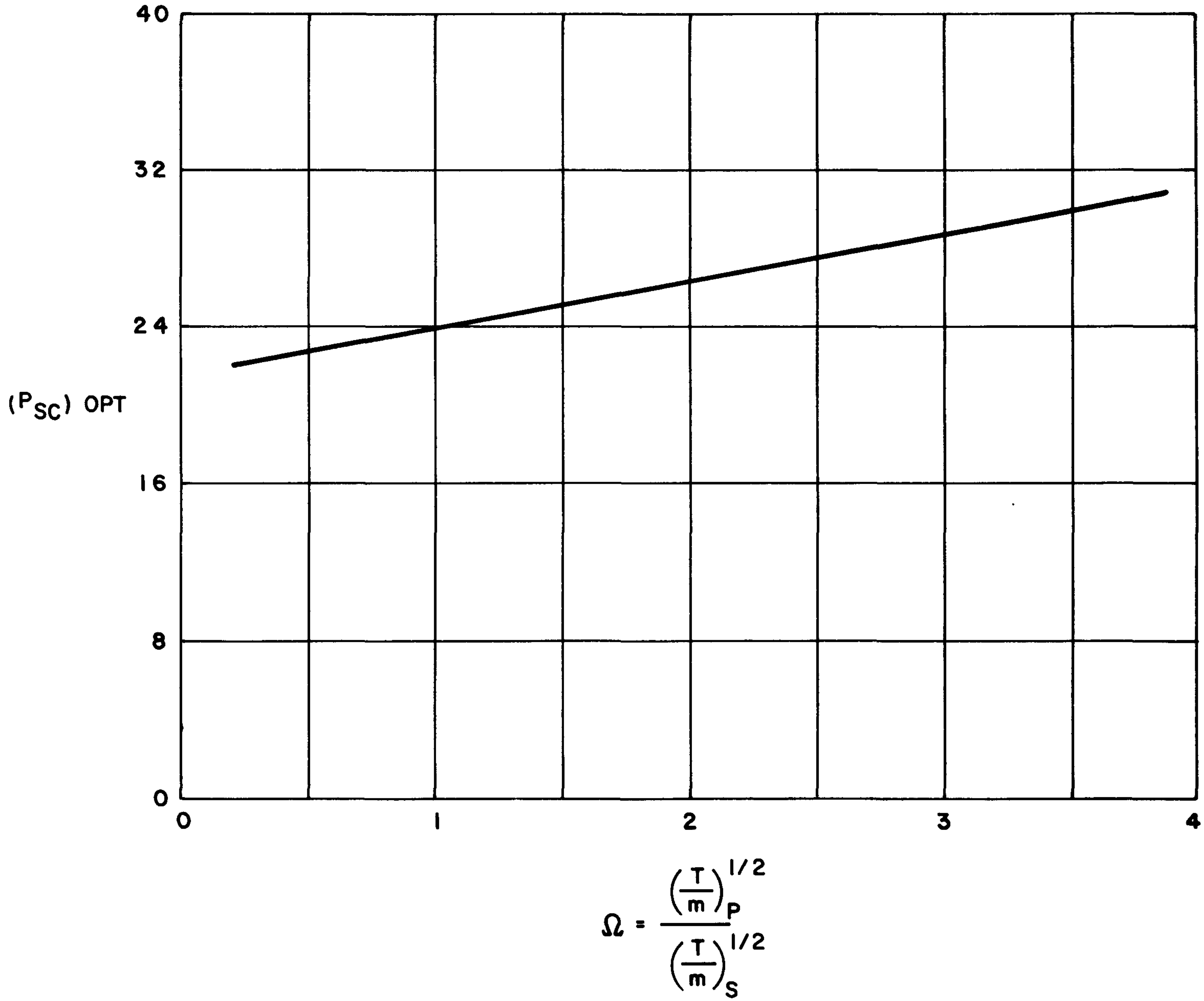


Figure 3

Optimum Ejector Chamber Pressure
As a Function of Ω

primary fluid of increased velocity, the secondary fluid must have additional momentum. Hence, for the fixed system, the momentum of the secondary fluid can be increased by increasing the chamber pressure in the secondary nozzle.

With regard to reason "B", if it is assumed that for a given system, the secondary fluid will supply sufficient momentum to accelerate the primary fluid and cause a start condition no matter what the value of Ω , another interesting possibility arises to explain the need of increased secondary chamber pressure. As pointed out above, when Ω is increased, the primary chamber pressure required to start is increased. At the chamber pressure where a start condition is reached, the pressure ratio (primary engine/primary duct exit) is a constant value, dependent only on primary ejector geometry. As Ω is increased, the chamber pressure to start is increased and therefore the pressure at the primary duct exit is increased. If this primary duct exit pressure is sufficiently large it will induce flow separation in the secondary nozzle. Once flow separation occurs, the pumping ability of the secondary fluid is decreased. One way to overcome this flow separation is to increase the secondary ejector chamber pressure.

Which of these two models more closely simulates the actual case is not known at this time, but it is imperative that the actual case be determined. For example, if an ejector system was designed to operate with a secondary ejector chamber pressure of 200 psi at an Ω of 1 and it was found that to use steam as an efficient pumping fluid, a secondary chamber pressure of 600 psi was required, this would mean an increased flow rate requirement of 3 times that originally planned. If, however, flow separation in the secondary nozzle is the governing factor, then the secondary nozzles can be properly designed and expanded at a minimum so that flow separation could be eliminated and the secondary chamber pressure held to a minimum. However, the relationship between primary velocity and secondary velocity required to obtain the lowest value of starting primary chamber pressure is, at this time, also unknown. Therefore, the lower limit, as far as the expansion of the secondary nozzles is concerned, cannot yet be determined.

The third problem area is the determination of the actual model configuration used for the analysis. Figure 2 shows the model based on current thinking (and is the basis of Aerojet's pumping analysis). This model assumes no mixing of the primary and secondary fluids until Station (E) is reached. A more rigorous mathematical analysis assumes a model in which mixing occurs starting at some arbitrary plane downstream of Station (4) . The degree of mixing at various sections of the secondary duct plays an important part in the analysis. Drs. Grey's and Layton's quasi-one dimensional and two-dimensional models will require scale model information as to the effects of mixing length.

Before an analysis can be finally selected, which is a necessity if any scaling is to be done with the results of this program, the correct model must be first determined.

In summary, there are four general areas in which further testing and analysis must be conducted to obtain a more thorough understanding of pumping characteristics. These areas are:

1. To determine if the necessary increase in secondary ejector chamber pressure with increasing Ω for optimum pumping is the result of insufficient secondary fluid momentum or flow separation in the secondary nozzles.

2. To determine the actual configuration of the model used for analysis purposes.

3. To determine the actual relationship between pumping efficiency and velocity ratio of primary and secondary fluids.

4. To determine the effect of ejector length-to-diameter ratio on the efficiency of the mixing process.

III. TECHNICAL DISCUSSION OF CENTERBODY DIFFUSERS

A. INTRODUCTION AND OBJECTIVES

Analytical and experimental studies of conventional diffusers and ejectors have been in good agreement and have actually provided the solution of altitude simulation for small as well as large nozzles. However, it is questionable whether the most sophisticated design tested could provide a solution for a thrust 5 times that of NERVA within reasonable economics and fabrication knowledge. This point can be best illustrated by Figure 4 showing comparative sizes of the present ETS-1 ejector system and the one of similar geometry capable of testing an engine with a thrust five times that of the NERVA rocket. As the figure shows, the required size for such a capability requires a very expensive excavation indicated by the cost trend shown in Figure 5.

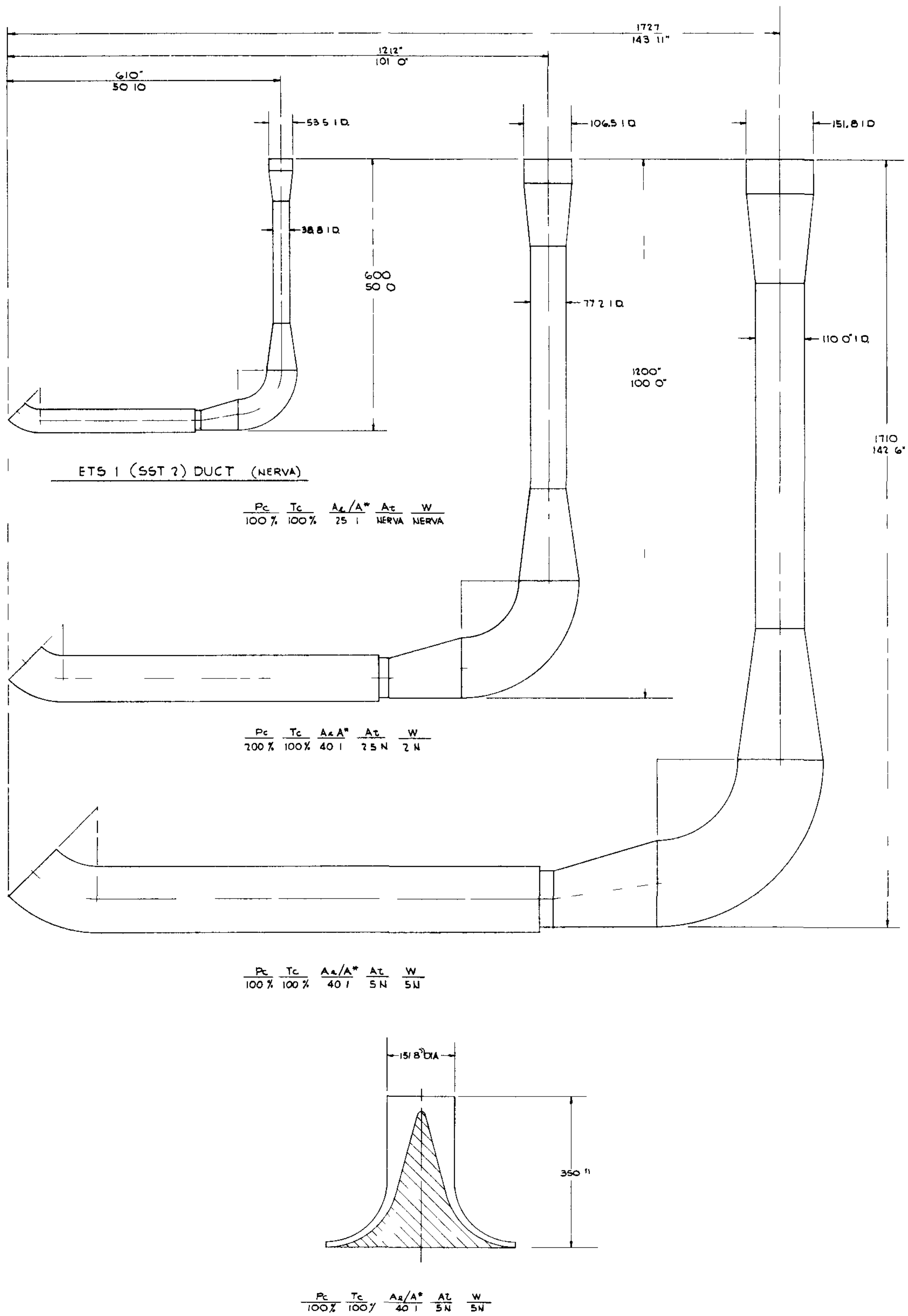


Figure 4

Comparison of Ejectors for 5X Nerva

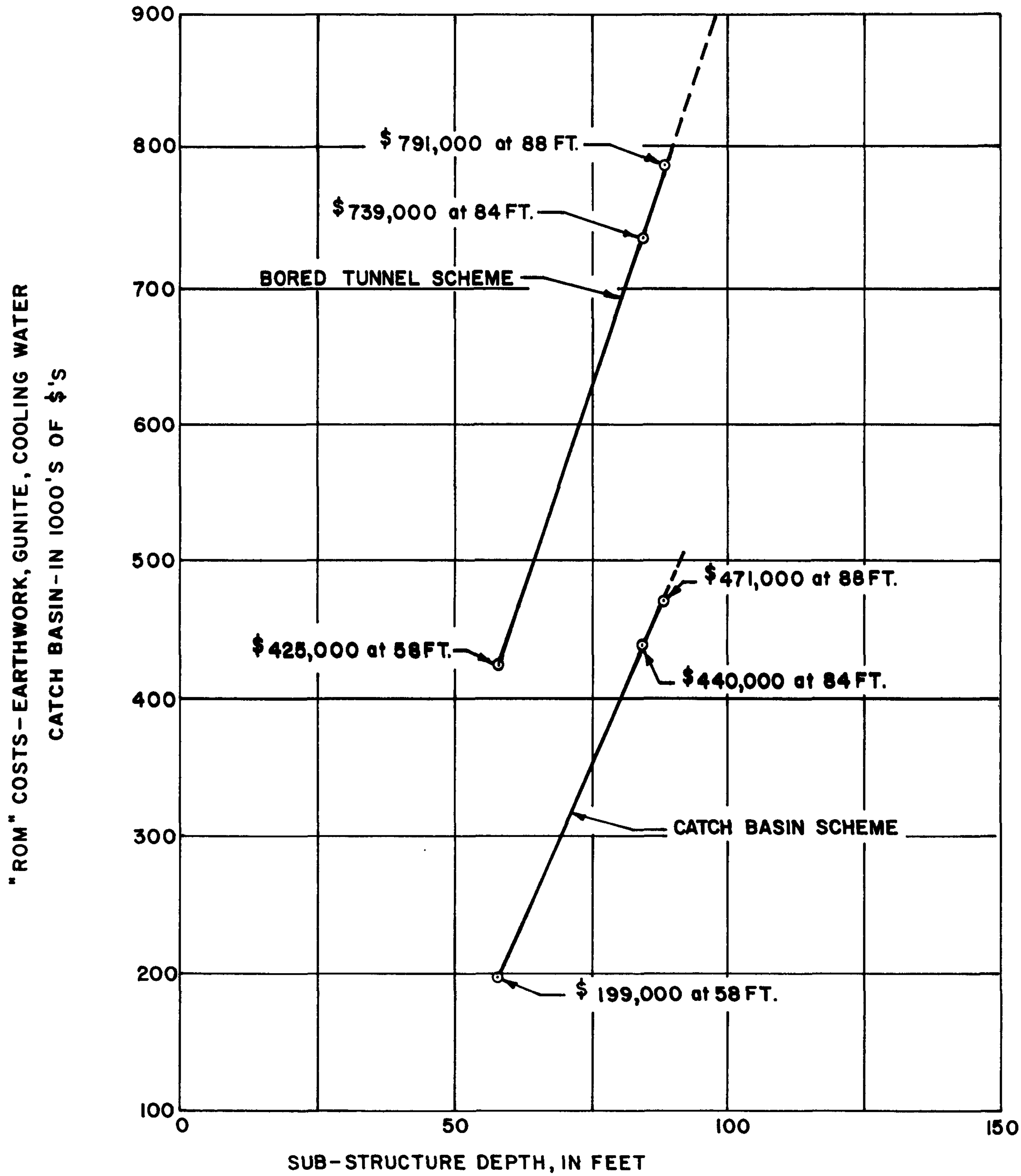


Figure 5
ROM Estimate Depth vs Costs
(From ETS-2 Studies)

B. SEARCH FOR ALTERNATE CONFIGURATIONS

For the study of conventional ejectors of the type mentioned, one of the basic parameters for favorable starting conditions is the ratio of ejector length to its diameter. It could be argued that a large L/D ratio could be reduced, for example, by taking advantage of the hysteresis characteristic, i.e. by over-pressurizing the chamber until a shock pattern is established and consequently reducing P_c until the low pressure limit of the hysteresis loop is obtained. However, it appears as though reduction of the duct length thus acquired would only be of minor proportions. A more drastic way seems mandatory and the most promising concept to date may be that of a center body diffuser, such as has been used on some chemical engine test stands. Feasibility studies of such a diffuser type should be initiated to determine if center-body diffusers are practical for a nuclear exhaust system. Basically, the program will consist of:

1. Heat transfer and aerodynamic analysis of a limited number of configurations.

2. Test the most promising systems.

3. Correlate test results with analysis and present conclusions.

The different systems to be tested will call for a subscale model test program with scale-up possibility to prove feasibility of eventual full-scale construction in conformity with the stringent requirements imposed upon nuclear exhaust systems and outlined in greater detail under "Problem Areas", below.

Possible configurations under consideration are:

1. Blunt nose spikes of simple conical shapes.

2. Blunt nose spikes of multiple conical shapes with increasing half angles.

C. PROBLEM AREAS

The major problem areas can be stated briefly in descending order of importance as:

1. Disposal of extremely high heating rates and adequate cooling methods.

2. Aerodynamic performance as a function of hardware shape and dimensions.

3. Vibration problems introduced by center-body position and possible supports within the main gas stream.

The solution to the last problem, although important, is considered less difficult than those regarding adequate cooling and minimum pressure ratio requirements for stable flow. It is therefore of essence to tailor any sub-scale test program with due regard to those two problems.

D. PROPOSED PROGRAM

For reasons of economics, it is suggested that the program shall be carried out in two parts: a preliminary and a final phase.

The preliminary study shall serve the following purposes:

1. Present a clear-cut definition of the major problems.

2. Determine a limited number of possible solutions and perform preliminary calculations to determine chances of feasibility.

3. Select system prototypes for additional study and testing.

The second part of the program will include a theoretical analysis with detailed calculations, and a subscale test plan with subsequent evaluation of the test results. By subdividing the task it seems possible to direct the major portion of costs and engineering efforts toward the final studies, thus increasing the chances of successful accomplishment.

E. AERODYNAMIC PERFORMANCE

A preliminary aerodynamic analysis shall culminate in a good evaluation of thermodynamic and aerodynamic effects caused by variation of the general geometry or its major components i.e. center body and outer wall. It is therefore necessary to outline some of the major variations which ultimately may facilitate optimization of the final design.

1. Spike Nose Curvature

The proper size (or radius) of the spike nose has a tremendous effect on both, stagnation point heating rate and flow pattern.

Best aerodynamic performance is obtained with a sharp pointed spike or extremely small nose curvature. Such a tip is practicably infeasible, because the high heating rates could not be absorbed by conventional cooling methods. It is necessary to obtain, by analytical methods, a reliable measure of the decrease in performance versus increase of curvature and delineate a region of optimization when allowable heating rates are taken into consideration. Preliminary calculations of this type are described in the Appendix and presented as a curve to indicate trends in Figure 6. From this preliminary analysis it appears that there is sufficient latitude between overheating and performance loss to develop a satisfactory system.

2. Spike Angle Variation and Cylindrical Shell Length

Once the degree of nose curvature has been explored, the next feature of interest is the spike angle. The upper part the spike, i.e. a certain length from the tip will be surrounded by cylindrical outer walls before shell divergence starts. This length, in combination with the initial spike angle, is an important parameter in performance evaluation. The spike angle will determine, how soon a second-throat effect is reached, and also what shock system is obtained. Theoretically a design to yield a one-shock system, possibly obtainable for a certain angle,

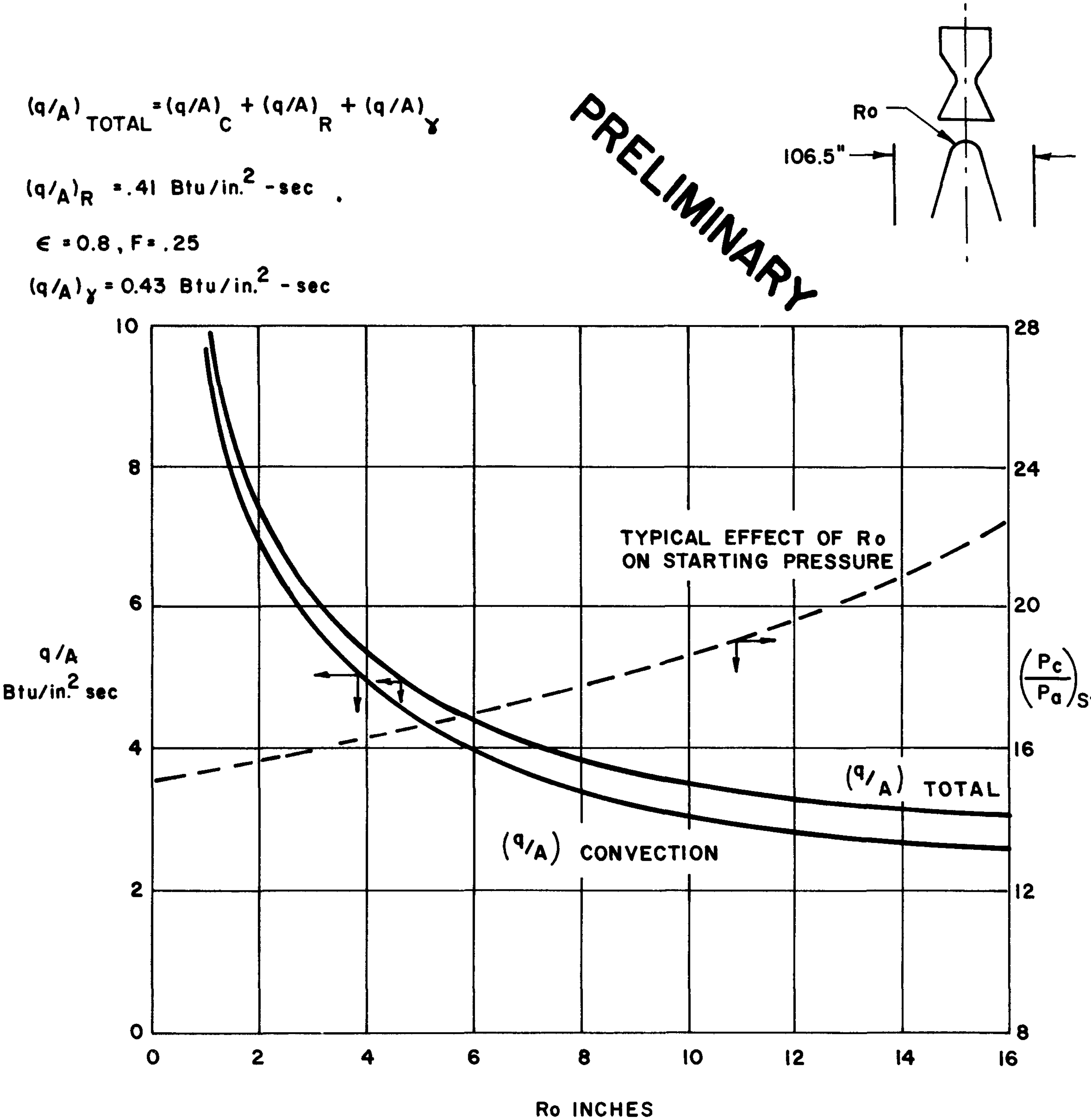


Figure 6

Estimated Heating Rates to Centerbody in 5X NERVA Ejector would have the advantage of simplicity, low cost and easy start. Disadvantages would be higher heating and less pressure recovery, consequently a less efficient system. A multiple shock system is probably more desirable. Such a system can be created by appropriate choice of initial spike angle with eventual angle change. From work done by NASA, it has been shown that the strength of the shock system and the resulting heating rates beyond the tip are proportional to the spike angle.

3. Two or Multiple Step Spikes

Performance improvement can be obtained by creating a system of multiple shocks with the spike to improve pressure recovery. One or more changes in spike divergence will increase the chances of obtaining such a system. Similar results may also be realized by the proper combination of spike angle and shell divergence will increase the chances of obtaining such a system. Similar results may also be realized by the proper combination of spike angle and shell divergence angle. An investigation by Church and Jones[4] showed that lower starting and operating pressure ratios can be arrived at by such a combination giving approximately constant flow area.

4.) Church, B. E., Jones, W. L. and Quentmeyer, R. J. Performance Evaluation of Fixed and Variable - Area Rocket Exhaust Diffusers Using Single and Clustered Nozzles with and without Gimbaling, NASA TN D-1306, July 1962.

F. PRELIMINARY EVALUATION OF HEATING RATES

1. Center Body Tip

Whatever the shape or size of the spike tip wall, the first and main problem consists in accurately analyzing the heat flow rates at the stagnation point and the immediate regions on both sides of the stagnation point, which are also subject to conductive heat flux from the tip. The stagnation point will be subjected to the high heating rates caused by the impact of hydrogen gas at supersonic speed with a high recovery temperature. Fortunately, a rather large number of studies have been performed in recent years to evaluate conditions of this nature to mention only stagnation point heat transfer analyses by J. A. Fay, F. R. Riddell, Lester Lees, N. H. Kemp, H. F. Romig, P. H. Rose and others. From preliminary estimates the convective heating rates from a properly designed spike could be 3 to 4 Btu/sec-in^2, but could be as high as 5 to 8 Btu/sec-in^2. Thermal and nuclear radiation heat may add a significant percentage to these rates and this calls for a careful evaluation of the overall heat flux. Preliminary calculations are shown in the Appendix.

2. Main Spike Body

Depending upon the location, the gas flow along the center body may be laminar or turbulent, subsonic or supersonic and consequently the heating rates may present substantial variations. In addition these rates will cause high local temperature peaks at all points where major and reflected shock waves hit the surface. Even though peak heating rates may be analyzed, it is assumed that during the transient flow period, the shock system will not be stationary, which makes it practically impossible to pinpoint local hot spots (other than the centerbody tip). However, a careful analysis should be made to determine at least the regions where high heating rates are most likely to be encountered.

3. Ejector Outer Shell

More or less the same comments for the spike body apply to the outer shell walls, although the cooling problem seems much less complicated. Some of the heat can be dissipated by convection or radiation cooling and the whole area is easily accessible for effective water cooling devices.

4. Center Body Supports

The supports are connecting links between various parts of the diffuser and in particular between the outer shell and the center body. Heat transfer will occur by conduction, convection and radiation. However, as these parts are exposed to the gas stream, the major heat flux will be by convection. As these parts may have elliptic shape, they can be analyzed in a fashion similar to that of leading edges of an aircraft wing.

G. COOLING METHODS

After all heat sources have been thoroughly computed, it is necessary to determine the most expedient heat disposal methods for the individual parts. It is evident that the spike tip is the most difficult to cool because it receives the highest heat flux and at the same time is the least accessible. This illustrates that each portion has to be considered separately.

A survey of cooling means will be performed and may include convective water cooling, cryogenic cooling and transpiration cooling.

H. SELECTION OF MOST PRACTICAL COOLING METHODS

The preliminary studies should be carried sufficiently to facilitate a firm decision as to what cooling devices shall be rejected or accepted for a particular section of the diffuser. Advantages and disadvantages have to be evaluated on the basis of operating safety, reliability, redundancy, hardware availability and cost.

SECTION IV

DIFFUSERS

WORK STATEMENT & MILESTONES

IV. DIFFUSERS - WORK STATEMENT & MILESTONES

A. SECONDARY EJECTOR SYSTEM

1. Engineering

a. Provide the engineering effort to plan, conduct and analyze data from scale model tests to define the influence of various flow and geometric parameters on the pumping ability of secondary ejectors.

b. Provide the engineering effort to define, verify and uprate, as scale model test data become available, a quasi one-dimensional and two-dimensional analysis of the mixing process in the secondary ejector.

2. Fabrication

Fabricate scale model hardware as required to support the scale model program.

3. Testing

Conduct scale model tests required to provide parametric data essential for definition of the influence of various flow and geometric parameters on the pumping ability of secondary ejectors.

4. Tooling - Not applicable

B. CENTERBODY DIFFUSERS

1. Engineering

a. Provide the engineering effort to perform analytical studies of heating rate to the centerbody tip and determine practical cooling methods.

b. Provide the engineering effort to plan, conduct and analyze data from scale model tests to determine feasibility of centerbody ejectors.

2. Fabrication

Fabricate scale model hardware as required to support the scale model program.

3. Testing

Conduct scale model tests required to determine heating rates in critical regions and the aerodynamic performance of a selected centerbody configuration.

4. Tooling - Not applicable

NERVA PROGRAM

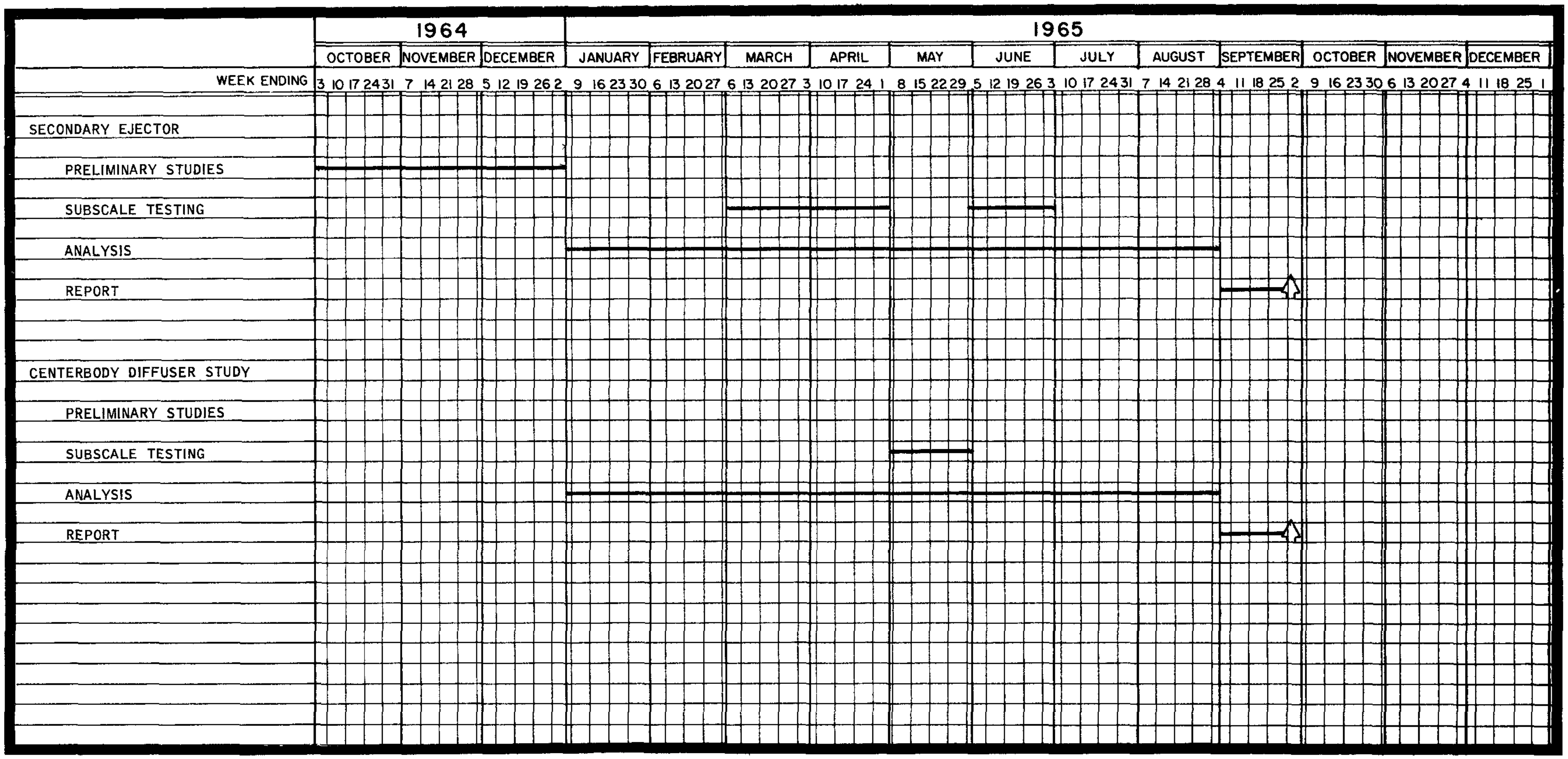
SCHEDULES AND MILESTONES

CONTRACT YEAR 1965

TASK ITEM

EXPERIMENTAL AND ANALYTICAL STUDIES OF DIFFUSER SYSTEM AUGMENTATION AND CENTER BODY DIFFUSERS

REPORT NO. RN-64010



⇧ SCHEDULED MILESTONE ◇ RESCHEDULED MILESTONE

⬆ MILESTONE ACHIEVEMENT ◆ RESCHEDULED MILESTONE ACHIEVEMENT

REON

SECTION V

APPENDIXES

APPENDIX

I. HEAT TRANSFER TO CENTER BODY NOSE

A. CONTRIBUTION FROM CONVECTIVE HEAT TRANSFER AT THE STAGNATION POINT

1. Method by LESTER LEES (ARS-Journal, April 1956, page 259)

The heating rates to the wall at the stagnation point are computed from equation (13) page 264.

$$\left(q_w\right)_o \cong \frac{2\,k/2\;\bar{P}^{\,2/3}\;G\quad H}{2\;R_o^{\,1/2}}\left[\mu_\infty\left(\rho_e\mu_e\right)_o\right]^{1/2}$$

for a body of revolution, the constant $k = 1$

$\bar{P}$ is an average Prandtl Number; assumes a value $\bar{P} = 0.68$

$\bar{P}^{\,2/3} = 0.774$

G as a dimensionless flow parameter is given as a function of specific heat ratios and free stream Mach Number by the relation

$$G = \left[\left(\frac{\bar{\gamma}-1}{\bar{\gamma}}\right)\left(1 + \frac{2}{(\gamma_\infty - 1)\,M_\infty^{\,2}}\right)\left(1 - \frac{1}{\gamma_\infty M_\infty^2}\right)\right]^{1/4}$$

as a simplification assume for hydrogen

$\bar{\gamma} = 1.3$ and $\gamma_\infty = 1.38$

$$G = \left[\left(\frac{0.3}{1.3}\right)\left(1 + \frac{2}{0.38x25}\right)\left(1 - \frac{1}{1.38x25}\right)\right]^{1/4} = (0.23x1.21x0.97)^{1/4} = (0.27)^{1/4}$$

$G = 0.721$

The free stream velocity (normal component to spike nose) u_{∞} is computed from

$$u_{\infty} = M_{\infty}\sqrt{\gamma_{\infty} \quad gRT \quad \infty}$$

from Tables (Report 1135) and M_{∞} = 5 the free stream temperature becomes

$$T_{\infty} = 0.1667\ Tc = 0.1667 \times 5000 = 838°R$$

gas constant $\qquad R = 767\ ft/°R$

$$u_{\infty} = 5\sqrt{1.38 \times 32.2 \times 767 \times 838} = 5 \times (28.4)^{1/2} \times 10^3$$

$$u_{\infty} = 26{,}700\ ft/sec\ u_{\infty}^{1/2} = 163.5$$

The enthalpy difference: $\Delta H \cong H_s \quad H_w \cong c_p \ (T_c - T)$

$$\Delta H = (5000 - 1500)\ 3.8 = 13300\ BTU/lb$$

Evaluate density and viscosity at the film temperature: $\left(\rho_e \mu_e\right)_o \approx \rho_f \mu_f$

$$T_f = \frac{5000 + 1500}{2} = 3250°R$$

$$\frac{T}{Tc} = \frac{3250}{5000} = 0.67 \text{ corresponds to } \frac{P}{P_c} \simeq 0.25$$

assuming a chamber pressure of P_c = 800 psia

$$\text{Density: } \rho_f = \frac{144Pc}{4RT} = \frac{144 \times 200}{767 \times 3250} = 1.15 \times 10^{-2}\ lb/ft^3$$

Viscosity: $\rho_f^{1/2} = 0.107$

$$\mu_f \cong 19 \times 10^{-6} \text{ lb/ft sec}$$

$$\mu_f^{1/2} = 4.36 \times 10^{-3}$$

$$(\mu_\infty \mu_f \rho_f)^{1/2} = 163.5 \times 4.36 \times 10^{-3} \times 0.107 = 0.076$$

$$(q_w)_o = \frac{0.707 \times 0.774 \times 0.721 \times 13{,}300 \times 0.076}{R_o^{1/2}}$$

$$(q_w)_o = \frac{400}{R_o^{1/2}} \text{ BTU/sec ft}^2$$

Heating rate versus spike nose radius:

R_o		$(q_w)_o$	Convective heating rate	Thermal Radiation heating rate	Nuclear Heating Rate	total
inch	ft	BTU/ft^2, sec	BTU/in.^{2}, sec	BTU/in.^{2}, sec.	BTU/in.^{2}, sec	BTU/in.^{2}, sec
1	$\frac{1}{12}$	1390	9.65	0.41	.043	10.10
2	$\frac{2}{12}$	985	6.85	0.41	.043	7.30
3	$\frac{3}{12}$	805	5.58	0.41	.043	6.03
4	$\frac{4}{12}$	695	4.82	0.41	.043	5.27
5	$\frac{5}{12}$	620	4.30	0.41	.043	4.75
6	$\frac{6}{12}$	568	3.95	0.41	.043	4.40
12	1	400	2.78		.043	3.23

2. Method by J. A. FAY and F. R. RIDDELL (Journal Aeronaut, Sciences, Feb. 1958 No. 2

The stagnation point heat transfer rate for a Prandtl Number of $P = 0.71$ becomes: (Eq. 63, Pg. 82)

$$(q_W)_o = 0.94 \left(\rho_W \mu_W\right)^{0.1} \left(\rho_s \mu_s\right)^{0.4} \left[1 + \left(L^{0.52} - 1\right) \frac{Ho}{Hs}\right] \left(H_s - H_W\right) \left(\frac{du_e}{dx}\right)_s^{1/2}$$

given and assumed values:

$$P_c = P_s = 800 \text{ psia}$$

$$T_c \cong T_s = 5000°R \qquad T_W = 1500°R$$

$$\Delta H = H_s - H_W = \underline{13300} \text{ BTU/lb}$$

As there is no dissociation, the term $(L^{0.52} - 1) \frac{H_D}{H_s} = 0$

The stagnation point velocity gradient from Eq. 64 is given by:

$$\left(\frac{du_e}{dx}\right)_s = \frac{\left[2g\left(P_s - P_\infty\right)/\rho_s\right]^{1/2}}{R_o}$$

$$\rho_s = \frac{144\ P_s}{R\ T_s} = \frac{144 \times 800}{767 \times 5000} = \underline{0.03} \text{ lbs/ft}^3$$

for $M = 5 \quad P_\infty = 0.00189 \times 800 = 1.5$ psia

$$\left(\frac{du_e}{dx}\right)_s = \frac{1}{R_o} \left[\frac{64.4 \times 798.5}{0.03}\right]^{1/2} = \frac{1310}{R_o}$$

$$\left(\frac{du_e}{dx}\right)^{1/2} = \frac{36.2}{R_o^{1/2}}$$

Density at T_w = 1500°R $\quad \frac{T_w}{T_c} = \frac{1500}{5000} = 0.3$ corresponds to pressure ratio

0.0148 or P = 11.85

$$\rho_W = \frac{144 \times 11.85}{767 \times 1500} = 0.00148 \text{ lbs/ft}^3$$

Viscosity at 1500°R

$$\mu_W = 12 \times 10^{-6} \text{ lb/ft sec}$$

$$\left(\rho_W \mu_W\right)^{0.1} = (12 \times 10^{-6} \times 14.8 \times 10^{-4})^{0.1} = (177.5 \times 10^{-10})^{0.1}$$

$$\left(\rho_W \mu_W\right)^{0.1} = \frac{177.5^{0.1}}{10} = \underline{0.168}$$

Viscosity at 5000°R:

$$\mu_s = 25 \times 10^{-6} \text{ lbs/ft sec}$$

$$\left(S_s \mu_s\right)^{0.4} = (0.03 \times 25 \times 10^{-6})^{0.4} = (0.075 \times 10^{-5})^{0.4}$$

$$\left(S_s \mu_s\right)^{0.4} = 0.075^{0.4} \times 10^{-2} = \frac{0.355}{100} = \underline{0.00355}$$

$$\left(q_W\right)_o = 0.94 \times 0.168 \times 0.00355 \times 13300 \times \frac{36.2}{R_o}^{1/2}$$

$$\left(q_W\right) = \frac{270}{R_o}^{1/2}$$

R_o		Convective Heating Rate	Thermal Radiation Heating Rate	Nuclear Heating Rate	Total
inch	BTU/lb^2, sec.	$BTU/in.^2$ sec	$BTU/in.^2$ sec	$BTU/in.^2$ sec	$BTU/in.^2$ sec
1	935	6.48	0.41	0.043	6.93
2	662	4.59	0.41		5.04
3	540	3.75	0.41		4.20
4	467	3.25	0.41		3.69
5	418	2.90	0.41		3.35
6	382	2.65	0.41	0.043	3.10
12	270	1.88	0.41	0.043	2.32

B. THERMAL RADIATION CONTRIBUTION

$$q_r = F \sigma \Sigma \quad (T_c^{\,4} - T_w^{\,4})$$

$$\Sigma = 0.333 \times 10^{-14}$$

$$g_r = 0.0666 \times 10^{-2} \left(\frac{T_c}{1000} - \frac{T_w}{1000}\right)^4$$

Assume view factor $F \cong .25$

And emissivity $\epsilon = 0.8$

(coated with carbon particles)

$$q_r = 0.0666 \times 10^{-2} (625 - 5) = 0.41 \text{ BTU/in.}^2 \text{ sec}$$

$$g_\gamma = 4.5 \times 10^9 (5) \text{ergs/gm/} \times .77 \times 10^{-11} \frac{\text{BTU/in.}^3 \text{ sec}}{\text{ergs/gm hr}} (.25) \quad .043 \frac{\text{BTU}}{\text{in.}^2 \text{ sec}}$$

for tungsten, 1/4-in. thick

Slivka

AEROJET-GENERAL CORPORATION
P. O. BOX 1947 • SACRAMENTO, CALIFORNIA

RN-64010

SACRAMENTO PLANT

2 September 1964

NERVA Engine Branch 9/14

Slivka	
~~Gerstein~~	
Helms	
Permut	
Scheib	
Siegel	

Space Nuclear Propulsion Office
Cleveland Extension
National Aeronautics and Space Administration
21000 Brookpark Road
Cleveland 35, Ohio

Attention: R. W. Schroeder, Chief

Subject: Proposal RN-64010 for Experimental and Analytical Studies of Nuclear Exhaust Systems

Reference: Verbal request by SNPO-C and SNPO-W Representatives on 29 June 1964

Gentlemen:

In response to your verbal request REON is pleased to submit the subject proposal for your review and consideration.

The information currently available from the Nuclear Exhaust System scale model test program of Contract SNP-1 is not sufficiently complete to define a reasonable extension to the ETS-1 capabilities either in altitude simulation or engine size. The test data has shown that it is feasible to provide altitude simulation with steam pumping. However, this system has not been optimized and the operational map is incomplete.

Investigations toward sizing the exhaust system for larger area ratio NERVA engines, or higher power level engines show that current technology leads to inordinately large ducts. This results in high costs of test stands due to the large duct vault and drainage ditch. Additionally, the fabrication technology requirements for larger ducts are a considerable extension over the requirements for the ETS-1 duct.

As a result of these observations, it is proposed that the scale model program be continued to define the requirements in a timely manner. Also, in the event this program is not continued, there will be no way of immediately checking problems which may occur during the ETS-1 duct fabrication or tests.

It is proposed to perform the work in accordance with the suggested Work Statement, outlined in Enclosure (1) on a Cost-Plus-Fixed-Fee basis of $230,671, which covers the period of October 1964 through September 1965. Cost summaries of the proposed amount are included as Enclosure (2). Additionally, performance under the proposed program is based on the rent-free-use, non-interference basis of the government facilities and equipment outlined in Enclosure (3).

Space Nuclear Propulsion Office
Cleveland Extension
2 September 1964

This proposal is valid for a period of thirty (30) days from the date of this document. If it is not possible to issue contractual authority to proceed within that time period, we request that we be permitted to review the proposal for applicability subsequent to that date.

Very truly yours,

AEROJET-GENERAL CORPORATION

H. E. Pharr
Manager of Contracts
Rocket Engine Operations - Nuclear

ENCLOSURES:

(1) Technical Discussions
(2) Cost Summaries
(3) Schedule of Government Facilities

Copies to:

W. H. Robbins, SNPO-C (2)
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B. J. Abrahams, Navy Audit, Azusa (1)
A. F. Audit, Sacramento (1)

Enclosure (3)
RN 64010
2 September 1964

Rent-Free Use of Government Facilities and Equipment

This program plan is based upon the Rent-Free Use, Non-Interference Basis, of the following government facilities and equipment by Aerojet-General:

ITEM	TITLE	ITEM NUMBER	CONTRACT NUMBER
1)	Carrier Oscillator	S/N 22438	USAF #743-1060
2)	Carrier Oscillator	S/N 356	USAF #15309-83
3)	Carrier Oscillator	S/N 1255	USAF #15309-309
4)	Carrier Oscillator	S/N 4675	USAF #743-1802
5)	Demodulator	S/N 29268	NAVY #91137-002041
6)	Coupling Unit	S/N 1262	USAF #2733-875
7)	Coupling Unit	S/N 5052	USAF #273-2068
8)	Coupling Unit	S/N 5047	USAF #743-1846
9)	L & N	S/N 803797	USAF #743-1829
10)	L & N	S/N 803797	USAF #2733-398
11)	L & N	S/N 58-75030-H	USAF #743-2130
12)	L & N	S/N 803534	USAF #113
13)	M. V. Calibrator	S/N 112	USAF #740-6162
14)	26 Channel Oscill.	S/N 27059	USAF #257-639
15)	Hagan Heater Controller		NASA 032-A1
16)	Hagan Heater Controller		AEC - 172623
17)	Heater (large)		SNP-1A NAS 032
18)	Heater (small)		AEC - 172628
19)	Patch Panel	S/N 16598	USAF #571174
20)	Patch Panel	S/N STM 9411	NAS #144
21)	Patch Panel	S/N STM 9407	NAS #143
22)	36 Channel Magazine	S/N 7038	USAF #743-3019

COST SUMMARY BY TASK

TASK NO.	TASK TITLE		
1.	SECONDARY EJECTOR SYSTEM		
	1a.	Supervision and Analysis	$ 87,037
	1b.	Fabrication of Hardware	3,231
	1c.	Testing, Instrumentation and Data Reduction	41,912
	1d.	Supporting Analysis	25,859
	1e.	Computer	2,440
		TOTAL TASK NO. 1	$160,479
2.	CENTERBODY DIFFUSER STUDY		
	2a.	Supervision and Analysis	52,989
	2b.	Fabrication of Hardware	3,231
	2c.	Testing Instrumentation and Data Reduction	13,972
		TOTAL TASK NO. 2	$ 70,192
	TOTAL - PROGRAM		$230,671

VON KARMAN CENTER

COST BREAKDOWN SUMMARY FOR THE PERIOD
00-020-037 DEC. 1964 THRU SEPT. 1965

DATE	PROPOSAL NO.
2 September 1964	RN 64010

SUMMARY TYPE	PLANT	FISCAL YEAR	TASK	SUB-TASK

COST ELEMENT		HOURS	RATE	SUB TOTALS	TOTALS
ENGINEERING DEPT. 612 BURDENED AT 127 %	SALARY	632	$ 4.60	$ 2,907	
	HOURLY	3,402	$ 3.57	$ 12,145	
	TOTAL DIRECT ENGINEERING			$ 15,052	
	ENGINEERING BURDEN			$ 19,116	
	TOTAL ENGINEERING				$ 34,168
MANUFACTURING DEPT. 573 BURDENED AT 135 %	SALARY	--	$	$ --	
	HOURLY	390	$ 3.57	$ 1,392	
	TOTAL DIRECT MFG			$ 1,392	
	MANUFACTURING BURDEN			$ 1,879	
	TOTAL MANUFACTURING				$ 3,271
TECHNICAL SERVICES -OUTPLANT BURDENED AT ____ %	SALARY		$		
	HOURLY		$		
	TOTAL DIRECT TECHNICAL SERVICES			$	
	TECHNICAL SERVICES BURDEN			$	
	TOTAL TECHNICAL SERVICES OUT-PLANT				$
MATERIAL BURDENED AT 10 %	RAW MATERIAL (INERT)		$ 2,000		
	PURCHASED PARTS		$		
	PROPELLANT MATERIALS		$ 10,195		
	SUB-CONTRACTS		$		
	OTHER		$ 1,750		
	TOTAL MATERIAL			$ 13,945	
	MATERIAL BURDEN			$ 1,395	
	TOTAL MATERIAL				15,340
OTHER	COMPUTER SERVICES			$ 2,065	
	TRAVEL			$	
	SPECIAL TOOLING			$	
	SPECIAL TEST EQUIPMENT			$	
	HOURLY LABOR PREMIUM				
	TYPE	HOURS	RATE		
	ENG		$	$	
	MFG		$	$	
	TECH SER.		$	$	
	TOTAL - OTHER				$ 2,065
TOTAL COST LESS ADMINISTRATIVE EXPENSE					$ 54,844
ADMINISTRATIVE EXPENSE AT 10.4 %					$ 5,704
TOTAL ESTIMATED COST					$ 60,548

REON
COST BREAKDOWN SUMMARY FOR THE PERIOD
00-020-037 DEC. 1964 THRU SEPT. 1965

DATE	PROPOSAL NO.
2 September 1964	RN 64010

SUMMARY TYPE	PLANT	FISCAL YEAR	TASK	SUB-TASK

COST ELEMENT		HOURS	RATE	SUB TOTALS	TOTALS
ENGINEERING DEPT. 7436 BURDENED AT 95.5 %	SALARY	7,825	$ 6.43	$ 50,315	
	HOURLY	0	$ --	$ 0	
	TOTAL DIRECT ENGINEERING			$ 50,315	
	ENGINEERING BURDEN			$ 48,050	
	TOTAL ENGINEERING				$ 98,365
MANUFACTURING BURDENED AT ____ %	SALARY		$	$	
	HOURLY		$	$	
	TOTAL DIRECT MFG			$	
	MANUFACTURING BURDEN			$	
	TOTAL MANUFACTURING				$
TECHNICAL SERVICES -OUTPLANT BURDENED AT ____ %	SALARY		$		
	HOURLY		$		
	TOTAL DIRECT TECHNICAL SERVICES			$	
	TECHNICAL SERVICES BURDEN			$	
	TOTAL TECHNICAL SERVICES OUT-PLANT				$
MATERIAL BURDENED AT 7.9 %	RAW MATERIAL (INERT)		$ --		
	PURCHASED PARTS		$ --		
	PROPELLANT MATERIALS		$ --		
	SUB-CONTRACTS		$ 20,000		
	OTHER		$		
	TOTAL MATERIAL			$ 20,000	
	MATERIAL BURDEN			$ 1,580	
	TOTAL MATERIAL				21,580
OTHER	COMPUTER SERVICES			$	
	TRAVEL			$	
	SPECIAL TOOLING			$	
	SPECIAL TEST EQUIPMENT			$	
	HOURLY LABOR PREMIUM				
	TYPE	HOURS	RATE		
	ENG		$	$	
	MFG		$	$	
	TECH SER.		$	$	
	TOTAL - OTHER				$
TOTAL COST LESS ADMINISTRATIVE EXPENSE					$ 119,945
ADMINISTRATIVE EXPENSE AT 11.99 %					$ 14,381
TOTAL ESTIMATED COST					$ 134,326

COST BREAKDOWN SUMMARY FOR THE PERIOD OCT. & NOV. 1964

00-020-037

DATE	PROPOSAL NO.
2 September 1964	RN-64010

SUMMARY TYPE	PLANT	FISCAL YEAR	TASK	SUB-TASK

COST ELEMENT		HOURS	RATE	SUB TOTALS	TOTALS
ENGINEERING DEPT. 7436 BURDENED AT 88 %	SALARY	1,655	$ 6.43	$ 10,642	
	HOURLY	0	$ --	$ 0	
	TOTAL DIRECT ENGINEERING			$ 10,642	
	ENGINEERING BURDEN			$ 9,365	
	TOTAL ENGINEERING				$ 20,007
MANUFACTURING BURDENED AT ___ %	SALARY		$	$	
	HOURLY		$	$	
	TOTAL DIRECT MFG			$	
	MANUFACTURING BURDEN			$	
	TOTAL MANUFACTURING				$ --
TECHNICAL SERVICES -OUTPLANT BURDENED AT ___ %	SALARY		$		
	HOURLY		$		
	TOTAL DIRECT TECHNICAL SERVICES			$	
	TECHNICAL SERVICES BURDEN			$	
	TOTAL TECHNICAL SERVICES OUT-PLANT				$ --
MATERIAL BURDENED AT ___ %	RAW MATERIAL (INERT)		$		
	PURCHASED PARTS		$		
	PROPELLANT MATERIALS		$		
	SUB-CONTRACTS		$		
	OTHER		$		
	TOTAL MATERIAL			$	
	MATERIAL BURDEN			$	
	TOTAL MATERIAL				--
OTHER	COMPUTER SERVICES			$	
	TRAVEL			$	
	SPECIAL TOOLING			$	
	SPECIAL TEST EQUIPMENT			$	
	HOURLY LABOR PREMIUM				
	TYPE	HOURS	RATE		
	ENG		$	$	
	MFG		$	$	
	TECH SER.		$	$	
	TOTAL - OTHER				$ --

TOTAL COST LESS ADMINISTRATIVE EXPENSE	$20,007
ADMINISTRATIVE EXPENSE AT 3.5 %	$ 700
TOTAL ESTIMATED COST	$20,707

COST SUMMARY BY COST ELEMENTS

REON PAGE 1 OF 1	$ 20,707
REON PAGE 1 OF 2	134,326
VON KARMAN PAGE 1 OF 3	60,548
SUB TOTAL	$215,581
FIXED FEE	15,090
TOTAL	$230,671