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A Proposal To

UNCLASSIFIED by AEC-NASA

SPACE NUCLEAR PROPULSION OFFICE

for

MASTER

NNRDC ENGINE TEST STAND EXHAUST SYSTEM
HOT-FLOW SCALE TEST PROGRAM

and

STRUCTURAL DESIGN STUDIES AND TEST

Proposal NO-62001

January 1962

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FOREWORD

Aerojet-General Corporation is pleased to submit this proposal to the AEC-NASA Space Nuclear Propulsion Office for the conduct of an experimental test program of the NNRDC Engine Test Stand exhaust deflector duct to include a Hot-Flow Scale Test Program and Structural Design Studies and Test.

These two programs are discussed separately in this volume as they represent two major related but distinct work tasks. Both are required to be completed before the final duct design proposed in Aerojet Proposal AE-62019 Design Criteria, Final Design and Construction Supervision for ETS-2, January 1962 can be initiated.

The two programs are scheduled to be conducted concurrently. Ten months will be required for these programs from the date of initiation of the work until delivery of the final report.

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SECTION I

HOT-FLOW SCALE-MODEL TEST PROGRAM

FOR

EXHAUST SYSTEM OF NNRDC ENGINE TEST STAND ETS-2

I. SUMMARY

During the period of planning for the NERVA engine development program conducted at Aerojet under Contract SNP-1, it became apparent that to ensure successful engine firing with minimum risk, a number of the NERVA engine components require extensive testing in the radiation environment that they are to encounter during engine operation. The Components Irradiation Test System (CITS) was conceived for this purpose, and the assumption was made that the NNRDC Test Stand ETS-1 would be used, permitting, among other things, longer durations for testing than could be otherwise achieved. It was further assumed that these tests, scheduled to start in June 1963, would continue at least through the second quarter of 1964 but could well extend beyond that date. In any case, Test Stand ETS-1 can be converted to accommodate the complete NERVA engine when it is no longer needed for the CITS program. As a result, the first NERVA engine test is tentatively scheduled for Test Stand ETS-2, with the first test occurring in the first quarter of 1964.

It is assumed that the design requirements for Test Stand ETS-2 are the same as those for ETS-1, viz., that it be sized to test the NERVA engine with stand growth capability to accommodate engines with power levels as high as 3.6 times that of NERVA. In addition, it is desirable to develop a duct which meets the same stand-height requirements as established for ETS-1, so that ETS-1 can accommodate the same duct and be useful for testing the NERVA engine at the conclusion of the CITS program.

In general, the requirements imposed on the ETS-1 (or ETS-2) deflector duct specify that it provide:

- A. Altitude simulation
- B. Explosion-free operation

I Summary (cont.)

- C. Safe ducting of explosive gases away from engine
- D. Structural integrity during operation
- E. Utilization of a reasonably sized envelope for vertical-engine testing.

Taken together, these interrelated requirements necessitate the verification of design utilizing scale-model tests. Tests results to date with the ETS-1 model indicate severe heat-transfer and flow-dynamics problems which require solution. At present, the cold-flow test program described in Aerojet Proposal AE-61029 (Ref. I-1) and performed under contract AT(29-2)1060 is completed and the heat-flux data obtained from the hot-flow program, also performed under Contract AT(29-2)1060, is being reduced. Preliminary data indicate that the duct design selected for Test Stand ETS-1 is acceptable, with reasonable heat-transfer rates everywhere but at the outer radius of the elbow. The maximum heat flux at the 45° location of the elbow for the NERVA operating conditions was estimated to be approximately $11 \text{ Btu/in.}^2\text{-sec.}$ This heat flux cannot be removed by convective cooling with the present design concept of aluminum construction. The present design will fail at the elbow if the heat rate exceeds $5 \text{ Btu/in.}^2\text{-sec.}$

This proposal includes discussion of a testing program designed to obtain additional data for successful design of the ETS-2 exhaust system. Test programs are outlined for a convectively cooled duct and for a configuration providing the addition of water into the duct at areas of high heat flux. Some of the data for planned test programs will be obtained for the present duct with necessary modification of the elbow to accommodate the high heat fluxes. However, since it is not certain that such an objective can be realized, parallel test efforts are proposed. These will include the following changes in duct configuration: slanting of the duct, changing the elbow radius, changing the overall duct height, and changing the duct diameter.

The necessity for this early and vigorous scale test program is obvious. If tests are conducted early enough in the program, design decisions need not

I Summary (cont.)

be made on the basis of analysis alone, thus avoiding the risk that ultimate tests do not verify the conclusions. Resultant delay could jeopardize the development time of the NERVA nuclear rocket engine. A schedule is submitted in this proposal which reflects the objective of obtaining critical data in the shortest possible time. Screening tests will be conducted, wherever possible, with minimum instrumentation to provide rapid answers in critical areas, e.g., the values and distribution of the heat-transfer coefficient of the hot gas. Final tests will then be conducted with more refined and elaborate instrumentation after the preliminary tests indicate the requirements for such measurements.

II. INTRODUCTION

Test Stand ETS-2 is to be designed to static-test downward-firing, full-scale, nuclear-rocket engines, upper stages of multistage space vehicles. Because the exhaust gas from a nuclear rocket is highly flammable hydrogen, the open type of flame deflector, utilized for testing chemically-fueled rockets, can not be used. The exhaust must be ducted out of contact with air to a considerable distance from the facility. Otherwise the test facility could be enveloped in flaming hydrogen, or be overheated by radiation from the hydrogen-air flame. Therefore, the exhaust ejector-deflector system for the ETS-2 facility must be designed to vent the hydrogen to a sufficient distance from the test facility so that the hydrogen can be disposed of safely by burning. The system must accomplish this disposal while excluding air from contact with the exhaust hydrogen at all points up to the burning area, because if air mixes with the hot hydrogen inside the duct system, an explosion will probably occur. Such an explosion not only could damage the exhaust system, the nuclear test engine, and the test stand, but also could scatter sufficient radioactive particles to render the test stand unapproachable for an extended period with a consequent delay in the engine development program.

For upper-stage vehicles, rocket engines with large-area-ratio exhaust nozzles are desirable to optimize performance. To test such engines at sea level under conditions that permit full expansion of the flow in the exhaust nozzle, it is necessary to provide some means of reducing the pressure into

II Introduction (cont.)

which the flow from the exhaust nozzle discharges. If properly designed, the exhaust-ejector duct for this purpose can use the energy of the rocket exhaust to establish and maintain a pressure rise in the duct, thus providing a reduced pressure around the exit of the exhaust nozzle.

The ETS-2 exhaust system is required to perform under conditions which impose more severe heat-transfer conditions than those imposed on chemical-rocket nozzle-exhaust systems. Heating rates are higher because hydrogen is an excellent heat-transfer fluid. The exhaust length dictated by the requirements for hydrogen disposal exceeds the length used on chemical-rocket nozzles. Heating rates are comparatively low in chemical-rocket systems, and cooling water costs are modest. Thus, for chemical rockets, the cooling system can be designed to use excess water to compensate for the uncertainty involved in the prediction of the cooling requirements. This situation does not apply to the nuclear-engine ejector, as the quantity of water used and the pressure required add substantially to the installation cost. At the same time, safe operation must be assured.

III. TECHNICAL DISCUSSION

While functions of the exhaust systems, and specifically the deflector duct for ETS-1 and ETS-2, are identical, it should be emphasized that design work completed on the ETS-1 duct served in large measure to define specific problems of duct design. Workable solutions were indicated in most problem areas, but uncertainty remained in other areas. Mechanical design requirements, in particular, appeared to be beyond the present state of the art. A vacuum-seal expansion joint for a tube from 80 to 90 in. in diameter, with provision for remote installation and removal, and a steam ejector consisting of an annular discontinuity in the duct wall and using superheated steam at 1350⁰F are examples of the types of mechanical problems encountered in design of the ETS-1 duct. Such problems; like those of heat transfer and gas dynamics, do not have simple solutions. A solution for one problem may involve severe penalties in other areas. In short, the problems of design, heat transfer, and gas dynamics must be integrated with those of the engine requirements.

III Technical Discussion (cont.)

The following discussion is concerned with the technical problems involved in the design of the exhaust duct as a result of testing done under Contract AT (29-2)-1060. Because analytical design data have been proved inadequate, the prediction of the magnitude and distribution of the heat transfer in the duct requires experimental investigations of a similar system.

Because the current state of the art does not permit accurate prediction of the ejector-system fluid-dynamic performance or heat transfer, additional scale-model experiments are proposed which will provide the data needed for the full-scale exhaust-system design.

A. GENERAL STATEMENT OF PROBLEMS

1. Heat Transfer

Gas expanded from the nozzle enters the ejector at supersonic velocity. Through a series of shock waves, the velocity head is converted to static pressure which increases with duct length, becoming ultimately near the exit atmospheric. It was expected that the highest heating rates would occur in the inlet section (at the nozzle exit) and in the 90° elbow. The high heat fluxes at the elbow were experimentally confirmed in model testing. The experimental heating rates were in excess of predicted rates (obtained by doubling the rates based on preliminary analysis). Figure I-1 shows the NERVA ejector configuration.

In determining the probable magnitude of the convective-heating rate in the ejector, three analytical models were considered: (1) Bartz's correlation, (2) Marenov's correlation (Ref. I-2), and (3) convective heating for flow over a wedge. This latter model is representative of the flow conditions at the ejector inlet. Marenov's correlation for supersonic flow in a straight tube comes closest to the physical model of the proposed ejector. Higher heating rates were expected on the full-scale ejector because of the discontinuity between engine nozzle and ejector and because of the turbulence or washing effect in the 90° elbow.

III Technical Discussion, A (cont.)

a. Critical Nature of Heat Transfer

The critical nature of the heat-transfer problem warrants review.

In order to permit personnel to approach the facility within a reasonable time interval (less than 30 days) after an engine test, it is desirable to fabricate the duct from a material which has a short half-life. One common structural material, aluminum, is best suited to satisfy this requirement. Because aluminum loses its strength rapidly above 400°F, the entire system must be water-cooled.

For use with chemically fueled rockets, such cooling would present little difficulty. For the specific ETS-2 problem, however, the limited supply of water and the cost of water delivery to the duct in terms of supply lines, makes the design of an efficient cooling system critical. A greater degree of safety is also required for the nuclear engine ejector as compared to the chemically fueled rocket ejector. If burnout should occur with a chemically fueled rocket, immediate repairs to the damaged duct can be made without hazard to the personnel. Such a failure cannot be tolerated on the nuclear engine ejector, since a burnout may produce or trap so much radioactivity that the duct could not be approached for prohibitive periods of time, and even then all repairs would have to be made by remotely controlled procedures. It probably would be necessary to discard the entire burnout section and replace it with a new one, although the construction of the duct is such that this would be a costly procedure.

Thus all requirements - economic, performance, and safety - of the ETS-2 ejector make the thermal design of this facility a critical consideration.

b. Regions of High Heat Flux

The highest heating rates occurred in the exhaust-system turning elbow. The proposed experiments will determine the location, extent, and magnitude of the heating rates as changes are introduced to reduce the high heat flux.

III Technical Discussion, A (cont.)

2. Gas Dynamics

The geometry of the deflector duct for ETS-1 (see Figure I-1) was selected on the basis of cold flow tests (Ref. I-3) in the 1/11-scale model facility. The results of these tests are shown in Figure I-2 and indicate that the deflector duct configuration was acceptable and that "pull-in" of the duct occurred simultaneously with "pull-in" of the environmental cell (Figure I-2) which occurred at a chamber pressure of 38 atm (475 psia at NTS). However, cold-flow tests of a constant-area duct indicated that the two events would not necessarily occur simultaneously (Figure I-3).

Hot-gas flow tests of the deflector duct design differed from the cold-flow tests in that "pull-in" of the duct occurred at a higher chamber pressure than was required for the environmental cell. This is shown in Figure I-4 which can be compared with Figure I-3. In addition, the hot-gas test data indicated that the "pull-in" points may not be reproducible to the extent shown in the figures. During one test, pressure measurements indicated a potential instability at a chamber pressure of 42 atm, which is right at the NTS operating point for the NERVA engine. This condition of potential instability must be removed during the effort to alleviate the high heat-transfer rates in the duct elbow.

Altitude-starting simulation of the NERVA engine, as well as the explosion-free operation requirement, necessitates use of a secondary ejector for the duct, which ideally should maintain altitude conditions in the environmental cell at all times during the startup and shutdown operation of the engine. Tests made with secondary ejectors in the deflector duct model have thus far not accomplished this objective. Figure I-5 shows the environmental cell pressure as a function of the secondary-fluid injection pressure for the constant-area duct system as shown in Figure I-6. Figure I-7 shows how increasing the duct diameter downstream of the secondary fluid injector (Figure I-8) helped reduce the environmental cell pressure to the desired 60,000 ft altitude ($P_v/P_a = .08$ for NTS). Both Figures I-5 and I-7 are for zero primary gas flow

III Technical Discussion, A (cont.)

from the NERVA engine. Figure I-9 shows how the primary flow affects the environmental cell pressure for the constant-area duct configuration.

No hot-flow tests have been made for a step increase in the duct area for a secondary ejector design as shown in Figure I-8. It is shown in Figure I-7 that gas-dynamics conditions in terms of secondary ejector performance would be improved; however, heating problems associated with this sudden expansion must be defined by experiments. These test results indicate that the desired operational point for the secondary ejector has not been established and that considerable improvement can be obtained by further tests.

3. Results of Hot-Flow Program on Test Stand ETS-1, Contract AT(29-2)-1060

The scale-model hot-flow program for Test Stand ETS-1 was conducted to verify that the selected duct configuration was adequately cooled by convection. The results of this test program indicate that, for the existing design, heat-transfer rates along the bottom center line of the elbow will reach a maximum of 11 Btu/in.²-sec when a NERVA engine is used. This heating rate occurs approximately at the 45° point in the bend, where the gas impingement is most pronounced and is too large a heat-transfer rate for an aluminum duct to withstand. The heat-transfer coefficients measured at the 45° location of the bottom center line of the deflector-duct scale model are shown in Figure I-10 as a function chamber pressure. These values can be corrected to the approximate full-scale heat flux in units of Btu/in.²-sec by multiplying by 8000.

Results of the hot-flow program for Test Stand ETS-1 are shown in Table I-1.

Arrangement of the manifold sections of the ejector duct is as shown in Figure I-11. It should be noted that for section 4, the duct design fluxes are much less than those determined from tests. It is this unfavorable comparison that motivates this request for further testing.

III Technical Discussion, A (cont.)

4. Working Fluid

In model testing, it is desirable to maintain as many as possible of the parameters which will occur in the prototype, to avoid the introduction of extraneous factors or unknowns. Because hydrogen is the actual propellant, ideally hydrogen should be used as the working fluid in the scale-model experiment. However, the use of hydrogen is impractical because of the enormous amount of energy required to heat the hydrogen to the desired working temperature. Heaters having this capacity are being built, but not for use with hydrogen. Heated hydrogen is difficult to handle because of the danger of explosion and because it produces hydrogen embrittlement in many structural materials. A heater for hydrogen with the necessary heating capacity can be fabricated, but some development studies will be involved and the time and cost are prohibitive.

In addition to the heater, there are other problems associated with the use of hydrogen in a test facility. Special precautions and rigorous safety measures must be taken to avoid the possibility of a fire or explosion, and special arrangements will be necessary to dispose of the hydrogen after its passage through the ejector. The whole experimental program might be delayed seriously.

Since the use of hydrogen as the working fluid is impractical, the problems associated with the use of other gases have been examined.

In any test set-up designed to simulate conditions in a somewhat different physical system, it is desirable to duplicate all of the pertinent dimensionless parameters. For the scale-model in question, these are:

Ratio of specific heats, γ

Prandtl number, Pr

Duct Mach number, M_j

Reynolds number based on ejector diameter, Re_d

Reynolds number per unit length, Re

III Technical Discussion, A (cont.)

Nozzle exit angle, θ

Ratio of pressures at ejector entrance to ambient static pressure, $\frac{P_j}{P_a}$

Ratio of wall temperature to free-stream temperature, $\frac{T_w}{T_\infty}$

Of the common diatomic gases ($\gamma = 1.4$) which could be used, nitrogen is especially desirable because of its chemical stability, inertness, noncorrosiveness, availability, and low cost. Moreover, the transport properties of nitrogen are well known, and a heater for this inert gas is readily available. The use of nitrogen involves no particular safety or disposal problems, and therefore the testing program can proceed expeditiously, limited only by the rate of data acquisition and interpretation.

The parameters of specific-heat ratio and Prandtl number for nitrogen and hydrogen are compared in Figure 12. In the temperature regions of interest, there is no significant difference in the values for the two gases, and therefore both the shock pattern (affected by γ) and the boundary layer buildup (affected by Pr) will be similar for the two gases.

The gaseous nitrogen used in the flow tests will be heated to a temperature of $1600^\circ R$. This temperature is high enough to provide a reasonable value of heat flux without having to cool the duct and is low enough to provide accuracy of measurements. The temperature of $1600^\circ R$ represents a practical upper limit of the stagnation-gas temperature for available and reliable heater equipment.

B. PROPOSED SOLUTIONS

The test results obtained from the scale-model tests conducted to date indicate that improvements in heat-transfer conditions, flow dynamics and secondary-ejector operation are necessary to the successful completion of the ETS-2 deflector-duct design. The solution of these problems should be considered from three viewpoints as related to the duct configuration - (1) solutions that enable the present duct geometry to be utilized, (2) solutions that maintain the present duct envelope so that test stand substructure changes

III Technical Discussion, B (cont.)

are not necessary, and (3) solutions that may require a larger duct envelope for satisfactory operation.

The solution, in general, will attempt to use proven design methods where scaling techniques are straightforward and adequate safety factors can be obtained for the final design.

1. Hydraulic Analogy

Because of the large number of tests that must be conducted to obtain the required data for the proposed solutions outlined above, it is desirable to conduct analyses by an appropriate analogy to permit a qualitative comparison of the expected solution choices with each other. Since the flow in the duct is too complicated to assure that the possibility of mathematical analysis, analogical methods appear desirable. The water-table analogy offers a means of qualitatively making such rapid comparisons. The validity of the hydraulic analogy to supersonic flow is shown in Ref. I-4 and is discussed below.

a. Theoretical Summary of the Hydraulic Analogy to Gas Dynamics

(1) Introduction to Flow Through A Normal Compression Shock or Hydraulic Jump

The analogy for the special flow condition of the normal compression shock or right-angle hydraulic jump is presented as background for the more general flow in which oblique shocks occur.

The type of flow to be considered is essentially one-dimensional both in hydrodynamics and gas dynamics. Specifically for hydrodynamics, a parallel uniform flow of liquid having a free surface in a horizontal channel of infinite width is assumed. Variations in the velocity occur only in the x direction and the flow is frictionless. In practice, the implications of this requirement are met indirectly by sloping the channel in the direction of flow until boundary resistance is balanced by gravity forces. Thus, initially, flow of uniform depth and constant velocity is obtained. For gas dynamics, flow in a duct of constant section is assumed without friction or heat transfer; that is, the gas flow is nonviscous and adiabatic. Variations in the flow take place only in the x direction.

III Technical Discussion, B (cont.)

There exists a direct analogy of a normal hydraulic jump to that of a normal shock occurring in a gas. The equations for such are based on the basic assumptions that the height ratio across the normal jump is equal to the density ratio across a normal shock; the Froude number of the incompressible fluid equals the Mach number of the compressible gas; the fluid height is equivalent to the density of the gas; and the momentum change across the jump is equivalent to the pressure change across a normal shock. The analogy equations and their mathematical derivations shown in Reference I-4 are as follows:

(a) Analogy of Continuity, Momentum, and Energy Equations

Hydrodynamics

Gas Dynamics

Continuity

$$H_1 V_{n1} = H_2 V_{n2}$$

$$\rho_1 V_{n1} = \rho_2 V_{n2}$$

Momentum

$$\frac{1}{2}g(H_2^2 - H_1^2) = H_1 V_{n1}(V_{n1} - V_{n2})$$

$$P_2 - P_1 = \rho_1 V_{n1}(V_{n1} - V_{n2})$$

Energy

$$\begin{aligned} (V_{n1}^2 / 2g) + H_1 + E_{w1} &= (V_{n2}^2 / 2g) \\ &+ H_2 + E_{w2} \end{aligned}$$

$$\begin{aligned} (V_{n1}^2 / 2) + P_1 / \rho_1 + E_{g1} &= (V_{n2}^2 / 2) \\ &+ P_2 / \rho_2 + E_{g2} \end{aligned}$$

(b) Analogy of Flow Properties Across a Normal Shock

The two continuity conditions are identical if H is equivalent to ρ , then $H_2/H_1 \sim \rho_2/\rho_1$.

The momentum conditions are identical if H is equivalent to p and $gH^2/2$ is equivalent to p ; then

$$(H_2/H_1)^2 \sim P_2/P_1$$

III Technical Discussion, B (cont.)

The above continuity and momentum conditions imply that

$$p_2/p_1 = (\rho_2/\rho_1)^2$$

and from the perfect-gas relation $p = \rho RT$, it follows that

$$H_2/H_1 \sim T_2/T_1$$

(c) Analogy of Mach Number

The speed of sound in a gas is $a = \sqrt{\gamma p/\rho}$. If p is replaced by $gH^2/2$, ρ by h , and with $\gamma = 2$ from the relation indicated above, the $a \sim \sqrt{gH}$ and the sonic velocity is analogous to the celerity $c = \sqrt{gH}$ of a vanishingly small gravity wave. Accordingly, the Mach number, $M = V/a$, in a gas is analogous to the Froude number, $F = V/\sqrt{gH}$, of a hydraulic fluid.

The energy equations also imply that

$$E_w = E_g.$$

(d) Normal Hydraulic Jump Description

Solving the momentum equation for V_{n_1} and eliminating V_{n_2} through continuity yields:

$$V_{n_1} = \left[1/2(gH_1)(H_2/H_1)(1 + H_2/H_1) \right]^{1/2}$$

since

$$F_{n_1} = V_{n_1} / \sqrt{gH_1} \quad \text{and } \gamma = 2,$$

$$H_2/H_1 = 1/2 \left[(8F_n^2 + 1)^{1/2} - 1 \right]$$

III Technical Discussion, B (cont.)

The increase in internal energy across the jump can be calculated from the energy equations by eliminating V_{n_1} and V_{n_2} by means of the momentum and continuity equations. Then,

$$E_{w_2} - E_{w_1} = 4E_w = (H_2 - H_1)^3 / 4H_1H_2$$

$$4E_w/H_1 = \left[H_2(H_1 - 1) \right]^3 / 4H_2/H_1$$

This equation is valid only in supercritical flow. The simplifications and limitations implied in the derivation of the hydraulic jump are summarized as follows:

;

III Technical Discussion, B (cont.)

Steady flow

Frictionless flow

Incompressible flow

Pressure on a free surface is constant

Hydrostatic pressure distribution

Negligible surface-tension forces

(2) Introduction to Flow Through an Oblique Compression Shock or Hydraulic Jump

The derivation of oblique shock relations by the applications of geometric considerations of the physical flow picture are applied to the hydraulic normal-jump equations in exactly the same manner as the compressible-gas Rankine-Hugoniot equations are used to derive the oblique shock relation for gases. The development of these analogy equations may be seen in Reference I-5. Following is a tabulation showing the analogous relationships:

<u>Gas Flow</u>	<u>Water Flow</u>
Density ratio, ρ/ρ_0	Depth ratio, (H/H_0)
Pressure ratio, p/p_0	Depth ratio, $(H/H_0)^2$
Temperature ratio, T/T_0	Depth ratio, (H/H_0)
Speed of sound, $a \sqrt{\gamma p/\rho}$	Wave velocity, $c \sqrt{gH}$
Mach number, v/a	Froude number, V/c
Subsonic	Streaming
Supersonic	Shorting
Compression shock	Hydraulic jump

b. Correlation of a Hydraulic Flow Model

A scale model of the problem to be analyzed is constructed. Water is then allowed to flow through the model and form a hydraulic

III Technical Discussion, B (cont.)

head representing the source pressure of the gas used in the actual case. The test results are expected to give qualitative results and semiquantitative results on a direct analogy of the water flow to a gas flow. While the form of the flow and shock patterns will be that of the gas flow, a direct numerical correlation is not possible without modification. There are two basic reasons for the lack of direct numerical correlation. First, a direct numerical correlation requires that $\gamma = 2$ for the gas, which is not realistic. Secondly, the change in internal energy for a gas is not equivalent to the change in internal energy for water. An attempt at direct correlation of the numerical values of flow properties may be expected to be in error with the aerodynamic values by as much as 40%.

To improve the theoretical agreement of the analogy, it is proposed that a departure be made from the derived relationships. The depth ratio will be used to determine the analogous density ratio only. With this density ratio, the other flow properties will be calculated by means of aerodynamic relations for the γ of the gas. Table I-2 shows a test made for a 9° wedge and with γ of the gas equal to 1.4. The improvement in flow data by the above modification is obvious. The maximum error is reduced to 8%.

A second modification is possible which includes the first and aims at a better numerical agreement for both the depth ratios and density ratios. The density ratios and depth ratios can be expected to be of the same magnitude only when deflection angles and shock-wave angles are identical for water and the gas. The adjustment will be accomplished by changing the Froude number of the water flow to give the same shock angle as predicted by aerodynamic theory for the same wedge angle and known Mach number. The depth ratios will then theoretically equal the density ratio and thus all quantities determined from this density ratio will be identical with the aerodynamic analysis. Figure I-13 shows a preliminary run with the water table for the present duct geometry and indicates how the shock structure can be established from the analogy. Figure I-14 shows a shadowgraph obtained from the flow visualization program performed under Contract AT(29-2)-1060. This photograph shows the actual shock structure in the duct. A similarity in shock structure between the water and gas can be observed.

III Technical Discussion, B (cont.)

2. Present Duct Geometry

Although the present duct configuration for ETS-1 does not meet all requirements for performance in testing the NERVA engine, it is a suitable design in terms of heat transfer at all locations other than the elbow. In addition, a large amount of design time has been spent on this duct from the point of view of details of construction, stresses, remote handling, etc. Hopefully, then, if the deficiencies of the duct can be remedied by limiting design changes to those which can be readily effected, the test program can be expedited, since extensive additional design effort is unnecessary. The following sections discuss proposed tests and design approaches to retain as much of the present design as possible.

The most promising method of utilizing the present duct geometry entails injection of water into the gas stream in the elbow region to alleviate the high local heat fluxes that exist in the bend. It is felt that the most feasible method of accomplishing this objective will be to use a series of closely spaced, but discrete, injection orifices to produce a cloud of small droplets next to the elbow surface. These droplets will be carried along by the stream and vaporized; they will cool the exhaust gases in contact with the elbow. A second, and perhaps more important effect, will be the impingement of unvaporized droplets on the surface of the elbow as the gas is turned downstream of the injection point. These effects should combine to produce a considerable reduction in heat fluxes in the elbow.

The effect of this additional mass on the operation of the deflector duct is unknown and must be evaluated by scale-model tests. The additional mass introduced by the water will be detrimental to duct operation, but the changes in shock structure caused by the injection of fluid into the stream may or may not compensate for this effect.

To evaluate the performance of a system of this nature by scale-model tests requires that several quantities be satisfactorily simulated. From heat-transfer considerations, it is necessary to simulate the behavior of

III Technical Discussion, B (cont.)

water in the full-scale duct by producing equivalent droplet sizes and vaporization rates so that the distance that each droplet is carried will be equivalent to the full-scale duct. This is accomplished by choice of the injection fluid for the scale-model tests and requires that attention be concentrated on physical and thermal properties of the fluid as well as the injection conditions. From flow considerations, the mass and momentum of the injected fluid also must be equivalent to full-scale conditions so that their effects on duct operation can be determined. Since it is unlikely that all of these conditions can be met with one fluid, several fluids will have to be used in a final evaluation of the duct configuration.

b. Material Change

Two important advantages occur in the high heat-flux areas when stainless steel is substituted for aluminum as a tube wall material. One is that less water is required to cool a stainless-steel tube in this very high heat-flux area since higher wall temperatures can be tolerated. The second is that unit stresses in the stainless steel can be less than those in the aluminum. The net effect of these advantages is that the probability is greater that the tube wall will remain intact and hold back the hot gases.

The above results are derived when one makes a heat-transfer analysis of an ejector-duct section. Independent variables that enter into such an analysis are the following:

$(q/A)_{\max}$	maximum heat flux in section
$(q/A)_{\text{ave}}$	average heat flux in section
D	diameter or hydraulic diameter of tube
A_2	total area of section exposed to hot gases
T_{wg}	maximum temperature of tube on hot-gas side
T_1'	temperature of water at entrance to tube
k	tube wall thickness
t	tube wall thickness
L	length of tube

III Technical Discussion, B (cont.)

Dependent variables that enter into the analysis are:

N	number of tubes in section
S	total water-flow area
$\dot{w}$	mass flow rate of flow of water
G	mass flow rate of flow of water per unit flow area
V	velocity of water
T_{wl}	temperature of tube wall on liquid side
T_{l2}	temperature of water leaving tubes
ΔP_f	friction loss

Equations used in the analysis are:

$$V = \frac{\dot{w}}{\rho S}$$

$$\Delta P_f = f L/D \rho \frac{V^2}{2g} \quad \text{where } f = 0.016 \text{ (assumed)}$$

$$(q/A)_{ave} A_s = \dot{w} C_p (T_{l2} - T_{l1})$$

$$(q/A)_{max} = (T_{wg} - T_{wl}) \frac{k}{t}$$

$$\frac{h_l}{C_p G} \left(\frac{C_p \mu}{k} \right)_f^{2/3} = \frac{0.023}{(DG/\mu_f)} (0.2)$$

The above equation is taken from Reference I-6. The variables used in it are:

h_l	coefficient of heat transfer between fluid and surface
μ	coefficient of viscosity
D	tube diameter
C_p	specific heat

III Technical Discussion, B (cont.)

- ρ density
- g gravitational constant
- P_{cr} steam saturation pressure at $(T_{wl} - 20^\circ) + \Delta P_f =$ static pressure required inside entrance of tube to prevent nucleate boiling

Fluxes applicable to aluminum and stainless steel are different. This is a result of being able to use a much higher hot-gas wall temperature.

The above relationships are solved for trial tube-wall thicknesses yielding temperatures and stresses in the wall. Values of the ratio of stress to the yield stress at the temperature are plotted against tube-wall thickness, and a minimum of this ratio indicates the optimum tube-wall thickness to use in that section. The argument, for considering the thickness derived in the above manner as optimum, is that a configuration in which a material is stressed the least is the one which is least likely to be destroyed.

c. High-Pressure Boost Pumps

In combination with the material change in the elbow, it may then be possible to utilize high-pressure boost pumps for pumping water at high velocities in the convectively cooled tubes.

With the given static water head at the NNRDC Engine Test Stands ETS-1 and ETS-2, only a certain velocity can be attained in the cooling tubes. This velocity can then remove only a certain heat flux from the duct. By using boost pumps to pump water at high velocities in the critical area of the duct, a greater amount of heat can be removed while avoiding burnout heat fluxes. Failure of the pumps during operation would, however, mean possible destruction to the duct.

3. Present Duct Envelope

Design of a deflector duct system that will fit within the present duct envelope appears quite feasible. Such a design change would not affect the test-stand operation in any way and would enable a large portion of the design engineering for the present ETS-1 deflector duct to be utilized.

III Technical Discussion, B (cont.)

Experience with open-flame deflectors (Reference I-7) has shown that the heat flux to a deflecting surface reaches a maximum in the region of the last impingement of the gas stream and varies roughly as the sine of the impingement angle at this point. Deflector experience has also shown that the heat flux depends strongly on the fluid Mach number in the turning region (primarily because of local mass-flow rates). Qualitative analysis of the hot-gas model duct tests indicates that this experience may also apply to the ETS-1 deflector duct, which would imply that configuration changes within the present envelope can be made to obtain a marked reduction in the peak heat fluxes in the duct.

For the same Mach number of the exhaust gases, and hence same duct diameter, a reduction in the maximum impingement angle from 53° to about 15° appears feasible in the existing envelope, making possible a reduction in peak heating rates by a factor of 3. This can be accomplished by increasing the elbow radius, slanting the inlet section or some combination of both variations. It is difficult to determine how these changes will affect the shock structure within the duct and hence what Mach numbers will exist near the elbow. Analysis of the hot-flow model duct data indicates a Mach number in the elbow region of 2.5 to 3. A stronger shock system before the elbow would reduce this Mach number and produce higher heat fluxes if the flow remains supersonic, while a weaker shock system would reduce peak heat fluxes in the elbow region.

The effects of these changes in duct design on operation of the duct as an ejector are not known and must be evaluated. However, a larger radius of curvature in the elbow region makes the duct closer to a straight pipe duct and hence should improve operation, since a straight ejector has considerably better performance than the present duct configuration. In a like manner, slanting the inlet section may improve duct operation. It is not anticipated that changes in duct design will greatly affect the requirements for the secondary ejector, so that secondary ejector requirements do not influence the validity of the choice of solution.

III Technical Discussion, B (cont.)

The validity of evaluation of this type of design change through scale-model tests is reasonably well established. Scaling is straightforward as compared to the scaling of mass injection systems that have not been verified by large scale tests.

4. Larger Duct Envelope

Possible solutions to the duct design under the restriction that the test stand height be unaltered from the present ETS-1 design are discussed in previous sections. Since there is no assurance that the proposed solutions discussed can be obtained satisfactorily, designs which remove the restriction of keeping to the present stand height must be considered. Further coupling of parameters such as impingement angle, length to diameter before the elbow and secondary ejector, and primary duct-to-nozzle-throat-area ratios can be investigated to produce a configuration with satisfactory system performance.

C. EXISTING FACILITIES

1. Test Facilities

Aerojet-General Corporation has ample facilities for the proposed test program at the Azusa Plant Proving Grounds, having successfully completed scale-model hot-flow and cold-flow testing for the ETS-1 exhaust system (Reference I-3).

Two stored energy heaters that can deliver nitrogen at 1100 psig and 1600°R are available. The small heater (used in previous scale-model hot-flow testing) delivers 8.0 lb/sec for a 30-sec run. The large heater has a 30-lb/sec capacity for a 30-sec run.

Many of the components of the previously tested ejector systems may be reused; the test personnel are experienced in scale-model flow-testing of ejector systems.

The hydraulic analogy tests are conducted on a water table designed by the Thermophysics Department and maintained by the Space General Laboratory, presently located in Azusa. The water table basically consists of a

III Technical Discussion, C (cont.)

rectangular sheet of glass, 5 by 15 ft, placed on an adjustable framework. The desired planforms are obtained by adding strips of Plexiglas to the plate glass to channel the water flow to the sump. The water enters the test-model reservoir through a pipe, is drained off the end of the table into the sump, and is re-circulated with a 200-gpm, 20-ft-head, centrifugal pump. Surface tension of the water is reduced by adding trisodium phosphate (detergent) or a wetting agent to the water. Water-depth measurements can be made directly and photographs of the flow phenomena can be taken by directing light up through the glass.

2. Measurements and Instrumentation

During these tests, the following measurements will be taken:

- a. Chamber pressure and temperature in the model engine
- b. Static pressure at points along the wall of the ejector
from entrance to exit
- c. Instantaneous wall temperatures at points along the
ejector system
- d. Internal wall static pressures and dynamic pressure
at ejector exit
- e. Pressure in the environmental cell
- f. Secondary-ejector chamber temperature and pressure
- g. Pressure in the purge nozzle
- h. Oxygen concentration in the environmental cell and at a
point just upstream of the secondary ejector
- i. Pressure in the film cooling manifold
- j. Pressure in the leakage nozzle
- k. Pressure at ejector entrance

Not all of the above measurements will be required for each test.

III Technical Discussion, C (cont.)

Pressure measurements will be taken by two methods. Key pressures that must be maintained or regulated during the course of an individual test will be observed and recorded by an oscillograph. The remaining pressure measurements are fed into IBM tape from a 100-channel electronic sampling switch. The IBM tape, containing the pressure history of an ejector system "firing" will then be fed into an IBM 704 computer, which will produce a typed output sheet.

Both the oscillograph-trace and IBM-tape methods of recording pressures use pressure transducers.

Pressures are fed into the transducers by 1/4-in. tubing located at the point of interest. The pressure transducers are mounted conveniently on a vertical panel (Figure I-15) and their respective pressure tubes are brought in through holes in the panel (Figure I-16). The pressure transducers are all referenced to vacuum via a tube evacuated by a vacuum pump (Figure I-15, lower left).

Temperature measurements will be taken with thermocouples - Chromel (+) to Alumel (-) welded directly to the outside of the ejector wall (Figure I-17). The voltages induced within the thermocouples are fed into the sampling switch and each thermocouple voltage is transferred to magnetic IBM tape. The IBM tape will be fed into an IBM 704 computer and the typed output sheet will provide a temperature history at each thermocouple location.

IV. PROPOSED PROGRAM

The proposed program, to find a solution applicable to the ETS-2 deflector design problems, will consist of a combined analytical and experimental scale-model evaluation of various deflector duct configurations having as its goal the selection of a duct that can be designed and fabricated to yield adequate safety factors for operation during engine testing.

To accomplish these objectives, a testing program at the 1/11-scale model size, using heated nitrogen as the primary engine fluid, is proposed to evaluate the various design configurations which are considered to be most suitable for the ETS-2 duct design. These tests will be supplemented by a preliminary screening of configurations with water-table tests that will allow the most suitable designs to be selected for model testing.

The model test-program plan is shown in Table I-3, where the proposed tests are divided into six blocks of tests that will not necessarily follow in order but which are necessary to provide data for an adequate duct design.

In each testing block, two types of tests will be made to obtain the desired design information. The first type will be used primarily to obtain heat-transfer information. A step change in engine-chamber pressure will be provided to produce transient thermocouple readings that can be converted to heat-transfer rates, as in the present program conducted under Contract AT-(29-2)-1060. The second type will be conducted to obtain operational data on flow characteristics and stability of the flow during transient and steady-state operation. They will lead to a better evaluation of the capabilities of each duct design. These tests will all be made using heated nitrogen to obtain the best simulation possible with the existing facility.

A. PRESENT DUCT GEOMETRY

Tests are proposed to evaluate the existing duct to determine its suitability for the proposed program. The effects of mass injection in the elbow region on both heat transfer and flow in the duct will be determined. These tests will provide qualitative data on heat-transfer conditions and quantitative data of flow in the duct.

IV Proposed Program, A (cont.)

The coolant fluid will be selected in the first month of the program to provide the best simulation of water in the full-scale duct systems, and tests will be made injecting the test fluid from a quiescent reservoir into the elbow. The experimental heat-transfer measurements will rely on detecting the transition from nucleate-pool boiling to film-pool boiling and hence will tell whether or not the heat flux exceeded a particular value. This heat flux will be equivalent to about $2 \text{ Btu/in.}^2\text{-sec}$ in the full-scale duct, which is considerably below the maximum that can be handled by water. Pressure measurements along the duct will verify satisfactory operation under these conditions.

Evaluation of the secondary-ejector system will be accomplished through a series of tests on the existing duct configuration to provide a secondary-ejector system that can operate independently of the engine being tested and that will provide the best simulation of altitude conditions in the duct at all times.

The most suitable combination of fluid-injection system and secondary-ejector system will then be tested to evaluate the range of operational capability of the design and to evaluate local heat-transfer conditions in the duct. These tests will involve the use of several injection fluids to provide better confidence in scaling the results to the ETS-1 design conditions.

B. PRESENT DUCT ENVELOPE

As discussed previously, this testing block is intended to evaluate the effects of changes in duct design (within the present envelope) on heat-transfer rates, operational capabilities and flow stability. It is proposed to evaluate four configurations in this test block that have the best promise of providing an operational ETS-2 duct. These configurations will be subjected to a preliminary screening through use of a water-table analogy during the first month of the program with the best designs tested in the heated-gas scale model facility. The configurations indicated in Table I-3 are considered to be the most promising at the present time. Figure I-18 shows a maximum-radius configuration of the type planned; Figure I-19 shows a slanted-inlet-section configuration. Both configurations achieve the intended purpose of minimizing the turning angle of the gases in the impingement region.

IV Proposed Program, B (cont.)

Since these designs are intended to be cooled entirely by convection, the test data will be correlated on a dimensionless basis to provide the necessary design criteria, which hopefully will allow the design of the ETS-2 deflector duct.

C. LARGE DUCT ENVELOPE

In the event that the heat fluxes obtained during the above test block are deemed too high for an adequate duct design, a third test block is proposed to evaluate the reduction in heat flux obtained by using a larger duct envelope. These configurations will use the same design concepts applied to ducts of 1.5 and 2 times the height of the present ETS-1 duct design and will provide quite general information on the operation of this type of a deflector duct. The design intent will again be to reduce the turning angle of the gases in the impingement region and both heat-transfer conditions and flow characteristics of the duct designs will be evaluated. Correlation of the test data on a dimensionless basis to provide design criteria will again be made for application to the ETS-2 duct design.

D. SUPPORTING TESTS

With the concurrence of SNPO, a configuration for the ETS-2 deflector duct will be selected based on these test results and transmitted to the design group so that detailed design work for the ETS-2 deflector duct can proceed. A series of design supporting tests will then be made to verify the design choice. These tests will evaluate the requirements for operation of this duct as a test tool and are intended to determine purge requirements, leakage tolerance of the design, effects of gimbaling the engine, and to match the secondary-injector system to the overall deflector duct requirements. These tests will also better define the heat-flux and operational limits of the final duct design by providing off-design point data for the system.

E. SELECTED DUCT ENVELOPE FOR THE ENGINE WITH 3.6-TIMES-NERVA ENGINE POWER LEVEL

To provide data that will enable the ETS-2 test stand to be used for a range of operational engines up to 3.6-times-NERVA power rating, a test block is proposed to evaluate a deflector-duct configuration under the higher-power conditions to verify the data obtained previously at NERVA conditions. This duct configuration

IV Proposed Program, E (cont.)

will be based on the data obtained earlier in the program and will be evaluated to determine heat fluxes, flow characteristics, and stability. It is planned that this configuration will be based on the ETS-2 duct and will probably have a larger envelope so that substantiation of the design is required to enable the ETS-2 test stand to accommodate the duct design.

F. SUPPORTING TESTS

As in the case of the ETS-2 duct configuration, the 3.6-times-NEVA duct design will be verified by a series of supporting tests to evaluate purge requirements, leakage tolerances, gimbal effects, and secondary ejector requirements.

G. DESIGN CRITERIA

The test program described in the previous sections has as its goal the provision of the data necessary for the design of the ETS-2 deflector duct for the NEVA engine and a deflector duct capable of operation with a 3.6-times-NEVA engine. Close coordination with the design group will be maintained to furnish the design engineers with design criteria for the duct system as required. These criteria will consist of both nominal design-point data and expected tolerances so that performance of the actual duct can be better described at all times during the design effort.

V. PROPOSED WORK STATEMENT

The following statement of work is suggested:

Task 1: Hot-Flow Scale Test Program

Item 1.1: The contractor, the Aerojet-General Corporation, shall provide the necessary personnel, facilities and materials to design and fabricate scale-model exhaust systems to be tested using heated nitrogen as the working fluid. These systems will include: (a) the present ETS-1 configuration modified to reduce the heat fluxes at the elbow by use of coolant injection, (b) a different configuration than the present ETS-1 configuration but remaining within the present height allowance for testing the NERVA engine, and (c) configurations that are not restricted to height for satisfactory test capabilities for the NERVA and 3.6 times power level NERVA engines. Because the state-of-the-art for ejector system designs is not well advanced, the above activities shall be considered as a level of effort activity.

Item 1.2: The contractor shall construct a water table analogy between the two-dimensional supersonic flow in the duct and the shooting-flow of water to demonstrate the expected internal flow within the duct for selected configurations. This item will not lead to detailed decisions on the selection of the ejector systems but is intended to provide a qualitative comparison of the configurations under consideration.

Item 1.3: The contractor shall test the selected scale-model exhaust systems for heat-transfer distribution and for coordinated performance with an attached secondary ejector system. Stability of operation at simulated operating conditions will be noted.

Item 1.4: The contractor shall reduce the data for heat-transfer distribution and calculate the expected heat fluxes for the prototype design. The contractor shall also correlate overall scale model performance with the prototype system performance.

Item 1.5: The contractor shall provide monthly status reports and a final report summarizing the results of the experimental program and correlate these results to the operation of the prototype design.

VI. SCHEDULE AND MILESTONES

A schedule with major milestones for the proposed program is presented in Figure I-20. The overall program duration is 10 months. Design of test hardware will be completed by the end of the fifth week. The hydraulic analogy task will be completed after 8 weeks. Testing is expected to begin 8 weeks after initiation of the program; duration of testing will be five months. The information necessary to determine if the ETS-1 duct can be used is expected to be available at the end of the fifth month. At this time, the necessary input to the design group to start detailed design work on the NERVA deflector duct will be available. After 7 months, the operational characteristics of the duct will be defined. Confirmation of the pit size will be submitted to the design group perhaps as early as 5 months after the program is initiated.

Monthly status reports will be submitted; the final report will be submitted 10 months after start of the program.

VII. PROGRAM MANAGEMENT

The scale-model exhaust-system test program will be assigned within the NERVA Operations Office to the Special Projects Department, headed by Mr. B. Mandell, which reports through Mr. W. D. Stinnett to Dr. C. H. Trent and Mr. W. C. House, Technical System Manager, Associate Director, and Director of the NERVA Operations, respectively. The Special Projects Department was formed within the NERVA Operations Office to assume responsibility for programs which are closely related to the NERVA engine development program.

Such a management structure is advantageous to the scale-model exhaust-system test program in that separate identifications of the program from other efforts is achieved at a high management level and yet technical knowledge and skills employed and developed for the NERVA program are readily available for consultation and supplementation.

LIST OF SYMBOLS

a	speed of sound
A	area
c	wave velocity
Q_L	centerline
D or d	diameter
E	internal energy
F	Froude number
g	gravitational constant
H	height
h	heat transfer coefficient
L	length
M	Mach number
p	pressure
Pr	Prandtl number
ΔP_f	frictional pressure drop
q	heat flux
R	engineering gas constant
Re	Reynolds number
T	temperature
V	velocity
ρ	density
γ	ratio of specific heats

LIST OF SYMBOLS (cont.)

Subscripts

1,2,3,	station locations
a	ambient conditions
c	chamber
D	duct
g	gas
n	normal to shock
o	stagnation conditions
s or sc	secondary ejector nozzle
se	secondary ejector nozzle exit
t	total
v	environmental cell
w	water or wall
∞	free stream

Superscripts

*	throat conditions
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TABLE I-1

HEAT FLUXES FOR NERVA IN BTU/IN²-SEC

<u>Section</u>	<u>Anticipated from Tests</u>		<u>Test Stand ETS-1</u>	
	<u>Average</u>	<u>Maximum</u>	<u>Average</u>	<u>Maximum</u>
1	0.38	0.48	0.73	5.0
2	0.46	0.68	1.5	5.0
3	0.73	0.83	2.3	5.0
4	11.	12.3	3.4	5.0
5	1.4	2.1	2.8	4.0
6	1.4	2.1	1.4	3.5

TABLE I-2

THEORETICAL CORRELATION OF AIR-WATER DATA
BY FIRST MODIFICATION OF THE ANALOGY

$$M_1 = 2.50$$

Initial Mach Number = 2.5 = Initial Froude Number $\theta = 9^\circ$						
Method of Analysis	Wave Angle	H_2/H_1	ρ_2/ρ_1	p_2/p_1	T_2/T_1	M_2/M_1
Aerodynamic Theory	$30^\circ 54'$	--	1.489	1.759	1.181	0.852
Direct Hydraulic Analogy	$32^\circ 30'$	1.465	1.465 (-1.6%)	2.146 (+22.0%)	(+24.0%)	(-11.6%)
First Modification Hydraulic Analogy	$32^\circ 30'$	1.465	1.465 (-1.6%)	1.718 (-2.3%)	1.173 (-0.7%)	0.858 (+0.8%)

$$M_1 = 5.00$$

Initial Mach Number = 5.00 = Initial Froude Number $\theta = 9^\circ$						
Method of Analysis	Wave Angle	H_2/H_1	ρ_2/ρ_1	p_2/p_1	T_2/T_1	M_2/M_1
Aerodynamic Theory	$18^\circ 27'$	--	2.004	2.759	1.377	0.820
Direct Hydraulic Analogy	$19^\circ 30'$	1.911	1.911 (-4.6%)	3.652 (+32.3%)	1.911 (+38.4%)	0.692 (-15.7%)
First Modification Hydraulic Analogy	$19^\circ 30'$	1.911	1.911 (-4.6%)	2.560 (-7.2%)	1.340 (-2.7%)	0.835 (+1.8%)

Note: Percentages are differences between the quantities obtained from the analogy and theoretical air results.

TABLE I-3PROPOSED TESTING PROGRAM FOR HOT FLOW & SECONDARY EJECTOR TESTS

<u>Type</u>	<u>Purpose</u>	<u>Parameters Investigated</u>	<u>Number of</u>	
			<u>Set-ups</u>	<u>Data Points</u>
A. Present Duct Geometry Utilized for ETS-1				
1. Injection of Fluid at Elbow	Inject low boiling point fluid at elbow to reduce heat flux. Investigate injection patterns and coupled effects on duct performance.	• w of coolant, local heat flux, local duct pressures	3	27
2. Suitable Secondary Ejector	Vary secondary ejector configuration and secondary ejector operating pressure. Obtain data for zero flow from nozzle to rated flow while secondary ejector is operating. Look for stable flow in duct as chamber pressure is cycled to represent start-up & shut-down conditions.	Call pressure, local duct pressures and relate to nozzle and secondary ejector chamber pressures.	3	45
3. System Test	For best results of 1 and 2 above (test purpose), run combined test to prove operation of assy. Use other coolants to prognosticate use of water as coolant in final design.	Local heat, flux, local duct pressures. Operation with joint primary and secondary flow.	6	30

TABLE I-3 (Cont.)

	<u>Type</u>	<u>Purpose</u>	<u>Parameters Investigated</u>	<u>Number of</u> <u>Set-ups</u>	<u>Data Points</u>
B.	Utilize Present Height for ETS-1				
1.	Maximum Elbow Radius - Reference Duct Diameter	Reduce angle at which gas stream intersects with duct wall in order to re- duce heat flux. Demon- strate simultaneous operation of secondary ejector and test engine.	Local heat flux, local duct pressures, flow stability in operating range	3	15
2.	Maximum Elbow Radius - Change Duct Diameter	Same as above	Same as above	3	15
3.	Slanted Inlet Section - same radius at elbow as A above - reference duct diameter - minimum impingement angle.	Same as above	Same as above	3	15
4.	Slanted Inlet Section - same radius at elbow as A above - change duct diameter (see B.2 above)-minimum impinge- ment angle.	Same as above	Same as above	3	15
C.	Allow Increased Height				
1.	Increase height 50% - maximum elbow radius - reference duct diameter.	Same as above	Same as above	3	15
2.	Same as 1 above but increase height 100% of reference.	Same as above	Same as above	3	15

TABLE I-3 (Cont.)

	<u>Type</u>	<u>Purpose</u>	<u>Parameters Investigated</u>	<u>Number of</u>	
				<u>Set-ups</u>	<u>Data Points</u>
C.	(Cont'd)				
	3. Same as 2 above but change duct diameter.	Same as above	Same as above	3	15
	4. Increase height 50% - Slanted Inlet Section same radius at elbow as A above - reference duct diameter - minimum impingement angle.	Same as above	Same as above	3	15
	5. Same as 4 above but increase height 100% of reference.	Same as above	Same as above	3	15
	6. Same as 5 above but reduce duct diameter.	Same as above	Same as above	3	15
D.	Supporting Tests for Selected Configuration	Evaluate range of operational capability of duct to verify design choice. Investigate purge requirements, leakage capabilities, Gimbal effects and secondary ejector capability.	Purge flow rate, residual oxygen content, leakage flow rate, cell pressures and heat transfer ratio related to operational conditions	6	30
E.	Selected Duct Envelope for Phoebus Condition	Evaluate cell pressures and heat transfer rates in duct for Phoebus conditions, based on NERVA design from D above.	Local heat flux, local duct pressures, flow stability in operating range	3	15

TABLE I-3 (Cont.)

<u>Type</u>	<u>Purpose</u>	<u>Parameters Investigated</u>	<u>Number of</u>	
			<u>Set-ups</u>	<u>Data Points</u>
F. Supporting Tests for Phoebus Duct	Determine range of operational capability of duct to verify design. Investigate purge requirement leakage tolerance, gimbal effects and secondary ejector capability.	Purge flow rate, residual oxygen content, leakage flow rate, cell pressure and heat transfer rates related to operational conditions.	6	30

NERVA EJECTOR

Notes:

1. All Diameters Are Internal.
2. All Dimensions Are in Duct Diameters.
3. For Use With Duct to Nozzle
Throat Area Ratios of 35.
4. Overall L/D Along The Center Line=17.28
5. Model Duct Dia=4.76 Inches

EJECTOR SYSTEM PRESSURES
vs CHAMBER PRESSURE
(PRESSURES ARE IN ATMOSPHERES)
SECOND THROAT EJECTOR
(COLD FLOW)

Gimbal $\angle$ 0°

Figure I-2

EJECTOR SYSTEM PRESSURES
vs CHAMBER PRESSURE
(PRESSURES ARE IN ATMOSPHERES)
CONSTANT AREA EJECTOR
(COLD FLOW)

Gimbal $\angle$ 0°

Figure I-3

EJECTOR SYSTEM PRESSURES
VS. CHAMBER PRESSURE
[PRESSURES ARE IN ATMOSPHERES]
(THE NERVA EJECTOR MODEL)
(HOT FLOW)

Figure I-4

CELL PRESSURE VS CHAMBER PRESSURE
FOR VARIOUS SECONDARY EJECTOR
CONFIGURATIONS

SECONDARY EJECTOR TEST MODEL CONFIGURATION ANGULAR INJECTION

DETAIL "A" SECONDARY EJECTOR
NOZZLE

$$\lambda = \theta - \beta$$

$$\phi = \frac{\theta + \beta}{2}$$

SECONDARY EJECTOR NOZZLE	A_D/A_s^*	A_{se}/A_s^*	ϕ	β	θ	λ	L/D ℓ	P_v/P_a min.
A	13.15	3.82	35	24	46	22	10.28	.45
B	10.35	2.34	30	14	46	32	10.28	.34
C	10.15	1.87	19.5	14	25	11	10.28	.292
D	10.66	2.62	12.5	5	20	15	10.28	.132 ①
Da	10.66	2.62	12.5	5	20	15	8.13	.166 ①
Db	10.66	2.62	12.5	5	20	15	5.76	.177 ①

① EJECTOR STARTED

PERFORMANCE OF SECONDARY EJECTOR MODEL "E"
PARALLEL INJECTION

SECONDARY EJECTOR TEST
MODEL CONFIGURATION
PARALLEL INJECTION

DETAIL "A" SECONDARY EJECTOR
NOZZLE

SECONDARY EJECTOR NOZZLE	A_{D_1}/A_s^*	A_{D_2}/A_s^*	A_{se}/A_s^*	λ	L/D_2 ϕ	P_v/P_a min.
E	10.66	15.5	5	40°	8.16	.0442

**CELL PRESSURE VS NOZZLE CHAMBER PRESSURE FOR VARIOUS
VALUES OF SECONDARY EJECTOR CHAMBER PRESSURE**
N₂ EXPERIMENTAL RESULTS
(NERVA EJECTOR MODEL)

HEAT TRANSFER COEFFICIENT
AT 45° POINT OF ELBOW
VS
CHAMBER PRESSURE
(NERVA EJECTOR SYSTEM)

ARRANGEMENT OF SECTIONS
NERVA EJECTOR

SPECIFIC HEAT RATIO AND PRANDTL NUMBER
VS
TEMPERATURE

Simulated Shock Pattern from Water Table Analogy (NERVA Ejector)

Shadowgraph of Shock Locations (NERVA Ejector)

1161-228

Transducer Panel, Rear View

1161-225

Transducer Panel, Front View

Thermocouple Positions on Elbow

NERVA EJECTOR TEST MODEL SYSTEM WITH
MAXIMUM RADIUS ELBOW
ETS-2

Figure I-18

NERVA EJECTOR TEST MODEL SYSTEM WITH
SLANTED INLET SECTION
ETS-2

Figure I-19

Figure I-20

SECTION II

STRUCTURAL DESIGN STUDIES AND TEST
FOR
NNRDC ENGINE TEST STAND ETS-2 EXHAUST SYSTEM

I. SUMMARY

Development of a workable design for the NNRDC engine test stand exhaust system requires studies of a number of specific design elements in addition to the heat transfer and gas dynamics investigations outlined in Section I. The need for such studies has become evident from the partially-complete detailed design work which is presently suspended. This proposal, therefore, includes a limited program comprising the most important of these preliminary design studies, which can be accomplished concurrently with the scale-model test program.

Clearly, the proposed testing and design-study programs are required before design work on the deflector duct can begin. Without the results of this research and development effort, further design work to solve the existing duct problems should not be undertaken.

This deflector duct is shown in Figures II-1 and II-2. One possible configuration change is shown in Figure II-3. None of the work proposed is duplicated in the proposal for ETS-2 facilities.

II. INTRODUCTION

It is proposed that a limited program of preliminary design work be conducted concurrently with the supplemental scale model heat transfer test program. The work planned covers only items which can be accomplished within the time schedule established for heat-transfer testing. Also, it includes only work which is of such a nature as to be essentially independent of heat transfer results.

A general design study will be conducted. This preliminary design investigation will cover first the area of structural acoustics, relating effects which are known regarding chemical rocket engine noise patterns and effects which may have been or can be obtained regarding nuclear rocket engine noise, to the specific duct structures envisioned. It will also cover the general problem of acceptance testing. This includes preliminary planning for a full-scale structural test of one duct section and a feasibility study of initial operation of the duct with a chemical engine to verify overall duct performance, prior to its use for nuclear engine firings. The brief study of materials and fabrication

II Introduction (cont.)

practices, made in connection with the duct design already completed, will be extended in scope. One specific area to be covered will be to establish the feasibility of using aluminum alloys more suited to brazing than the alloys originally selected.

Finally, preliminary design investigations will be made as necessary, including design layout studies, to verify the feasibility of design proposals originating from heat transfer and gas dynamics considerations. These may include, but are not limited to, an investigation of the proposed use of a multi-segment combination cast-aluminum and stainless steel duct elbow, new zero-angle secondary ejector configurations, etc.

Duct coatings will be investigated. Protective refractory coatings as a thermal barrier on the interior surface of the deflector duct were being considered for the vertical section and for the 90° elbow. At the time detailed design work was suspended because of prohibitively high heat fluxes in these areas, a test program to evaluate various coating materials was in process. Since it is likely that a lining or coating will have application in whatever duct configuration is selected, this program should be carried forward.

Tests of flow in the coating tubes are suggested. Pressure drop calculations made for duct design were based on well-established engineering flow data. However, the complex inter-relationships between heat flow, coolant velocity, and pressure, together with the intricate arrangement of the cooling system, makes experimental verification of the calculated U-tube pressure drops highly desirable. The proposed program will include evaluation of tube inlet and outlet orifice effects as well as the probability of cavitation.

A duct seal feasibility study and testing program is required. This study will evaluate the lead-bismuth freeze seal designed for ETS-1 in comparison with other promising concepts that have not yet been given full consideration because of lack of time for proper development (see Figures II-4 and II-5). Activity will be directed specifically toward an improved duct seal possessing a high degree of reliability and minimum operational requirements.

It is desirable, if possible, to separate model testing and preliminary design studies of a general nature from a detailed design effort. Completion

II Introduction (cont.)

of basic gas dynamics and heat transfer testing prior to design initiation is virtually mandatory. Accomplishment of the general design studies, as proposed, prior to commencement of final duct design, will speed design completion by concentrating effort on the most promising of an almost unlimited range of design alternatives.

III. TECHNICAL DISCUSSION

A. GENERAL DESIGN STUDY PROGRAM

1. Acoustic Studies

A preliminary acoustic vibration study was made of the partially-completed design of the deflector duct. This study indicated that information is needed on the vibration spectra and power levels to be experienced during a nuclear rocket firing. Specifically, the following information is required before detailed designs can be completed:

Excitation vibration measurements in the acoustic field at the outlet of a nuclear rocket engine are required. Apparent noise sources should be identified by their location with respect to distance downstream from the exit plane. Instrumentation should record low-frequency vibration, from zero to 500 cps, and higher frequencies in the range from 3000-5000 cps.

Sound power levels in the acoustic field associated with the excitation described in the previous paragraph are required.

The above information is needed for two sources of sound for duct firings. First, it is needed for the turbulent jet of hot hydrogen gas at the entrance of the duct and, second, for the air entrainment area immediately downstream of the duct exit. The latter is expected to be the principal source of duct noise.

Data are required for extrapolating measured values from small nuclear engines to engines of NERVA, upgraded NERVA, and larger sizes.

The above information may be obtainable through LASL from tests already run in connection with the Kiwi engine. Whatever information exists should be made available to this program. If it is not complete, further research and testing may have to be proposed for the acquisition of suitable duct design information.

III Technical Discussion, A (cont.)

This proposal includes only the work necessary to obtain and evaluate available data. The assumption is made that a considerable quantity of data will be available from chemical engine firings. This will be useful for purposes of extrapolating from small to large engines, and for comparing duct firings for altitude simulation with conventional firings where gases are discharged directly into the atmosphere. It is expected, however, that very little data will be available on nuclear engine firings, and that a supplemental proposal for instrumentation of a Kiwi engine run may prove desirable.

2. Acceptance Testing

Two acceptance-test-procedure outlines are based on design work already completed. The first outline covers testing of a full-scale duct section. It was originally planned to include fabrication of the test specimen and the required test work as part of the final duct fabrication.

The second outline contemplated a detailed investigation of the feasibility, cost, and justification for an acceptance test of the completed duct using a chemical rocket engine. The desirability for such a test was predicated upon the essential requirement that a duct for nuclear firings must perform properly in all respects on the first firing; there is no possibility for testing a nuclear engine without nuclear hazard.

It is now proposed that both of the acceptance procedures originally suggested be investigated only for feasibility. The investigation will have as its purpose the determination of a recommended method of testing and final acceptance of the duct.

Pertinent excerpts from both of the original procedures are included below for reference:

a. Evaluation and Testing of NERVA Deflector Duct - Program Description

The design of the small deflector duct is predicated on the data derived from the engine requirements and model testing. Empirical data, theory, and scale-model test experience have been utilized to predict the final duct design and performance. The duct design should be completely verified prior

III Technical Discussion, A (cont.)

to final duct installation and usage. It is therefore necessary that a full-scale duct test be investigated with the end result directed toward obtaining valuable engineering data and experience for the existing as well as future designs.

Aerojet therefore proposes to conduct studies in the following areas:

(1) Determination of the type and extent of the duct tests required, including duct scheduling, transportation to required facility, instrumentation, detailed duct performance and diagnostic parameters, steam ejector evaluation, manpower requirements, and costs.

(2) Evaluation is required of existing test facilities with respect to capabilities, handling techniques, support equipment, duct accommodation, and ability to conduct the required tests. The necessity of evaluating interface problem areas will be studied with special emphasis on remote techniques. Since the duct, in its final test environment, will be elevated into position and held in place by well-supported trunnion mounts, it is evident that such methods must be evaluated as part of the test program. Suitable steam and water supply systems must be available at the testing area. Furthermore, the NNRDC Jackass Flats facility must be compared with other possible test facilities to determine the best economic approach to the overall program.

(3) Evaluation is required of assembly techniques and costs involved for duct assembly at the test site prior to tests. A team of liaison personnel will be required to evaluate and recommend necessary changes that come about due to fabrication and installation.

(4) A feasibility study is required to establish the practicality of using a chemical engine to simulate reactor engine heat flux, thrust, gas temperature and velocity and duct loads.

(5) Evaluation is required of duct delivery-schedule conflict with duct testing requirements and schedule and the resultant influence on the NERVA engine program.

(6) Comparison is required of capabilities of existing facilities with NNRDC (ETS-1) with respect to:

III Technical Discussion, A (cont.)

Chemical engine-installation problems

Propellant storage and supply

Conflict of test program vs test site activation.

(7) Investigation is required of other sources of prime movers.

(8) Review is necessary of all problem areas and implications of above to arrive at a conclusion and recommendations.

b. Structural Tests for Manifold Section

The following is quoted from the preliminary ETS-1 duct specification Par. 4.4, Testing:

Static tests shall be made on a full-scale test specimen of the manifold section to demonstrate the structural integrity of the manifold section, duct wall U-tubes, and ring stiffeners, and to evaluate weld joints and bolted connections. Combinations of loadings shall be performed as applicable. Cycle tests shall be conducted to determine any fatigue strength limitations. The structural tests shall be completed and evaluated prior to shipment of the duct, to permit the making of structural modifications. The tests shall be done under the direction and shall be subject to the approval of the Aerojet structural design test engineer. Requirements for structural testing not specifically specified herein shall conform to the A.S.M.E. Boiler and Pressure Vessel Code, section VIII, UG-101. The tests shall be performed in the following sequence.

4.4.3.1.1 Static tests. - The static tests shall be performed as follows:

- (a) Leak test: The U-tubes and manifolds of the duct test specimen shall be leak tested at 215 ± 10 psig with water at approximately 80°F .
- (b) Proof test: The duct test specimen shall be proof tested at 315 ± 10 psig with water as in 4.4.3.1.1(a).

III Technical Discussion, A (cont.)

Instrumentation for both tests shall include the following:

- (1) Recording pressure gauge
- (2) Deflection reeds
- (3) Strain gauges

(c) Pressure tests:

- (1) The U-tubes shall be pressurized to 215 ± 10 psig and the pressure maintained while the cavity of the duct is evacuated to 1 psig. Visual inspection shall be made while the tubing pressure and the duct vacuum is maintained. Any excessive deformation or buckling shall be noted. Lime wash or other brittle coating shall be applied to critical areas designated by the Aerojet test engineer. Instrumentation for the test shall include the following:

- a Dial indicators
- b Recording pressure gauges
- c Strain gauges

Brittle coating shall be applied to critical areas as designated by the Aerojet test engineer. Instrumentation shall be as in 4.4.3.1.1(b).

- (2) The U-tubes shall be pressurized as in 4.4.3.1.1(c)(1). Axial and bending loads in combination shall be applied to the duct, with the duct in either a horizontal or vertical position. External loads shall be applied in increments beginning at 50 percent of nominal and increasing in increments of 10 percent to 100 percent nominal load. The loading shall be continued to a maximum of 150 percent nominal load in increments as authorized by the Aerojet test engineer. The approximate

III Technical Discussion, A (cont.)

nominal axial and bending loads shall be as follows, and are subject to change in the detailed test procedure:

<u>a</u>	Axial compressive load produced by vacuum, lb	27,800
<u>b</u>	External axial compressive load, lb	14,200
<u>c</u>	External bending moment, at manifold, ft-lb	238,000

4.4.3.1.2 First cycle test.- A duct specimen shall be subjected to the following cycle test.

- (a) The specimen shall be evacuated and subjected to 100 percent nominal axial and bending loads (see 4.4.3.1.1(c)(2)).
- (b) The U-tubes and manifold shall be cycled between 0 and 260 ± 10 psig for 50 cycles.
- (c) Cycling pressure shall be built up in no less than 30 seconds, maintained for at least one minute, and decreased to zero in 5 seconds or less.

4.4.3.1.3 Acoustic test.- The duct specimen shall be subjected to the following vibration loading:

- (a) The duct U-tube section shall be pressurized to 215 ± 10 psig and the inner cavity of the duct evacuated to 1 psig.
- (b) Nominal axial and bending loads of 100 percent shall be applied as in 4.4.3.1.1(c)(2).
- (c) The duct shall be subjected to an acoustic energy input for approximately 15 minutes. Vibration spectra and sound power level shall be approved by the Aerojet test engineer. Instrumentation shall be provided to record the following data:
 - (1) Frequency
 - (2) Acoustic intensity
 - (3) Water pressure
 - (4) Vacuum

III Technical Discussion, A (cont.)

4.4.3.1.4 Second cycle test.- The duct specimen shall be subjected to a second cycle test as in 4.4.3.1.2 except that the test shall be for 100 cycles. Instrumentation shall be at predetermined critical points as established by the Aerojet test engineer from analysis of previous tests.

4.4.3.1.5 Final proof test.- The U-tubes and manifolds shall be subjected to a proof test as in 4.4.3.1.1(b) with no external load or internal vacuum.

4.4.3.1.6 Test to destruction.- A final test to destruction shall be performed provided the Aerojet test engineer finds that the results of the foregoing tests and the condition of the test specimen warrant such a test. The destruct test shall include, but not be limited to the following:

- (a) Bending moment test.- With the U-tubes and the manifold under normal water pressure and the duct evacuated, the duct specimen shall be loaded to failure in bending.
- (b) Pressure test.- With the duct under full vacuum, either with or without external load, the manifold and U-tubes shall be pressurized to failure.

3. Material Selection and Fabrication

The materials selected for the basic duct structure and accessories were two aluminum alloys, 5454 and 5456, in the annealed condition. This selection was made after a study of various aluminum alloys and various types of steel, including the stainless steels. The study considered such factors as:

- Weight and structural strength
- Fabrication problems
- Strength reduction with elevated temperatures
- Heat transfer and thermal conductivity
- Radiation activation and handling problems

III Technical Discussion, A (cont.)

Tube wall design for convective cooling

Corrosion and hydrogen embrittlement

Vibration response, fatigue strength, and related considerations

Instrumentation and general interface problems

Particle penetration.

The two aluminum alloys selected are representative of the non-heat-treatable high-strength aluminum alloys designed for use in structures operating for prolonged times at elevated temperatures in the range between 150°F and 300°F. (Alloy 5454 is suitable for the somewhat higher operating temperatures encountered on the duct wall.) Both alloys have characteristics adequate for welded fabrication. Generally, aluminum was selected in preference to steel because of radiation effects; its greater thermal conductivity was a distinct advantage in comparison to steel.

Detailed design work indicates the existence of certain structural advantages to the use of brazing rather than welding for fabricating the water-cooled wall of the duct. However, the aluminum alloys selected suffer from a major disadvantage in that they cannot be brazed. Consequently, an investigation was made into the possible substitution of an alloy that can be welded and brazed and which has equal or better mechanical properties for the expected temperature range of operation. Minimum mechanical properties at ambient and elevated temperatures were compared. Time of exposure to elevated temperatures proved to be a factor affecting strength, but one for which complete information could not be obtained for the alloys of interest in the time available. Chemical content and activation by radiation were also compared, and on the basis of this preliminary work it was recommended that aluminum alloy 6061-T6 be considered if fabrication of the duct by brazing becomes desirable.

Concurrent with the heat transfer studies proposed, reflecting the requirements of these studies on duct configuration, it is recommended that materials and fabrication methods be further investigated. All of the factors listed above will be considered, so that further selection of an optimum material can be made immediately upon completion of heat transfer tests and prior to initiation of final design.

III Technical Discussion, A (cont.)

4. Design Feasibility Studies

In the course of analytical investigations which accompany the test work proposed, it is anticipated that many concepts will be investigated which may be feasible from the theroretical standpoint but which suffer from practical design, fabrication, or operational disadvantages. Close liaison with the test program is proposed so that design input will be available in the concept stages of the heat transfer and gas dynamics program. Layout and preliminary design investigations may be required in some cases. Two areas in which such assistance can prove to be of great value are in elbow "fixes" and in revised steam ejector concepts.

III Technical Discussion (cont.)

B. DUCT COATINGS

1. General

Fulfillment of the operational requirements of the deflector duct are closely related to the selection of an adequate protective coating. Major problems associated with operational requirements and environmental conditions are compatibility with hydrogen gases at very high temperatures and velocities, as well as exposure to high density nuclear radiation. The refractory coating system is intended to protect the structural components of the duct from excessive thermal exposure and damage.

2. Problem Areas

The apparent problem areas associated with the coating of the deflector duct are the mechanical and physical behavior of the coating at operational conditions, including adherence to the substrata; thermal-shock resistance; spalling resistance under random low and intermediate vibration; dimensional, chemical, and metallurgical stability at high temperatures; abrasion resistance; thermal endurance; and thermal stability.

The operational requirements and environmental condition are not completely defined and need to be more firmly established. This should include temperature range, vibration level, duct deformations, and gas velocities.

Data on mechanical and physical properties of refractory materials, as far as it is available, is not directly applicable to the duct design.

The merits, advantages and disadvantages of different methods of application of different coating materials need careful investigation. The three leading methods (flame-sprayed, plasma-sprayed, and fused coatings) need to be investigated, compared, and evaluated.

Another problem area requiring investigation is whether coating of the interior duct surface shall be done with or without filler material between the tubes.

III Technical Discussion, B (cont.)

3. State-of-the-Art

Considerable research work with refractory coating materials has been conducted by different companies in conjunction with different applications. Many coatings developed and used in the industry are tailored for a particular application. Research and development studies are presently being conducted at Aerojet-General's Sacramento Plant for coating systems of different rocket engines. Titan II first- and second-stage chambers are being coated for full-scale engine test evaluation. Experience has been gained in developing procedures and methods of applications of thermal barrier coatings for the Polaris and Minuteman solid propellant rocket nozzles, experimental tubular combustion chambers, gas generator nozzles, etc. This experience will be utilized in conducting this program.

4. Conclusion

In view of all problems associated with the selection of a protective coating system for the deflector duct, a proposed research program is considered necessary and is regarded as a minimum effort.

C. COOLING TUBE FLOW TESTING

Empirical data from the hot and cold gas flow testing program have been used for determining heat transfer and water flow parameters. The water flow calculations are further based on empirical flow coefficients. Existing charts and tables of coefficients are limited to more common and simple inlet and discharge conditions and more uniform tubing than can be incorporated in the duct design. Thus, an interpretation of actual flow conditions, and applicable flow factors, has been required in the past, with the result that calculations have not been made with complete reliability or sufficient dependability to permit optimum flow distribution.

Because of the high velocities, the pressure drop in the tubes is quite high. Since pressure drop is proportional to the square of the velocity, and since available pressure drop is rather small, it becomes quite important that flow conditions be dependably chosen and verified.

By performing flow tests on both long and short tubes with open ends, and on similar length tubes with simulated inlet and outlet conditions, sufficient

III Technical Discussion, C (cont.)

data should be accumulated to accurately define pressure drop per unit length of tube and to define inlet and outlet conditions.

Calculated water flow data are shown for reference purposes in Table II-1.

III Technical Discussion (cont.)

D. DUCT SEAL FEASIBILITY AND TESTING

1. General

The engine compartment and duct connection must be sealed air-tight to prevent the accumulation of an explosive air and hydrogen mixture and to permit pulling a vacuum to simulate high altitude conditions. Any accumulation or concentration of air leakage creates an explosive hazard and presents the possibility of the destruction of the engine and test stand.

Thus, there is a need for an extremely high level of reliability in making and holding the seal regardless of engine operation or other occurrences. Furthermore, the duct must be readily removable from the test stand. To meet these requirements the seal should actually be fail-safe during removal (must not hang up).

While the seal must be positive it must accommodate a considerable amount of duct movement and mismatch in fit-up. The duct is expected to grow due to thermal expansion, approximately 1-3/8 in. in height and approximately 3/4 in. radially. Vibration forces may also be considerable. A flexible connection, or expansion joint, is therefore a prerequisite for nearly any sealing concept.

Pressurization with gaseous nitrogen between duplicate seal elements is considered as an added precaution, where applicable. Pressurization can then be held slightly above atmospheric so that any leak will bleed N₂ into the duct or to the atmosphere, but will at all times prevent air leaking in.

The remote acutation concepts given greatest consideration to date are as follows:

Differential-pressure loaded seal (Figure II-4)

Frozen metal seal (lead-bismuth seal designed for ETS-1) (Figure II-5).

Mechanical (or other) clamp-type seal.

Some of the problem areas connected with these concepts are discussed in the following paragraphs.

III Technical Discussion, D (cont.)

2. Problem Areas

a. The desirability of effecting a seal in the easiest possible manner suggests that the means of duct positioning should also be the means of seal actuation. This presents the problem of requiring a mechanism which fully actuates the seal with duct raised to a certain height and yet permits duct to grow (thermally) to a greater height.

b. Differential pressure between atmosphere and engine compartment can be utilized for providing seal clamping force (Figure II-4). No metal O-rings have, however, been found which are readily adaptable to this application because they require an excessively high sealing load. At 100 lb/lin in. of force on an O-ring and 12 psi differential, the required pressurizing area is 2750 in². This requires approximately 20-in. diameter flange around duct (radial measurement). There is a need for other more resilient gasket or O-ring material which will withstand the high radiation encountered.

c. The use of remote-actuated clamping means presents the same problems of O-ring squeeze loading as in paragraph b, above. Seal members must be made very rigid and heavy to take any large clamping forces, especially if clamping loads cannot be evenly distributed.

d. The completion of the frozen metal seal (Figure II-5) requires verification to a number of items including the following:

Temp control system (requires heating and cooling)

Stability of the eutectic alloy of lead and bismuth in radiation and vacuum environments.

Adherence to mating seal members (container and inserted member) and effects of melt-metal contamination and corrosion)

Effects of radiation and other heating

Effectiveness of liquid core in sealing of cracks or voids in solidified boundary structure

Method of initially melting metal to make connection. Method of making electrical and coolant connections.

IV. PROPOSED PROGRAM

In general, details of the proposed program with regard to design studies and testing is best presented by reference to the schedules and milestones presented in Figure II-6. This is particularly true of the general program which has been covered in considerable detail in the preceding technical discussion.

A. DESIGN STUDY

The investigation and resolution of specific problems related to the design and fabrication of the exhaust system for a nuclear rocket engine test stand will be undertaken. These investigations will include consideration of the acoustic environment to determine, if possible, the probable acoustic environment in the exhaust duct cavity and to result in recommendations for a test program where existing data are inadequate. Requirements for the acceptance testing of the completed exhaust deflector duct will be considered and recommendations regarding structural tests and the feasibility of conducting full-scale tests with a chemical rocket engine will be made. Study of materials and fabrication methods will be continued considering design requirements and new test results. Design feasibility reviews will be conducted of concepts for specific duct components which evolve during the hot-flow test program.

B. COATINGS

Refractory coatings for the small deflector duct will be analyzed and fabrication and test of specimens, models, and system components will be effected. A review of the design considerations for establishing the operational requirements and loading conditions on the duct and its coating shall be made prior to establishing the range and type of tests necessary for obtaining pertinent information on the candidate coatings.

An evaluation of the results obtained from the presently conducted coating test at Aerojet-General, Sacramento Plant shall precede a firmly established test program for the coating of the deflector duct.

The following methods of application are considered at the present time: flame-sprayed coatings; plasma-sprayed coatings; and fused-type coatings.

IV Proposed Program, B (cont.)

In addition, two design conditions are considered: filler material provided between the tubes; and tubes coated without filler material between them.

The evaluation program shall include, but not be limited to, the following coating materials and design:

Zirconium oxide directly applied on the aluminum tubing

Metallic sublayer and zirconium oxide in variable mixtures

Metallic sublayer, zirconium oxide and zirconium carbide in variable mixtures

Nichrome primer, nichrome and zirconia gradated, zirconia top layer

Molybdenum primer, zirconia and tungsten carbide gradated, molybdenum top layer

Molybdenum primer, molybdenum and zirconia gradated, molybdenum top layer

Blend zirconia + AMS4775 - fused-type coating

Blend zirconia + Coast Metal Co. No. 60 or GE 8100 type fused coating.

It is realized that not all mechanical, thermal, and radiation effects on the coatings can be evaluated with these tests. For a proper evaluation a more extensive program is required. However, as a minimum requirement, the following tests are presently considered:

Tests samples consisting of an arc 6 in. wide, corresponding to the duct configuration, and 18 in. long, shall be subjected to tensile tests, thermal shock, a thermal cycling test, a bend test, and a vibration test.

Test samples consisting of entire circumferential section and 18 in. long shall be subjected to similar loading conditions: longitudinal tensile load, thermal shock, thermal cycling, external circumferential compressive load, and vibration.

Data to be obtained from these tests are: tensile strength at various temperatures, thermal shock resistance, endurance resistance against thermal cycling, bend strength, spalling and vibration resistance.

IV Proposed Program, B (cont.)

Correlation, comparison and evaluation studies of all test results shall be made and if fulfillment of anticipated operational conditions of the entire duct are indicated, a selection of two or three candidate coating systems shall be made for further studies and testing prior to a final recommendation for application in the deflector duct.

A study shall be made of all possible service requirements, such as surface protection, oxidation protection, cooling requirements, mechanical damage and repair. Also, it shall be recommended that these requirements be incorporated in a maintenance manual.

C. DUCT WALL TUBING FLOW

A program to obtain a verification of design flow calculations in the duct wall tubing and to determine flow factors as a basis for accurately establishing practical water velocity limits will be conducted. It is proposed that a water flow test be conducted through duct-wall tubing as dictated by existing design (or by subsequent current design at time of test). This testing is to be aimed at obtaining flow factors and other empirical data. To obtain the necessary information from a minimum amount of testing, it is proposed that all pressure drop and flow factor information be obtained by flowing the following for each configuration of tubing and manifold considered:

Maximum length tube in any section with simulated inlet and outlet conditions (maximum length approximately 120 in.)

Very short (approximately 5 d) tube with simulated inlet and outlet conditions

Maximum length tube in any section with open inlet and outlet conditions

Very short (approximately 5 d) tube with open inlet and outlet conditions.

To accomplish this, the following steps must be taken. First, a review of methods of meeting the flow requirements shall be made with the aim of verifying flow conditions incorporated in the then current design and of providing criteria required design revisions dictated by the results of further heat transfer studies. Based on this review the actual selection of items to

IV Proposed Program, C (cont.)

be tested, and the flow ranges, shall be decided. The basic methods of conducting the tests shall then be defined. Second, test specimens are to be designed as single tubes which will produce exactly the same flow conditions achieved in the actual duct. The holding fixture, or tube manifold, shall be designed to simulate conditions in an actual duct manifold (near static conditions). The following tasks will then be accomplished:

Test specimens and fixtures will be fabricated

Four tests will be performed on each tube design in accordance with items (a) through (d) of 4.1. For each test, the flow rate shall be varied over a range of 1.05 lb/sec (approximately 30 ft/sec) to 3.5 lb/sec (approximately 100 ft/sec), or as determined in 4.1.1, or by limiting tube pressurization to 200 psi. A back pressure of 30 psi minimum will be maintained throughout.

The results obtained shall be evaluated to determine flow (friction) factors for inlet-to-tubing and per unit-length of tubing. Results shall be compared with design calculations. Recommendations shall be made if objectives are not met.

D. VACUUM SEALS

A program will be conducted to provide a workable remotely-actuated vacuum seal design and to verify the success of the design by proper test evaluation. It is proposed that a program be conducted to develop a completely dependable vacuum seal to connect the duct to the engine compartment. The following steps are planned:

Determine requirement criteria in regard to size of components, axial and radial movement, out-of-roundness, misalignment and fit-up, permissible leakage, remote control requirements, etc.

Make investigation of existing applications, flexible connections included

Evaluate and compare concepts, e.g., O-ring with vacuum balance, frozen metal remote-actuated clamp sealing, etc.; consider whether applicable to remote coupling and what possible problems may arise; select most promising concept and resolve fabrication and test methods

IV Proposed Program, D (cont.)

Define with drawings which are sufficient for prototype manufacture. Include test fixture, or other design; test fixture must provide for axial and lateral movement similar to that of actual duct (to scale)

Fabricate test seal and test fixturing; procure purchased parts Include bellows, or other flexible connection, if part of system

Perform tests according to plan of 4.3 above, interpret data, and write report.

V. PROPOSED WORK STATEMENT

The following statement of work is suggested:

Task 2: Design Studies and Testing

Item 2.1: The contractor, the Aerojet-General Corporation, shall provide the necessary personnel and facilities to investigate and resolve specific problems related to design and fabrication of the exhaust system for a nuclear rocket engine test stand. The investigation shall include: (a) review of existing data on the acoustic environment of nuclear and chemical rocket engine test stands; to determine therefrom, if possible, the probable acoustic environment in the duct cavity of the stands for NERVA engines; and to recommend a test program for acquisition of data where existing sources are inadequate; (b) study requirements for acceptance testing of a completed exhaust deflector duct, and make recommendations regarding structural tests and the feasibility of conducting full-scale tests with a chemical engine; (c) continue studies of materials and fabrication methods, considering design requirements as presently known and new test results; (d) make design feasibility reviews of concepts for specific duct components which evolve during the hot flow test program, including dimensional layout studies as required.

Item 2.2: The contractor shall provide the necessary personnel, facilities and materials to design, fabricate and test such specimens, models and system components as may be necessary to provide detailed recommendations for final specification or design of the following components: (a) duct coatings; (b) U-tube flow conditions; (c) vacuum seal between duct and engine compartment.

V Proposed Work Statement (cont.)

In each area, investigations and/or conceptual studies shall be conducted to the extent required to establish operating requirements, environmental conditions and other pertinent factors prior to testing.

Item 2.3: The contractor shall provide monthly status reports and a final report summarizing the results of the study and testing program, correlating these reports with requirements of the prototype design.

VI. SCHEDULES & MILESTONES

A schedule for the proposed program is shown in Figure II-6. The overall program will be completed within 10 months. The general design studies will be completed after 4.5 months. The duct coating studies will start at the end of the first month with the testing program starting 1.5 months later and continuing for 3 months. The flow testing of the duct wall tubing will start immediately and be completed within 3 months. The vacuum cell development will culminate in a test program of approximately 1 month duration starting 5 months after program initiation. Monthly status reports will be submitted, with a final report delivered 10 months after the start of the program.

VII. PROGRAM MANAGEMENT

The scale model exhaust system test program will be assigned within the NERVA Operations Office to the Facilities Department, headed by Mr. L. E. White, which reports through Mr. W. D. Stinnett to Dr. C. H. Trent and Mr. W. C. House, Technical System Manager, Associate Director, and Director of NERVA Operations, respectively.

TABLE II-1

DUCT U-TUBE WATER FLOW PARAMETERS

<u>Section</u>		<u>H₂O Flow (lb/sec)</u>	<u>H₂O Velocity (ft/sec)</u>	<u>Max Friction* Loss (psi)</u>
1.	Super-Sonic Section	690	46	70
2.	" " "	650	44	36
3.	" " "	740	50	68
4.	" " "	850	57	105
5c.	Elbow-Upper	400	54	88
5d.	Elbow-Lower	343	46	80
6.	Turbulent Mixing Section	640	43	78
7.	" " "	480	32	48
8.	" " "	490	33	50
9.	" " "	430	29	46

Total 5713 (41,000 GPM)

* Friction losses are based on Fanning formula with friction factor = 0.016 and smallest hydraulic diameter in section.

SMALL NERVA DEFLECTOR DUCT

ORIGINAL NERVA DUCT CONFIGURATIONS

SCALE $\frac{1'}{8} = 1'-0"$

Figure 11-2

ELBOW CHANGE SMALL DEFLECTOR DUCT

Figure II-3

VACUUM BALANCED SEAL

FROZEN METAL SEAL

TASK 2 SCHEDULE AND MILESTONES

ITEM NUMBER AND TITLE

TIME IN MONTHS