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STATUS OF SUB-SONIC TURN INVESTIGATION

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STATUS OF SUB-SONIC TURN INVESTIGATION

I. INTRODUCTION

As of the date of this report all basic ejector configuration (Figures 1 through 4) have been built and tested. This corresponds to the "Primary Configuration Tests" of Table I. The approximate location of the instrumentation is shown in Figures 5 through 8.

II. TEST RESULTS

In general, all systems tested, Figures 1 through 4 exhibited starting chamber pressures between 16 and 21 atm. provided that choking of the primary gas did not occur in the constriction downstream of the elbow. The minimum operating point as a function of ejector exit area ratio is shown in Figure 9.

On the first series of tests (Ejector #1) it was verified that constrictions of 3" ID and 4" ID would not permit the system to start. For one test a constriction of 4.25 was used, and a start condition was not obtained until the engine was in its shutdown transient. A 4.5 in constriction exhibited no difficulty in starting, however the starting chamber pressure was higher than for larger diameter constrictions.

Selected wall pressures as a function of chamber pressure for the four configurations are shown in Figures 10 through 13. With the assumption of one-dimensional flow, Mach numbers were obtained from the local static pressures and are shown in Figures 14 - 17.

The preliminary scale model heat transfer coefficients are shown in Table II. As of this date the data is unchecked and incomplete.

III. ANALYSIS

A. STABLE FLOW CRITERIA FOR SUBSONIC TURN CONFIGURATIONS

The subsonic turn configurations being tested have a limitation on exit area that was not realized at the start of the test program. This limitation

is caused by the desirability to reduce the exit flow area of the system and shorten the overall system length as well as to reduce the secondary fluid requirements.

The operation of a second throat ejector system depends on the establishment of an oblique shock system to produce sub or transonic flow at the second throat exit plane. This is normally followed by a diffuser section downstream of the second throat. When the ejector pulls in, the Mach number at the exit of the second throat is low and the flow is subsonic. However, as the chamber pressure is raised above the pull-in point the shock structure keeps developing and the Mach number at the second throat exit increases. When the flow is re-accelerated by an additional converging section, the exit flow becomes sonic at much lower chamber pressures and has a strong influence on ejector performance. For the NERVA engine it is desired to operate the ejector system at chamber pressures 3 times the pull-in pressure initially and to upgrade the system to chamber pressures 10 times the pull-in pressure.

A simple inequality can be established to determine when sonic flow will exist at the ejector exit from a comparison with the nozzle throat conditions. Thus for sonic flow at the exit

$$\frac{P_c}{P_{e_t}} \geq \epsilon_e \quad (1)$$

Since exit area ratios from 20 to 30 are being considered as reasonable based on the analysis of ejector performance, it can be seen that at the NERVA design point, sonic flow will exist at the ejector exit.

To evaluate the effect of sonic flow at the ejector exit on flow in the diffuser section, the assumption of a normal shock in this area will be made. The static pressure upstream from this shock can then be estimated from

normal shock relations. This gives

$$P_s = \left(\frac{P_s}{P_{t3}} \right) P_{te} = \left(\frac{P_s}{P_{te}} \right) \frac{P_e}{E_e} \quad (2)$$

Multiplying by E_s/P_e gives

$$\frac{E_s P_s}{P_e} = \left(\frac{P_s}{P_{te}} \right) \left(\frac{E_s}{E_e} \right) = \frac{.571}{M \left(1 + \frac{\gamma-1}{2} M^2 \right)^{1/2}} \quad (3)$$

A graphical solution is then used to determine the relationship between E_s/E_e and Mach number just upstream of the shock. This shows that for $E_s/E_e = 1.2$, the upstream Mach number is 2 and hence to stabilize the $M = 1$ location in the second throat would require an exit area ratio of 1.4 times the minimum area ratio. The exit area ratio should therefore be between 1.0 and 1.4 times the second throat area ratio to avoid separation problems when P_e is much larger than the pull-in pressure. For $E_s/E_e > 1.2$ the Mach number upstream of the shock increases rapidly and becomes unrealistic physically.

This effect will be most pronounced when the secondary ejector is used for pumping and indicates that for some ejector designs the secondary ejector could cause separation of flow to occur in the diffuser and elbow region which would not occur when the secondary ejector was not in operation.

B. PREDICTION OF EJECTOR PERFORMANCE FROM MOMENTUM LOSSES

Up to the present time, ejector performance prediction has been made on the basis of a rule of thumb. The work done in CY 1962 has indicated that a substantial improvement in this rule of thumb can be made by considering the momentum losses in an ejector system.

Although the CY 1962 work developed relationships for curved systems, the equations developed here will be for a one-dimensional system. Consider

A momentum balance for (1) to (3) can be stated as follows:

$$F + P_v A_t (\epsilon_{D1} - \epsilon_{Pe}) = f \frac{L}{D} \left(\frac{P V^2}{2g} \right) + P_e A_t \epsilon_{D3} (1 + \gamma M_e^2) \quad (4)$$

Thrust + Pressure force in = losses + leaving momentum

However a more realistic momentum balance can be made between stations (1) and (2).

$$F + P_v A_t (\epsilon_{D1} - \epsilon_{Pe}) = f \frac{L}{D} \left(\frac{P V^2}{2g} \right) + P_2 A_t \epsilon_{D2} (1 + \gamma M_2^2) \quad (5)$$

The pressure P_e is known so that a mass balance can be used to determine the Mach number at station (3)

$$\gamma M_3^2 = \frac{\gamma}{\gamma - 1} \left\{ \left[1 + \frac{2(\gamma - 1)}{\epsilon_e^2} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}} \left(\frac{P_c}{P_e} \right)^2 \right]^{\frac{1}{2}} - 1 \right\} \quad (6)$$

When $M_3 > 1$, Equation (6) can also be used to determine M_2 based on P_e . This simplification will be used throughout the analysis. The static pressure at station (2) can then be found from the Mach numbers and the assumption that stagnation pressure remains constant between stations (2) and (3).

$$P_2 = P_e \frac{(P_2/P_t)}{(P_3/P_t)} = P_e \frac{\left(1 + \frac{\gamma - 1}{2} M_e^2 \right)^{\frac{\gamma}{\gamma - 1}}}{\left(1 + \frac{\gamma - 1}{2} M_2^2 \right)^{\frac{\gamma}{\gamma - 1}}} \quad (7)$$

Therefore

$$P_2 \approx P_e \frac{\left(1 + \frac{\gamma}{2} M_e^2 + \frac{\gamma^2 M_e^4}{8\gamma}\right)}{\left(1 + \frac{\gamma}{2} M_2^2 + \frac{\gamma^2 M_2^4}{8\gamma}\right)} \quad (8)$$

Now the kinetic energy of the exhaust gases can be related to the thrust of a nozzle flowing full as follows:

$$f \frac{L}{D} \left(\frac{P V^2}{2g} \right) = \frac{\epsilon_{D2}}{\epsilon_{Pe}} \left(\frac{L}{D} \right) \left[C_{Fvac} - \frac{P_v}{P_c} \epsilon_{Pe} \right] P_c A_t \quad (9)$$

Combining Equations (5), (8) and (9) gives

$$\begin{aligned} C_{Fvac} - \frac{P_v}{P_c} (2\epsilon_{Pe} - \epsilon_{D1}) &= \frac{\epsilon_{D2}}{\epsilon_{Pe}} \left(\frac{L}{D} \right) f \left(C_{Fvac} - \frac{P_v}{P_c} \epsilon_{Pe} \right) \\ &+ \frac{P_e}{P_c} (1 + \gamma M_2^2) \frac{\left(1 + \frac{\gamma}{2} M_e^2 + \frac{\gamma^2 M_e^4}{8\gamma}\right)}{\left(1 + \frac{\gamma}{2} M_2^2 + \frac{\gamma^2 M_2^4}{8\gamma}\right)} \end{aligned} \quad (10)$$

Solving for Equation (10) for f yields

$$f = \frac{C_{Fvac} - \frac{P_v}{P_c} (2\epsilon_{Pe} - \epsilon_{D1}) - \frac{P_e}{P_c} (1 + \gamma M_2^2) \frac{\left(1 + \frac{\gamma}{2} M_e^2 + \frac{\gamma^2 M_e^4}{8\gamma}\right)}{\left(1 + \frac{\gamma}{2} M_2^2 + \frac{\gamma^2 M_2^4}{8\gamma}\right)}}{\frac{\epsilon_{D2}}{\epsilon_{Pe}} \left(\frac{L}{D} \right) \left(C_{Fvac} - \frac{P_v}{P_c} \epsilon_{Pe} \right)} \quad (11)$$

The unknowns in Equation (11) are f and P_v/P_c . P_v/P_c can be estimated reasonably well by using isentropic flow tables and an average area ratio between C_{pe} and C_{D1} . This enables calculation of f as a function of P_c/P_e . Although the correct value of f is not known it must be greater than zero and less than about .03.

An error exists in Equation (11) due to an incorrect M_2 , but this error is small for most cases of interest. When $C_{D3} = C_{D2}$ there is no error and only for $M_2 > 1$ does the error become significant when $C_{D3} > C_{D2}$. In this form, Equation (11) enables predictions to be made for the effect of ejector inlet area ratio, contraction ratio and exit area as well as predicting the effects of different nozzle geometries in the same ejector (i.e. different area ratios or contours). The effect of increasing the length of the second throat is also predicted for lengths beyond the minimum required for satisfactory performance.

According to this theory, the flow characteristics in the elbow of the subsonic turn configurations should not affect the ejector performance and hence predictions can be made in terms of the second throat length and the exit area ratio of the system. For these configurations, only a minor error should be introduced by the one-dimension flow assumption.

Figure 9 shows the predicted performance of the subsonic turn configurations as a function of the exit area ratio. It can be seen that a definite penalty is incurred at the exit area ratios, and hence only area ratios greater than 20 are of interest in selecting a primary ejector system for ETS-1.

C. OUTSIDE AND INSIDE ELBOW PRESSURES

Using the method derived in AGC Report 2403, the outside and inside pressures in the elbow were computed for Ejector Configurations 1c, 2c, 3c and are shown in Figure 18.

TEST PROGRAM SUMMARY

SUBSONIC TURN EJECTOR 1

12-27-62
amp
REV 12-28-62

NOTES:

1. EJECTOR EXPANSION RATIO
 $A_D/A^* = 19.9$
2. THIS IS A $\frac{1}{8.15}$ SIZE MODEL
3. ALL DIMENSIONS IN INCHES
4. MATERIAL:
CRES 347 OR 321

Fig 1
SCALE $\frac{1}{10}$ SIZE

SUBSONIC TURN EJECTOR 2

NOTES:

1. EJECTOR EXPANSION RATIO
 $A_0/A^* = 19.9$
2. THIS IS A $\frac{1}{8.15}$ SIZE MODEL
3. ALL DIMENSIONS IN INCHES
4. MATERIAL:
CRES 347 OR 321

Fig 2

SCALE $\frac{1}{10}$ SIZE

SUBSONIC TURN EJECTOR 3

12-27-62
 REV. 12-28-62

NOTES:

1. EJECTOR EXPANSION RATIO
 $A_0 / A^* = 19.9$
2. THIS IS A $\frac{1}{8.15}$ SIZE MODEL
3. ALL DIMENSIONS IN INCHES
- 4 MATERIAL:
 CRES 347 OR 321

Fig 3
 SCALE $\frac{1}{10}$ SIZE

SUBSONIC TURN EJECTOR 4

12-28-62

ALP

NOTES:

1. EJECTOR EXPANSION RATIO
 $A_{D_2}/A^* = 19.9$
2. THIS IS A $\frac{1}{8.15}$ SIZE MODEL
3. ALL DIMENSIONS IN INCHES
4. MATERIAL:
CRES 347 OR 321

Fig 4

SCALE $\frac{1}{10}$ SIZE

PRIMARY EJECTOR 3c

PRESSURE TAPS

THERMOCOUPLES

PRESSURE
TAP

L/D

THERMO-
COUPLE

L/D

PD 1
PD 2
PD 3
PD 4
PD 5
PD 6
PD 7
PD 8
PD 9
PD 10

1/6 SIZE

PRIMARY EJECTOR 1c

PRESSURE TAPS

THERMOCOUPLES

PRESSURE
TAP

L/D

THERMO-
COUPLE

L/D

PD-1
PD-2
PD-3
PD-4
PD-5
PD-6
PD-7
PD-8
PD-9
PD-10

PRIMARY EJECTOR 2c

PRESSURE TAPS

THERMOCOUPLES

PRESSURE
TAP

L/D

THERMO-
COUPLE

L/D

PD 1
PD 2
PD 3
PD 4
PD 5
PD 6
PD 7
PD 8
PD 9
PD 10

Fig 6
1/6 SIZE

PRIMARY EJECTOR 4c

PRESSURE TAPS		THERMOCOUPLES	
PRESSURE TAP	L/D	THERMO-COUPLE	L/D
PD 1			
PD 2			
PD 3			
PD 4			
PD 5			
PD 6			
PD 7			
PD 8			
PD 9			
PD 10

1/6 SIZE

Fig 8

Aerjet-General
CORPORATION

Fig 9

Fig 9

Avcojet-General
CORPORATION

CLEARPRINT CHARTS

WALL PRESSURES - SST #1-C

P_c / P_a

R. E. M.
2/28/63

P/P_a

Fig 10

Aerjet-General
CORPORATION

WALL PRESSURES - SST #2-C

2/20/63
REN

Aerjet-General
CORPORATION

WALL PRESSURES - SST #3-C

2/25/63
R8 m

Aerjet-General
CORPORATION

WALL PRESSURES - SST #4-C

3-5-63
Yop

Aerjet-General[®]
CORPORATION

MACH NUMBER VS CHAMBER PRESSURE
EJECTOR 1-C

M

5

4

3

2

1

0

- — P₀₁
- — P₀₄
- ◇ — P₀₅
- × — P₀₁₇

P_c/P_a

3/5/63
R E N

Aerjet-General
CORPORATION

Avjet-General
CORPORATION

CLEARPRINT CHARTS®

MACH NUMBER VS CHAMBER PRESSURE
EJECTOR 3-C

3/5/63
RSE

Aerjet-General
CORPORATION

CLEARPRINT CHARTS

MACH NUMBER VS CHAMBER PRESSURE
EJECTOR 4-C

3/5/63
REN

FIG 17

Aerjet-General[®]
CORPORATION

**CALCULATED AND TEST ELBOW PRESSURES FOR
FOR SST CONFIGURATIONS 1c, 2c, AND 3c,
FOR SUBSONIC FLOW IN ELBOW**

CALCULATED PRESSURES

— P_0/P_a , ALL DUCTS

— P_1/P_a , 1c, 2c, 3c CONF.

TEST PRESSURES

○ P_0/P_a , ALL DUCTS

□ P_1/P_a , 3c CONF.

⊙ P_1/P_a , 2c CONF.

EXIT DIAM. 4.76 (E=19.9)

3-5-63
EJS

P_0/P_a
 P_1/P_a