REPORT NO. 2678

ETS-1, NES PERFORMANCE
AND
DESIGN CRITERIA

ROCKET ENGINE OPERATIONS - NUCLEAR

SEPTEMBER 1963

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

AEROJET - GENERAL CORPORATION
A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

DISTRICT NO. 1

750

2

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

This report presents the test results of the ejector scale model test program of Contract Year 1963 as they apply to the full scale Engine Test Stand-1 (ETS-1). The purpose of this evaluation was to determine the performance and design criteria for subsonic turn ejector systems in the NERVA Exhaust System (NES) for the ETS-1. The experimental tests were conducted on 1/8 scale models. The analytical and experimental results, and the evaluation of the sub-scale model tests, are presented in REON Report No. 2679. As a result of the data obtained through this experimental and analytical evaluation, the design implications for the NES for ETS-1 have been drawn.

Approved:

B. Mandell Jr

W. D. Stinnett
NERVA Technical Systems Manager
REON

FOREWORD

This report is presented in partial fulfillment of SNP-1 Contract Task Item 3.1.3 which states in part: "Conduct scale model tests which will provide information to develop design criteria.....for the ETS-1.....NES system".

TABLE OF CONTENTS

	<u>Page</u>
Table and Figures _____	iv
Introduction _____	v
I. EJECTOR CONFIGURATION _____	1
II. PERFORMANCE _____	2
A. Aerodynamic _____	2
B. Heat Transfer _____	2
C. Safety Purge _____	2
D. Pre-Fire Purge _____	3
E. Exhaust Plume _____	3
III. METHOD AND CONFIDENCE OF PREDICTIONS _____	5
A. Aerodynamic _____	5
B. Heat Transfer _____	5
C. Safety Purge _____	6
D. Pre-Fire Purge _____	7
E. Exhaust Plume _____	7
APPENDIX _____	<u>Page</u>
Table and Figures _____	A-ii
A. Configuration _____	A-1
B. Aerodynamic Performance _____	A-7
1. Ejector Performance _____	A-7
2. Pressure and Mach No. Profile _____	A-10
3. Pressure Fluctuations _____	A-15

TABLE OF CONTENTS (cont.)

a.	Ejector _____	A-15
b.	Engine Compartment _____	A-16
4.	Steam Safety Purge _____	A-25
5.	Operation with Turbine Exhaust and Seal Leakage _____	A-32
6.	Exhaust Plume Shape _____	A-36
7.	Pre-fire Ejector System Purge _____	A-39
C.	Heat Transfer Evaluation _____	A-42
1.	Ejector Wall Heat Transfer Coefficients _____	A-42
2.	Exhaust Plume Thermal Radiation _____	A-47
	Nomenclature and Symbology _____	A-50

INTRODUCTION

This report is a presentation of the results of the ejector scale model test program of Contract Year 1963, as they apply to the full scale ETS-1 ejector design. The test results and analyses pertinent to the NERVA Exhaust System were incorporated into the preliminary design and integrated within the design schedule.

A brief genealogy of the selected ejector system is given where applicable, but this report reflects current thinking in all areas whether or not the areas covered were changed by design modifications.

To be of any value, this report must be kept current, indicating effect of design modifications as they affect aerodynamic performance and heat transfer. Periodic section revisions will therefore be made and distributed as they become applicable.

I. EJECTOR CONFIGURATION

The internal configuration of the NERVA Exhaust System (NES) ejector for use in ETS-1 is illustrated in Figure 1. This configuration evolved through extensive scale model testing, having demonstrated the best compromises in the aerodynamic and heat transfer areas. The turbine exhaust fluid must be introduced through two supersonic nozzles located at the NERVA nozzle exit plane (as shown in Section B.5 of the Appendix) when testing a 25:1 area ratio NERVA nozzle to prevent flow separation in the NERVA nozzle. The ejector will operate properly and allow 10:1 area ratio nozzles to flow full when the turbine exhaust fluid is introduced into the engine compartment.

II. PERFORMANCE

A. AERODYNAMIC

The performance, environmental cell pressure as a function of nozzle chamber pressure, of the selected configuration with the defined safety purge and no turbine exhaust fluid is illustrated in Figure 2. It is not expected that this performance will change with 1 lb/sec nitrogen seal leakage and rated turbine exhaust flow when injected into the engine compartment as illustrated in Figure B.5-1 of the Appendix. To obtain the performance in PSIA at the Nevada Test Site, multiply the pressure ratios by 12.8 psia. A region of pressure instability (buzzing) was noticed at the starting and at minimum operating chamber pressures when turbine exhaust fluid was not introduced into the engine compartment. This buzzing was not noticeable when turbine fluid was introduced. All presented data is for a contoured, 25:1 NERVA nozzle with the nozzle exit plane located 9" above the ejector inlet.

The internal wall pressures of the selected system are illustrated in the graphs in Figures 3 and 4 and the internal Mach numbers are given in Figures 5 and 6.

The expected internal pressure fluctuations are listed in Table I. The location of these pressures is shown and discussed in Section B.3 of the Appendix.

B. HEAT TRANSFER

The expected maximum heat transfer coefficients in the selected ejector system is illustrated in Figure 7.

C. SAFETY PURGE

The secondary safety purge fluid for the selected ETS-1 ejector system is steam with the following properties:

Ratio of specific heats	1.3
Molecular weight	20.2
Nozzle stagnation pressure	100 psia
Nozzle stagnation temperature	1650°R
Flow Rate	120 lb/sec
Nozzle throat area	119 in. ²

The secondary safety purge flow rate is equal to the sum of the choked flow rate (97 lb/sec) required to fill the environmental cell without allowing air to enter the ejector in the event of an instantaneous termination of the reactor working fluid, and the flow rate (23 lb/sec) required to prevent penetration of 35 mph air into the ejector (see section B.4 of Appendix).

D. PRE-FIRE PURGE

The environmental cell and the ejector must be purged with an inert gas prior to operation. The purge gas should be introduced through many orifices located at the top of the environmental cell and at points where air could possibly be trapped. A 2,000 lb nitrogen supply is recommended. It is also recommended that the purging process take place over at least a 30 second period to allow thorough mixing to take place. A checkout run at NTS to determine the O_2 content in different locations (corners, thrust structure, etc.) in the cell as a function of pre-fire purge flow duration, is required for safety considerations.

E. EXHAUST PLUME

The predicted exhaust plume size and shape, based on test data as well as analysis, is illustrated in Figure 8 and the predicted thermal radiation from this exhaust plume is illustrated in Figure 9.

The temperature increase as a function of time of an object exposed to this thermal radiation, with the assumption that all the energy is absorbed and that the object is not cooled, is expressed by the following relationship.

$$\frac{dT}{d\theta} = \frac{(Q/A)_r}{\rho C_p t} \quad (1)$$

when

$\frac{dT}{d\theta}$ = rate of temperature rise in $^{\circ}F/sec$

$(Q/A)_r$ = radiant heat flux from flux map in $Btu/ft^2 \text{ sec}$

ρ = density of object in lb/ft^3

C_p = heat capacity of object in $Btu/lb \text{ } ^{\circ}F$

t = thickness of object in ft

Densities and heat capacities of selected materials are tabulated below.

	<u>Aluminum</u>	<u>Stainless Steel</u>	<u>Concrete</u>
ρ - lb/ft ³	173	500	144
C_p - Btu/lb °F	0.18	0.12	0.16

Therefore, from Equation 1 and the preceding table, the temperature rise of a stainless steel object 1/4-in. thick exposed to a thermal heat flux of 2 Btu/ft² sec is 1.6°F/sec.

It is recommended that areas of concern be checked out by the above method to determine if any structure require cooling.

III. METHOD AND CONFIDENCE OF PREDICTIONS

A. AERODYNAMIC

The aerodynamic performance, pressure profile, pressure fluctuations, and local Mach numbers, of the full scale duct will be essentially the same as that obtained from the sub-scale model since the independence of scale size (boundary layer is small with respect to physical dimensions of scale model), working fluid (providing the ratio of specific heats are the same) and total temperature on pressure and Mach number. The performance, pressure profiles, and local Mach numbers given in Figures 2 through 6 are without simulated cell leakage or turbine exhaust fluid. The introduction of these fluids will not change the curves of Figures 2 through 6 to any significant degree as shown in Section B of the Appendix. The ejector configuration used to obtain the pressure profiles, pressure fluctuations, and local Mach numbers was not the selected system, Figure 1, but the slight difference in geometry should not change the values of the presented data significantly.

An analytical model to predict nozzle separation as a function of turbine exhaust flow rate was not verified by the test data. Therefore, to increase the low level of confidence in scaling the phenomena, all full scale parameters (such as temperatures, molecular weights, chamber pressures, and ratio of flow rates) where possible were duplicated.

B. HEAT TRANSFER

Conversion of the scale model heat transfer coefficient data to the full scale condition required that a correlation be developed to interpret the test data. Since the local Mach number and mass flow rate vary considerably along the ejector wall, it was not possible to obtain a direct correlation of the test data. Instead, the test data was converted to a form where a comparison could be made between the test data, and a turbulent pipe flow correlation, based on the assumption that the shock structure in the ejector remained fixed.

Thus, it was assumed that the local mass flow rates throughout the ejector would vary as chamber pressure to the 0.8 power and a plot of $h_r/P_c^{0.8}$

should form a single curve. Figure 7 provides the normalized heat transfer data for the impingement side as a function of L/D of the primary ejector. The normalized test data spread (3σ) was found to be $\pm 25\%$ for the tests run with heated nitrogen and indicated good agreement with turbulent pipe flow correlation theory.

When using hydrogen gas as the test fluid the test data falls within the $\pm 25\%$ normalized data spread of the nitrogen data.

The conversion of the scale model heat transfer coefficients to full scale values is the same as previously reported.¹

The heat transfer tests were run with the SST 2-1.05-82.5 ejector system (see Section A in the Appendix for definition of ejector nomenclature). Enlarging the primary ejector exit (1.05 to 1.14) will not appreciably affect the shock system upstream of the expansion section and does not affect the pressure and mass distribution in the elbow at steady state chamber conditions; therefore, the heating rates will not change significantly. Enlarging the entrance will increase the heating rates in that region, but the heat transfer coefficients obtained are conservative in this region because of the lack of turbine exhaust fluid being introduced for these tests. The relatively cold turbine exhaust fluid will decrease the driving temperature and consequently the heat flux in the entrance section.

It is, therefore, assumed that the given heat transfer data applies to the latest ejector modification and can be used for coolant passage design.

C. SAFETY PURGE

Many safety purge tests were run, varying the different parameters, to check out the analysis. The safety purge fluid molecular weights tested were 2, 28, and 121 lb/mol and the fluid temperature was varied between 60 and 650°F. Other variables in the analysis were varied over similar ranges and the experimental data verified the analysis. The maximum deviation from the predicted values

¹AGC Report No. 2403 - Evaluation Report, 90° Turn Ejectors for Engine Test Stand-1, November 1962.

for 75% of the data was $\pm 10\%$ and in no case did the deviation exceed $\pm 22\%$. The maximum deviation for the selected system illustrated in Figure B.4-3 of the Appendix, is $+11\%$ and -22% . The majority of this data scatter is believed to be instrumentation and reading error.

The scaled full scale safety purge flow rate was increased by the amount calculated to prevent penetration into the ejector of a 35 mph gust of air occurring simultaneously with instantaneous termination of the reactor working fluid.

D. PRE-FIRE PURGE

The scale model experimental test results indicate that a safe oxygen content, less than 4% by volume, is obtained by purging with approximately 1.5 ejector system (including environmental cell) volumes of nitrogen. This amounts to approximately 1000 lb of nitrogen if the ejector system volume is at one atmosphere. Because of the strong dependence of purge nozzles location and orientation on reducing the oxygen content in semi-isolated areas, it is recommended that serious consideration be given to the location and orientation of these nozzles. A checkout run at NTS to determine the oxygen content in various locations in the environmental cell (corners, thrust structure, and other semi-isolated areas), as a function of pre-fire purge flow duration, is required for safety considerations. Since safe operation of the ejector system must be assured, a safety factor of at least 2 is recommended in the amount of nitrogen used for purging.

E. EXHAUST PLUME

The photographed scale model exhaust plume checks out reasonably well with the predicted plume size. Since the flame length is predicted in terms of duct exit diameters, the value of flame length predicted applies to the full scale system.

Partial verification of the theoretical radiative heating rates given in Figure 9 was made through an actual measurement of the emittance of the hydrogen flame from the scale model system. Steam was used as the safety purge fluid for these tests.

It is recommended that during the first short duration tests, measurements of thermal radiation and metal wall temperature rise at points of interest be obtained. If the results indicate that cooling (or additional cooling) is required for full thrust-full duration firings, it would be known prior to possible damage of surrounding structures or surfaces.

Tables and Figures

TABLE I
PRESSURE FLUCTUATIONS IN EJECTOR SYSTEM

Function or Sta. No.	Press P _{sig}	Freq cps	Press P _{sig}	Freq cps	Press P _{sig}	Freq cps	Press P _{sig}	Freq cps	(1) Press P _{sig}	Freq cps	(2) Press P _{sig}	Freq cps	(3) Press P _{sig}	Freq cps
<u>Run Number 228 (Secondary Ejector Not Fired)</u>														
P _c	200 ± 10	250	300 ± 12	160	480 ± 18	200	225 ± 6	200	220 ± 6	150	220 ± 6	200		
P _{SD}	0 ± 0	0	-.005 ± .015	0	-.08 ± .01	0	0 ± .005	0	-.04 ± .015	150	0 ± .005	0		
PD-2 12.5	-11.7 ± .1	450	-12.0 ± .15	350	-6.6 ± .2	150	-12.5 ± 0	0	-5.9 ± 1.7	150	-8.3 ± .2	200		
(4) PD-3 76.8											-4.4 ± 4.4	150		
PD-42 704 (Top)	-.9 ± 0	0	-1.8 ± .1	0	-5.5 ± .2	0	1.1 ± .02	0	-.6 ± .2	275	-.98 ± 0	0		
PD-84 704 (Bottom)	0 ± 0	0	-.15 ± 0	0	-.15 ± .15	0	0 ± 0	0	0 ± .15	175	0 ± 0	0		
<u>Run Number 229 (Secondary Ejector Was Fired)</u>														
P _c	200 ± 7	160	300 ± 12	160	460 ± 20	150	85 ± 5	160	85 ± 3	160	80 ± 3	150		
P _{SD}	-.40 ± .07	0	-.29 ± .07	0	-.53 ± .1	250	-.24 ± .07	0	-.27 ± .07	0	-.29 ± .07	0		
PD-2 12.5	-12.7 ± .2	350	-12.0 ± .05	400	-10.7 ± .05	500	-13.4 ± .05	380	-13.0 ± .7	150	-13.6 ± .05	450		
(4) PD-3 76.8											-10.3 ± 1.5	150		
PD-42 704 (Top)	-7.8 ± .1	200	-7.9 ± .24	170	-6.3 ± .2	0	-9.3 ± 0	0	-9.5 ± .05	0	-9.3 ± 0	0		
PD-84 704 (Bottom)	-6.4 ± 0	0	-5.1 ± .05	0	-1.1 ± .1	450	-8.5 ± 0	0	-8.8 ± .05	0	-8.5 ± 0	0		
<u>Run Number 230 (Secondary Ejector Not Fired)</u>														
P _c	200 ± 8	175	300 ± 10	150	475 ± 22	160	230 ± 10	150	220 ± 5	150	215 ± 10	160		
P _{SD}	-.02 ± .005	0	-.05 ± .005	0	-.09 ± .01	0	-.02 ± 0	0	-.07 ± .01	170	-.02 ± 0	0		
(4) PD-6 151											-.98 ± 2.94	400		
PD-42 704 (Top)	-1.1 ± 0	0	-1.9 ± .1	0	-5.7 ± .2		-1.1 ± .05	0	-.07 ± .1	250	-1.1 ± 0	0		
PD-84 704 (Bottom)	-.05 ± 0	0	-.3 ± 0	0	-.3 ± .05		-.1 ± .05	0	-.05 ± .1	200	-.1 ± 0	0		

TABLE I (cont.)

	Function or Sta No	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	(1)		(2)		(3)		
								Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	
	Run Number 231 (Secondary Ejector Was Fired)													
	P _c	200 ± 10	160	300 ± 10	200	477 ± 15	150	90 ± 5	160	85 ± 4	160	80 ± 1	160	
	P _{SD}	- 35 ± .06	0	- 30 ± .05	0	- 56 ± .12	200	- 29 ± .07	0	- 29 ± .1	0	- 32 ± .05		
	PD-42 704 (Top)	-7 8 ± .04	0	-7 9 ± .09	0	-5 8 ± .09	0	-9 2 ± .025	270	-9 4 ± .04	270	-9 3 ± .025	270	
(4)	PD-65 104									-8 7 ± 1 45	275			
	PD-84 704 (Bottom)	-6 4 ± 0	0	-4 9 ± 1	0	- 54 ± .05	0	-8 4 ± 1	0	-8 9 ± 1	150	-8 6 ± .05		
	Run Number 232 (Secondary Ejector Was Fired)													
	P _c	200 ± 5	160	300 ± 5	160	520 ± 25	160	85 ± 5	160	85 ± 5	160	85 ± 5	160	
	P _{SD}	- 44 ± .15	0	- 29 ± .07	0	- 60 ± .07	250	- 41 ± .12	0	- 34 ± .07	0	- 34 ± .1	0	
	PD-42 704 (Top)	-7 7 ± .04	0	-7 9 ± .04	0	-5 2 ± .2	0	-9 0 ± .05	300	-9 3 ± .05	0	-9 1 ± 0	0	
(4)	PD-50 248									-8 6 ± 1 6	150			
	PD-84 704 (Bottom)	-6 3 ± 0	0	-4 9 ± .05	0	69 ± .15	0	-8 3 ± 0	0	-8 6 ± .05	0	-8 4 ± 0	0	
	Run Number 233 (Secondary Ejector Not Fired)													
	P _c	200 ± 10	170	300 ± 5	170	520 ± 20	170	220 ± 7	170	220 ± 7	170	215 ± .10	170	
	P _{SD}	0 ± 0	0	- .02 ± .005	0	- .10 ± .02	0	0 ± .005	0	- .02 ± .01	0	0 ± 0	0	
	PD-42 704 (Top)	- 98 ± .05	0	-1 7 ± 1	0	-5 0 ± .15	0	- 93 ± .05	0	- 78 ± .15	0	- 98 ± .05	0	
(4)	PD-50 248									-1 7 ± 3 5	400			
	PD-84 704 (Bottom)	- .05 ± 0	0	- .25 ± 1	0	49 ± 1	0	- .05 ± 0	0	0 ± 1	0	- .05 ± 0	0	
	Run Number 234 (Secondary Ejector Was Fired)													
	P _c	200 ± 5	160	300 ± 7	160	518 ± 22	160	85 ± 3	160	85 ± 3	160	85 ± 3	160	
	P _{SD}	- 34 ± .10	0	- 34 ± .10	0	- 68 ± .07	0	- 29 ± .07		- 31 ± .07	0	- 34 ± .07	0	
(4)	PD-12 297									-3 9 ± 2 0	160			
	PD-42 704 (Top)	-8 0 ± .05	0	-8 0 ± .05	0	-4 8 ± .25	0	-9 3 ± 0	0	-9 5 ± 0 5	0	-9 4 ± 0	0	
	PD-84 704 (Bottom)	-6 5 ± 0	0	-5 1 ± 0	0	49 ± 2	0	-8 5 ± 0	0	-8 9 ± .05	0	-8 6 ± 0	0	

TABLE I (cont.)

Function or Sta No	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps
(1)												
(2)												
(3)												
Run Number 235 (Secondary Ejector Not Fired)												
P _c	200 ± 10	160	300 ± 10	160	498 ± 22	160	224 ± 6	160	219 ± 6	160	219 ± 6	160
P _{SD}	- 005 ± 0	0	- 04 ± 0	0	- 10 ± 005	0	- 02 ± 0	0	- 05 ± 02	180	- 02 ± 0	0
(4) PD-12 297									-2 0	Unreadable		
PD-42 704 (Top)	- 9 ± 0	0	- 1 8 ± 09	0	- 5 1 ± 14	0	- 1 1 ± 0	0	- 5 ± 36	170	- 1 1 ± 0	0
PD-84 704 (Bottom)	0 ± 0	0	- 2 ± 05	0	25 ± 0	0	- 05 ± 0	0	0 ± 2	170	- 05 ± 0	0
Run Number 236 (Secondary Ejector Was Fired)												
P _c	200 ± 5	160	300 ± 6	160	528 ± 25	160	85 ± 5	160	85 ± 2	160	85 ± 2	160
P _{SD}	- 36 ± 10	0	- 34 ± 10	0	- 63 ± 05	250	- 34 ± 08	0	- 34 ± 08	0	- 34 ± 08	
PD-42 704 (Top)	- 8 0 ± 05	0	- 8 0 ± 05	0	- 4 7 ± 05	250	- 9 3 ± 0	0	- 9 4 ± 05	175	- 9 4 ± 0	
PD-55 379	- 8 1 ± 9	400	- 6 4 ± 74	400	- 2 5 ± 2 2	350	- 8 6 ± 29	400	- 8 8 ± 98	400	- 8 6 ± 1	400
PD-84 704 (Bottom)	- 6 4 ± 0	0	- 4 9 ± 05	0	1 2 ± 49	-	- 8 4 ± 0	0	- 8 8 ± 05	0	- 8 6 ± 0	
Run Number 237 (Secondary Ejector Not Fired)												
P _c	200 ± 10	160	300 ± 10	160	458 ± 11	160	224 ± 10	160	219 ± 7	160	219 ± 5	160
P _{SD}	- 02 ± 0	0	- 04 ± 005	0	- 10 ± 005	0	- 01 ± 0	0	- 05 ± 01	175	- 3 ± 0	0
PD-42 704 (Top)	- 1 0 ± 0	0	- 1 8 ± 05	0	- 5 6 ± 25	0	- 1 1 ± 05	0	- 69 ± 44	175	- 1 0 ± 05	260
PD-55 379	- 49 ± 49	500	- 2 4 ± 1 3	450	- 3 5 ± 1 2	400	- 49 ± 98	400	- 49 ± 2 3	350	- 39 ± 64	370
PD-84 704 (Bottom)	- 05 ± 0	0	- 25 ± 0	0	- 49 ± 15	0	0 ± 0	0	0 ± 15	150	0 ± 0	0
Run Number 29 (Secondary Ejector Was Fired)												
P _c	200 ± 10	220	300 ± 12	215	558 ± 25	230	165 ± 5	230	138 ± 5	220	128 ± 5	220
PD-30 545 (Inside)	- 5 83 ± 74	500	- 3 53 ± 74	430	3 53 ± 1 22	220	- 4 75 ± 78	450	- 5 39 ± 39	450	- 4 95 ± .1	450
PD-71 545 (Outside)	- 4 31 ± 1 22	420	- 1 22 ± 1 72	450	9 65 ± 2 45	220	- 4 12 ± 59	450	- 4 70 ± 78	450	- 4 70 ± 24	450

TABLE I (cont.)

Function or Sta. No.	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	Press (1) Psig	Freq cps	Press (2) Psig	Freq cps	Press (3) Psig	Freq cps
<u>Run Number 31 (Secondary Ejector Not Fired)</u>												
P _c	200 ± 12	210	300 ± 10	220	570 ± 25	220	246 ± 5	200	230 ± 5	200	210 ± 5	200
PD-30 545 (Inside)	.39 ± .24	470	.29 ± .74	420	3.82 ± 1.52	350	.29 ± .29	450	.49 ± 1.52	480	.29 ± .29	430
PD-71 545 (Outside)	.74 ± .49	480	1.96 ± 1.47	400	-9.11 ± 1.96	350	1.27 ± .74	450	.83 ± 1.22	480	.74 ± .49	430

NOTES:

- (1) Data point prior to ejector drop out.
- (2) Data point during ejector drop out transition.
- (3) Data point following ejector drop out.
- (4) Of the functions monitored, these showed the largest fluctuations at the data point indicated.
- (5) Runs 228 through 237 were conducted on Test Series D-266-LQ, Ejector Configuration SST 2-1.14 - 22.7.
- (6) Runs 29 and 31 were conducted on Test Series D-275-LQ, Ejector Configuration SST 2-1.14 - 16.7.

NOTES:

1. ALL DIMENSIONS ARE MULTIPLES OF D_2
2. DIAMETERS ARE INTERNAL
3. $A_{D_2} / A_p^* = 19.9$
4. $A_s / A_s^* = 17.9$
5. $A_{se} / A_s^* = 4$

Figure 1
Selected Subsonic Turn Ejector System
For Use In ETS-1

NOTES:

1. Subsonic Turn Ejector System SST 2-1.14 - 25.2
2. Run No. D-266-LQ-164
3. Primary Fluid 1600°R N₂
4. Secondary Safety-Purge Fluid-N₂, $P_{sc}/P_a = 14.6$, $T_{sc} = 540^\circ\text{R}$
5. No Leakage

Figure 2

Performance of Subsonic Turn
Ejector System with Secondary
Safety-Purge Flow

NOTES:

1. Subsonic Turn Primary Ejector SST 2-1.05
2. Run No. D-266-LQ-56 thru 59
3.

Symbol	P_{pc}/P_a
○	16
△	21.5
□	38
◇	43
4. Primary Fluid - 1600°R GN₂
5. No Secondary Duct, No Secondary Flow

Figure 3

Wall Pressure Along the Outside
of Primary Ejector SST 2-1.05

NOTES:

1. Subsonic Turn Primary Ejector SST 2-1.05
2. Run No. D-266-LQ-56 thru 59

Symbol	P_{pc}/P_a
○	16
△	21.5
□	38
⬢	43

4. Primary Fluid - 1600°R GN₂
5. No Secondary Duct, No Secondary Flow

L/D LOCATIONS

Figure 4
Wall Pressure Along the Inside
of Primary Ejector SST 2-1.05

NOTES:

1. Subsonic Turn Primary Ejector SST-2-1.05
2. Run No. D-266-LQ-56 thru 59
3. Primary Chamber Pressure, $P_{pc}/P_a = 49$ atmospheres
4. Primary Fluid - 1600°R GN_2
5. No Secondary Duct, No Secondary Flow

Figure 5

Mach Numbers Along the Outside
of Primary Ejector SST 2-1.05

NOTES:

1. Subsonic Turn Primary Ejector SST 2-1.05
2. Run No. D-266-LQ-56 thru 59
3. Primary Chamber Pressure, $P_{pc}/P_a = 49$
4. Primary Fluid - $1600^{\circ}\text{R GN}_2$
5. No Secondary Duct, No Secondary Flow

L/D LOCATIONS

Figure 6

Mach Numbers Along the Inside
of Primary Ejector SST 2-1.05

NOTES:

1. Selected Subsonic Turn Ejector System for Use in ETS-1
2. Points Taken on Impingement Side of Elbow
3. Curve Shown is 3σ Upper Limit of Scaled Test Data

Figure 7

Full-Scale Heat Transfer Coefficients

NOTES:

1. Selected Subsonic Turn Ejector System for Use in ETS-1
2. Ejector Exit Angle = 45°

Figure 8

Predicted Full Scale
Hydrogen Exhaust Plume

NOTES: 1.

Symbol	Heat Flux (Btu/Ft ² -Sec)
□	55.0
△	23.2
0	10.4
◊	5.6
○	0.6 - 0.8
◇	0.2 - 0.4

Figure 9
Radiation Flux Map for Full-Scale
Subsonic Turn Ejector System

APPENDIX
TABLES AND FIGURES

<u>Tables</u>	<u>Title</u>	<u>Page</u>
B.3-I	Pressure Fluctuations in Ejector System	A-17
B.4-I	Secondary Safety Purge Test Results	A-28
C.1-I	Heat Transfer Coefficients for Subsonic Turn Ejector System	A-44

<u>Figures</u>	<u>Title</u>	<u>Page</u>
A-1	Subsonic Turn Ejector System, SST 2-1.05-82.5	A-2
A-2	Subsonic Turn Ejector System, SST 2-1.14-25.2	A-3
A-3	Subsonic Turn Ejector System, SST 2-1.14-22.7	A-4
A-4	Subsonic Turn Ejector System, SST 2-1.14-22.7 Mod. 1	A-5
A-5	Subsonic Turn Ejector System, SST 2-1.14-22.7 Mod. 2	A-6
B.1-1	Performance of Subsonic Turn Ejector System Without Safety Purge Flow	A-8
B.1-2	Performance of Subsonic Turn Ejector System With Safety Purge Flow	A-9
B.2-1	Wall Pressure Along Outside of Primary Ejector	A-11
B.2-2	Wall Pressure Along Inside of Primary Ejector	A-12
B.2-3	Mach Numbers Along Outside of Primary Ejector	A-13
B.2-4	Mach Numbers Along Inside of Primary Ejector	A-14
B.3-1	Pressure Tap Locations, SST-2-1.05	A-18
B.3-2	Ejector Wall Pressure PD-30 vs Primary Chamber Pressure, $P_{sc} = 0$	A-19

TABLES AND FIGURES (cont.)

<u>Figures</u>	<u>Title</u>	<u>Page</u>
B.3-3	Ejector Wall Pressure PD-30 vs Primary Chamber Pressure, $P_{sc} \neq 0$	A- 20
B.3-4	Ejector Wall Pressure PD-71 vs Primary Chamber Pressure, $P_{sc} = 0$	A-21
B.3-5	Ejector Wall Pressure PD-71 vs Primary Chamber Pressure, $P_{sc} \neq 0$	A-22
B.3-6	Ejector Wall Pressure, PD-55 vs Primary Chamber Pressure, $P_{sc} = 0$	A-23
B.3-7	Ejector Wall Pressure, PD-55 vs Primary Chamber Pressure, $P_{sc} \neq 0$	A-24
B.4-1	Reference Cell Pressure, P_{vo} , vs Secondary Safety Purge Chamber Pressure	A-29
B.4-2	Simplified Model for Backflow Analysis	A-30
B.4-3	Comparison of Predicted and Experimental Flow Rate into Environmental Cell	A-31
B.5-1	Location of Turbine Exhaust Nozzles	A-33
B.5-2	Nozzle Separation with Turbine Exhaust, Supersonic Turbine Exhaust Nozzles	A-34
B.5-3	Performance of Subsonic Turn Ejector System With and Without Turbine Exhaust Flow	A-35
B.6-1	Hydrogen Exhaust Plume	A-38
B.7-1	Oxygen Content of Ejector System During Purge	A-40
B.7-2	Recommended Location of Pre-Fire Purge Nozzles	A-41
C.1-1	Thermocouple Locations, Subsonic Turn Ejector System	A-45
C.1-2	Normalized Subscale Heat Transfer Coefficients	A-46
C.2-1	Radiation Flux Map for Sub Scale Subsonic Turn Ejector System	A-49

APPENDIX A

A. CONFIGURATIONS

Five subsonic turn ejector systems were flow-tested extensively in order to select the most favorable one for use as the internal configuration of the NERVA Exhaust System (NES) for which the overall height and length were specified. These five subsonic turn ejector systems are illustrated in Figures A-1, A-2, A-3, A-4, and A-5.

The nomenclature for Subsonic Turn Ejector Systems SST-2-1.14-22.7 Mod. 1 has the following significance. The 2 represents a unique elbow configuration, the most favorable of four tested in the pre-system tests. (All five of the subject SST ejector systems have "number 2" elbows, nevertheless this number is retained for identification of primary ejector configurations not covered in this report.) The second number of the SST ejector system nomenclature is the exit diameter of the primary ejector, or the diameter at which the primary fluid enters the secondary safety purge ejector (1.14). The third and last number of the SST ejector system nomenclature gives the area expansion ratio of the secondary safety purge nozzles into the secondary safety purge duct, A_s/A_s^* (22.7). Modifications to SST 2-1.14-22.7 (Figure A-3) are simply designated Mod 1 and Mod 2 as illustrated in Figures A-4 and A-5. Mod 1 has a larger entrance cone and a 45° return elbow at the exit. Mod 2 incorporates a rounded entrance cylinder ($0.166^\circ R$) and a 15° return elbow at the exit.

The primary ejector exit diameter, $1.14 D_2$, as illustrated in Figures A-2, A-3, A-4, and A-5, was a compromise between larger diameters which permit a lower starting chamber pressure, but force the flow to separate in the elbow at high chamber pressure, and smaller diameters which choked the flow and increased the starting chamber pressure.

Figure A-1

Subsonic Turn Ejector System
SST 2-1.05 - 82.5

A-2

Figure A-2
Subsonic Turn Ejector System
SST 2-1.14-25.2

Figure A-3

Subsonic Turn Ejector System
SST 2-1.14 - 22.7

Figure A-4

Subsonic Turn Ejector System
SST 2-1.14 - 22.7 Mod 1

A-5

Figure A-5

Subsonic Turn Ejector System
SST 2-1.14 - 22.7 Mod 2

B. AERODYNAMIC PERFORMANCE

1. Ejector Performance

Ejector performance is defined as the effect of engine chamber pressure on the pressure in the environmental cell. Figure B.1-1 illustrates this effect for the selected (SST 2-1.14-22.7 Mod. 2) ejector system. This test was conducted with 1600°R hydrogen gas for the primary or NERVA engine fluid and ambient temperature hydrogen for the turbine exhaust fluid. The chamber pressure required to start the ejector is shown to be approximately 230 psia at NTS. There was essentially no difference in starting pressure between configuration SST 2-1.14-22.7 Mod. 2 and SST 2-1.05-82.5. A $(P_{pc}/P_a)_{start}$ of approximately 17.3 was also shown to be the starting chamber pressure with ambient temperature nitrogen as the primary fluid. For this particular test, the secondary safety purge system was not in operation. Results from previous tests indicate that when the secondary safety purge system is operating, the starting chamber pressure is increased by about 1-1/2 atmospheres because of aerodynamic blockage as illustrated in Figure B.1-2.

On tests where no turbine exhaust fluid was introduced into the cell, a region of ejector instability or "buzzing" was noted at or near $(P_{pc}/P_a)_{start}$. This instability region begins at a chamber pressure of about one atmosphere before normal pull-in and extends for about one atmosphere beyond normal pull-in. Cell pressure varies by a factor of two during this instability. Cell pressure during this time is quite low and therefore even a fluctuation by a factor of 2 does not appear to be a problem. When the turbine exhaust fluid is introduced into the cell, the instability during pull-in vanishes.

Taking into account all factors mentioned, the $(P_{pc}/P_a)_{start}$ will occur somewhere between 18 and 20 atmospheres chamber pressure.

NOTES:

1. Subsonic Turn Ejector System SST 2-1.14 - 22.7 Mod. 1
2. Run No. D-266-LQ-361 Thru 364
3. Primary Fluid 1600°R H_2
4. No Secondary Safety-Purge Flow
5. No Leakage
6. Turbine Exhaust Flow Rate, $\dot{W}_t$, Equals or Exceeds NERVA Requirements

Figure B.1-1

Performance of Subsonic Turn Ejector System
Without Secondary Safety-Purge Flow

NOTES:

1. Subsonic Turn Ejector System SST 2-1.14 - 25.2
2. Run No. D-266-LQ-164
3. Primary Fluid 1600°R N₂
4. Secondary Safety-Purge Fluid-N₂, $P_{sc}/P_a = 14.6$, $T_{sc} = 540^\circ\text{R}$
5. No Leakage

Figure B.1-2

Performance of Subsonic Turn
Ejector System with Secondary
Safety-Purge Flow

2. Pressure and Mach Number Profile

Figures B.2-1, B.2-2, B.2-3 and B.2-4 illustrate the local wall pressures and Mach numbers for the outside, or impingement side, and the inside of the ejector. The Mach numbers were obtained from the wall pressures and the assumption of one-dimensional adiabatic flow.

The pressure measurements were obtained on Ejector SST 2-1.05. Spot checks of various locations on Ejector SST-1.14-22.7 Mod. 2 show that the wall pressures are essentially the same. The increase in primary ejector exit diameter slightly increased the average Mach number in the ejector for a specific chamber pressure. This effect is hardly noticeable.

The increase in ejector inlet diameter will, of course, decrease the pressure and hence increase the Mach number at the ejector entrance. The increase in contraction angle, at the entrance to the second throat, has resulted in a slight shift in entrance Mach number profile.

In general, the aforementioned results do not change the pressure and Mach number profile to any significant degree.

NOTES:

1. Subsonic Turn Primary Ejector SST 2-1.05

2. Run No. D-266-LQ-56 thru 59

Symbol	P_{pc}/P_a
○	16
△	21.5
□	38
◇	43

4. Primary Fluid - 1600°R GN₂

5. No Secondary Duct, No Secondary Flow

Figure B.2-1

Wall Pressure Along the Outside
of Primary Ejector SST 2-1.05

NOTES:

1. Subsonic Turn Primary Ejector SST 2-1.05
2. Run No. D-266-LQ-56 thru 59

Symbol	P_{pc}/P_a
○	16
△	21.5
□	38
◇	43

4. Primary Fluid - 1600°R GN₂
5. No Secondary Duct, No Secondary Flow

L/D LOCATIONS

Figure B.2-2
Wall Pressure Along the Inside
of Primary Ejector SST 2-1.05

NOTES:

1. Subsonic Turn Primary Ejector SST-2-1.05
2. Run No. D-266-LQ-56 thru 59
3. Primary Chamber Pressure, $P_{pc}/P_a = 49$ atmospheres
4. Primary Fluid - 1600°R GN_2
5. No Secondary Duct, No Secondary Flow

Figure B.2-3

Mach Numbers Along the Outside
of Primary Ejector SST 2-1.05

NOTES:

1. Subsonic Turn Primary Ejector SST 2-1.05
2. Run No. D-266-LQ-56 thru 59
3. Primary Chamber Pressure, $P_{pc}/P_a = 49$
4. Primary Fluid - 1600°R GN_2
5. No Secondary Duct, No Secondary Flow

L/D LOCATIONS

Figure B.2-4

Mach Numbers Along the Inside
of Primary Ejector SST 2-1.05

A-14

3. Pressure Fluctuations

a. Ejector

A series of tests was conducted to determine the magnitude and frequency of pressure fluctuations in the ejector system. To obtain this information, short coupled unfiltered pressure transducers, located at various positions on the ejector system, were used. The data presented in this report (Table B.3-1) shows a representative pressure in each section of the ejector system (see Figure B.3-1 for pressure tap locations). For Runs 228 through 235 a pressure other than the representative one showed the largest fluctuation and is tabulated (see Note (4) in Table B.3-1).

The first three data points in Table B.3-1 were taken during primary chamber pressure increase at chamber pressures of 115 psia, 215 psia, and maximum respectively. The last three data points are just prior to, during, and just after drop-out. This covers the previously reported instability region in Section B.1. The last three points were recorded because this was the area of greatest pressure fluctuation and frequency.

Of the functions monitored, only Pd-30, Pd-71, and Pd-55 indicated large fluctuations continuously throughout a test. These functions are plotted in Figures B.3-2, B.3-3, B.3-4, B.3-5, B.3-6, and B.3-7. These same functions indicate that as the magnitude of the pressure fluctuation increases, the frequency decreases. Pd-3 indicated the largest fluctuation in magnitude (± 4.4 psi) of any of the functions recorded. This occurred in Run No. 228 (no secondary flow) during the drop-out transient.

In general, the data indicates that the magnitude of the ejector wall pressure fluctuations is directly related to the primary chamber pressure. The magnitude of the pressure fluctuations in the full scale are the same as in the sub-scale model because of the 1 to 1 correspondence in pressure.

The test data for Runs No. 228 through 237 were obtained using Ejector System SST 2-1.4-22.7 and the test data for Runs No. 29 and 31 were obtained in Ejector System SST 2-1.14-16.7. However, it is felt that the results are comparable because the primary ejector is the controlling factor and the same configuration was used for all tests.

b. Engine Compartment

An important factor in gas dynamics is the backflow of engine exhaust gas into the engine compartment prior to pull in and after drop out of the ejector system. A large space between the nozzle exit plane and the ejector entrance is needed for the radiation shield when the engine is in place but not in operation. This relatively large area permits peripheral exhaust gas to circulate throughout the engine compartment before the plume from the nozzle attaches itself to the ejector wall and establishes the shock system in the ejector.

The starting (and minimum operating) point of the ejector occurs near an engine chamber pressure of 230 psia. For chamber pressure lower than this value, the engine compartment pressure is higher than for steady state conditions with a resulting increase of hot hydrogen in the engine compartment. The temperature corresponding to this chamber pressure (230 psia) during both start-up and shut-down engine transients should be the temperature utilized in designing such hardware as fittings, and cables, in the engine compartment.

TABLE B.3-I

Pressure Fluctuations in Ejector System

Function or Sta. No.							(1)		(2)		(3)	
	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps
<u>Run Number 228 (Secondary Ejector Not Fired)</u>												
P _c	200 ± 10	250	300 ± 12	160	480 ± 18	200	225 ± 6	200	220 ± 6	150	220 ± 6	200
P _{SD}	0 ± 0	0	-0.005 ± .015	0	-0.08 ± .01	0	0 ± .005	0	-0.04 ± .015	150	0 ± .005	0
PD-2 12.5	-11.7 ± .1	450	-12.0 ± .15	350	-6.6 ± .2	150	-12.5 ± 0	0	-5.9 ± 1.7	150	-8.3 ± .2	200
(4) PD-3 76.8									-4.4 ± 4.4	150		
PD-42 704 (Top)	-9 ± 0	0	-1.8 ± .1	0	-5.5 ± .2	0	1.1 ± .02	0	-6 ± .2	275	-98 ± 0	0
PD-84 704 (Bottom)	0 ± 0	0	-1.5 ± 0	0	-1.5 ± .15	0	0 ± 0	0	0 ± .15	175	0 ± 0	0
<u>Run Number 229 (Secondary Ejector Was Fired)</u>												
P _c	200 ± 7	160	300 ± 12	160	460 ± 20	150	85 ± 5	160	85 ± 3	160	80 ± 3	150
P _{SD}	-.40 ± .07	0	-.29 ± .07	0	-.53 ± .1	250	-.24 ± .07	0	-.27 ± .07	0	-.29 ± .07	0
PD-2 12.5	-12.7 ± .2	350	-12.0 ± .05	400	-10.7 ± .05	500	-13.4 ± .05	380	-13.0 ± .7	150	-13.6 ± .05	450
(4) PD-3 76.8									-10.3 ± 1.5	150		
PD-42 704 (Top)	-7.8 ± .1	200	-7.9 ± .24	170	-6.3 ± .2	0	-9.3 ± 0	0	-9.5 ± .05	0	-9.3 ± 0	0
PD-84 704 (Bottom)	-6.4 ± 0	0	-5.1 ± .05	0	-1.1 ± .1	450	-8.5 ± 0	0	-8.8 ± .05	0	-8.5 ± 0	0
<u>Run Number 230 (Secondary Ejector Not Fired)</u>												
P _c	200 ± 8	175	300 ± 10	150	475 ± 22	160	230 ± 10	150	220 ± 5	150	215 ± 10	160
P _{SD}	-.02 ± .005	0	-.05 ± .005	0	-.09 ± .01	0	-.02 ± 0	0	-.07 ± .01	170	-.02 ± 0	0
(4) PD-6 151									-.98 ± 2.94	400		
PD-42 704 (Top)	-1.1 ± 0	0	-1.9 ± .1	0	-5.7 ± .2		-1.1 ± .05	0	-.07 ± .1	250	-1.1 ± 0	0
PD-84 704 (Bottom)	-.05 ± 0	0	-.3 ± 0	0	-.3 ± .05		-.1 ± .05	0	-.05 ± .1	200	-.1 ± 0	0

TABLE B.3-1

Pressure Fluctuations in Ejector System (Continued)

Function or Sta. No.							(1)		(2)		(3)	
	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps
<u>Run Number 231 (Secondary Ejector Was Fired)</u>												
P _c	200 ± 10	160	300 ± 10	200	477 ± 15	150	90 ± 5	160	85 ± 4	160	80 ± 1	160
P _{SD}	-.35 ± .06	0	-.30 ± .05	0	-.56 ± .12	200	-.29 ± .07	0	-.29 ± .1	0	-.32 ± .05	
PD-42 704 (Top)	-7.8 ± .04	0	-7.9 ± .09	0	-5.8 ± .09	0	-9.2 ± .025	270	-9.4 ± .04	270	-9.3 ± .025	270
(4) PD-65 104									-8.7 ± 1.45	275		
PD-84 704 (Bottom)	-6.4 ± 0	0	-4.9 ± .1	0	-.54 ± .05	0	-8.4 ± .1	0	-8.9 ± .1	150	-8.6 ± .05	
<u>Run Number 232 (Secondary Ejector Was Fired)</u>												
P _c	200 ± 5	160	300 ± 5	160	520 ± 25	160	85 ± 5	160	85 ± 5	160	85 ± 5	160
P _{SD}	-.44 ± .15	0	-.29 ± .07	0	-.60 ± .07	250	-.41 ± .12	0	-.34 ± .07	0	-.34 ± .1	0
PD-42 704 (Top)	-7.7 ± .04	0	-7.9 ± .04	0	-5.2 ± .2	0	-9.0 ± .05	300	-9.3 ± .05	0	-9.1 ± 0	0
(4) PD-50 248									-8.6 ± 1.6	150		
PD-84 704 (Bottom)	-6.3 ± 0	0	-4.9 ± .05	0	.69 ± .15	0	-8.3 ± 0	0	-8.6 ± .05	0	-8.4 ± 0	0
<u>Run Number 233 (Secondary Ejector Not Fired)</u>												
P _c	200 ± 10	170	300 ± 5	170	520 ± 20	170	220 ± 7	170	220 ± 7	170	215 ± 10	170
P _{SD}	0 ± 0	0	-.02 ± .005	0	-.10 ± .02	0	0 ± .005	0	-.02 ± .01	0	0 ± 0	0
PD-42 704 (Top)	-.98 ± .05	0	-1.7 ± .1	0	-5.0 ± .15	0	-.93 ± .05	0	-.78 ± .15	0	-.98 ± .05	0
(4) PD-50 248									-1.7 ± 3.5	400		
PD-84 704 (Bottom)	-.05 ± 0	0	-.25 ± .1	0	.49 ± .1	0	-.05 ± 0	0	0 ± .1	0	-.05 ± 0	0
<u>Run Number 234 (Secondary Ejector Was Fired)</u>												
P _c	200 ± 5	160	300 ± 7	160	518 ± 22	160	85 ± 3	160	85 ± 3	160	85 ± 3	160
P _{SD}	-.34 ± .10	0	-.34 ± .10	0	-.68 ± .07	0	-.29 ± .07		-.31 ± .07	0	-.34 ± .07	0
(4) PD-12 297									-3.9 ± 2.0	160		
PD-42 704 (Top)	-8.0 ± .05	0	-8.0 ± .05	0	-4.8 ± .25	0	-9.3 ± 0	0	-9.5 ± 0.5	0	-9.4 ± 0	0
PD-84 704 (Bottom)	-6.5 ± 0	0	-5.1 ± 0	0	.49 ± .2	0	-8.5 ± 0	0	-8.9 ± .05	0	-8.6 ± 0	0

TABLE B.3-1

Pressure Fluctuations in Ejector System (Continued)

Function or Sta. No.	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps
							(1)		(2)		(3)	
Run Number 235 (Secondary Ejector Not Fired)												
P _c	200 ± 10	160	300 ± 10	160	498 ± 22	160	224 ± 6	160	219 ± 6	160	219 ± 6	160
P _{SD}	-0.005 ± 0	0	-0.04 ± 0	0	-0.10 ± .005	0	-0.02 ± 0	0	-0.05 ± .02	180	-0.02 ± 0	0
(4) PD-12 297									-2.0	Unreadable		
PD-42 704 (Top)	-0.9 ± 0	0	-1.8 ± .09	0	-5.1 ± .14	0	-1.1 ± 0	0	-0.5 ± .36	170	-1.1 ± 0	0
PD-84 704 (Bottom)	0 ± 0	0	-0.2 ± .05	0	.25 ± 0	0	-0.05 ± 0	0	0 ± .2	170	-0.05 ± 0	0
Run Number 236 (Secondary Ejector Was Fired)												
P _c	200 ± 5	160	300 ± 6	160	528 ± 25	160	85 ± 5	160	85 ± 2	160	85 ± 2	160
P _{SD}	-0.36 ± .10	0	-0.34 ± .10	0	-0.63 ± .05	250	-0.34 ± .08	0	-0.34 ± .08	0	-0.34 ± .08	
PD-42 704 (Top)	-8.0 ± .05	0	-8.0 ± .05	0	-4.7 ± .05	250	-9.3 ± 0	0	-9.4 ± .05	175	-9.4 ± 0	
PD-55 379	-8.1 ± .9	400	-6.4 ± .74	400	-2.5 ± 2.2	350	-8.6 ± .29	400	-8.8 ± .98	400	-8.6 ± .1	400
PD-84 704 (Bottom)	-6.4 ± 0	0	-4.9 ± .05	0	1.2 ± .49	-	-8.4 ± 0	0	-8.8 ± .05	0	-8.6 ± 0	
Run Number 237 (Secondary Ejector Not Fired)												
P _c	200 ± 10	160	300 ± 10	160	458 ± 11	160	224 ± 10	160	219 ± 7	160	219 ± 5	160
P _{SD}	-0.02 ± 0	0	-0.04 ± .005	0	-0.10 ± .005	0	-0.01 ± 0	0	-0.05 ± .01	175	-0.3 ± 0	0
PD-42 704 (Top)	-1.0 ± 0	0	-1.8 ± .05	0	-5.6 ± .25	0	-1.1 ± .05	0	-0.69 ± .44	175	-1.0 ± .05	260
PD-55 379	-0.49 ± .49	500	-2.4 ± 1.3	450	-3.5 ± 1.2	400	-0.49 ± .98	400	-0.49 ± 2.3	350	-0.39 ± .64	370
PD-84 704 (Bottom)	-0.05 ± 0	0	-0.25 ± 0	0	-0.49 ± .15	0	0 ± 0	0	0 ± .15	150	0 ± 0	0
Run Number 29 (Secondary Ejector Was Fired)												
P _c	200 ± 10	220	300 ± 12	215	558 ± 25	230	165 ± 5	230	138 ± 5	220	128 ± 5	220
PD-30 545 (Inside)	-5.83 ± .74	500	-3.53 ± .74	430	3.53 ± 1.22	220	-4.75 ± .78	450	-5.39 ± .39	450	-4.95 ± .1	450
PD-71 545 (Outside)	-4.31 ± 1.22	420	-1.22 ± 1.72	450	9.65 ± 2.45	220	-4.12 ± .59	450	-4.70 ± .78	450	-4.70 ± .24	450

TABLE B.3-1

Pressure Fluctuations in Ejector System (Continued)

Function or Sta. No.	Press Psig	Freq cps	Press Psig	Freq cps	Press Psig	Freq cps	Press (1) Psig	Freq cps	Press (2) Psig	Freq cps	Press (3) Psig	Freq cps
<u>Run Number 31 (Secondary Ejector Not Fired)</u>												
P _c	200 ± 12	210	300 ± 10	220	570 ± 25	220	246 ± 5	200	230 ± 5	200	210 ± 5	200
PD-30 545 (Inside)	.39 ± .24	470	.29 ± .74	420	3.82 ± 1.52	350	.29 ± .29	450	.49 ± 1.52	480	.29 ± .29	430
PD-71 545 (Outside)	.74 ± .49	480	1.96 ± 1.47	400	-9.11 ± 1.96	350	1.27 ± .74	450	.83 ± 1.22	480	.74 ± .49	430

NOTES:

- (1) Data point prior to ejector drop out.
- (2) Data point during ejector drop out transition.
- (3) Data point following ejector drop out.
- (4) Of the functions monitored, these showed the largest fluctuations at the data point indicated.
- (5) Runs 228 through 237 were conducted on Test Series D-266-LQ, Ejector Configuration SST 2-1.14 - 22.7.
- (6) Runs 29 and 31 were conducted on Test Series D-275-LQ, Ejector Configuration SST 2-1.14 - 16.7.

PRIMARY EJECTOR			
PRESSURE TAP	L	PRESSURE TAP	L
PD 1	04	PD 43	37
PD 2	37	PD 44	80
PD 3	1 98	PD 45	1 21
PD 4	2 65	PD 46	1 54
PD 5	3 28	PD 47	2 00
PD 6	3 89	PD 48	3 87
PD 7	4 63	PD 49	5 13
PD 8	5 21	PD 50	6 40
PD 9	5 76	PD 51	7 65
PD 10	6 40	PD 52	8 95
PD 11	7 03	PD 53	9 35
PD 12	7 65	PD 54	9 57
PD 13	8 29	PD 55	9 78
PD 14	8 91	PD 56	10 00
PD 15	9 35	PD 57	10 15
PD 16	9 58	PD 58	10 40
PD 17	9 80	PD 59	10 60
PD 18	10 01	PD 60	10 81
PD 19	10 22	PD 61	11 02
PD 20	10 42	PD 62	11 23
PD 21	10 63	PD 63	11 56
PD 22	10 84	PD 64	11 87
PD 23	11 05	PD 65	2 68
PD 24	11 24	PD 66	12 20
PD 25	11 57	PD 67	12 51
PD 26	11 88	PD 68	12 89
PD 27	12 28	PD 69	13 21
PD 28	12 92	PD 70	13 52
PD 29	13 49	PD 71	13 83
PD 30	14 05	PD 72	14 15
PD 31	14 61	PD 73	14 48
		PD 74	14 79
		PD 75	15 14
PD 34	15 18	PD 76	15 42
PD 35	15 84	PD 77	15 72
PD 36	16 53	PD 78	16 04
PD 37	16 87	PD 79	16 52
PD 38	17 22	PD 80	16 77
PD 39	17 55	PD 81	17 26
PD 40	17 91	PD 82	18 01
PD 41	18 26	PD 83	18 41
PD 42	18 58	PD 84	18 75

NOTES:

- ALL "L" DIMENSIONS ARE ALONG
CENTERLINE OF PRIMARY EJECTOR
AND ARE MULTIPLES OF D_2

Figure B.3-1

Pressure Tap Locations
Subsonic Turn Primary Ejector
SST 2-1.05

NOTES:

1. Subsonic Turn Ejector System SST 2-1.14 - 16.7
2. Run No. D-275-LQ - 31
3. Primary Fluid - Ambient H_2
4. No Secondary Safety-Purge Flow
5. Broken lines represent the magnitude of the pressure fluctuations during steady state operation.
6. Pressure fluctuation during drop-out was ± 1.52 psi

Figure B.3-2
Ejector Wall Pressure PD-30 vs Primary Chamber Pressure, $P_{sc} = 0$

NOTES:

1. Subsonic turn Ejector System SST 2-1.14 - 16.7
2. Run No. D-275-LQ - 29
3. Primary Fluid - Ambient H_2
4. Secondary Safety-Purge Fluid-Ambient N_2
5. Broken Lines Represent the Magnitude of the Pressure Fluctuations During Steady-State Operation
6. Pressure Fluctuation During Drop-Out was $\pm .39$ psi

Ejector Wall Pressure PD-30 vs Primary Chamber Pressure, $P_{sc} \neq 0$

Figure B.3-3

A-20

NOTES:

1. Subsonic Turn Ejector System SST 2-1.14 - 16.7
2. Run No. D-275-LQ - 31
3. Primary Fluid - Ambient H_2
4. No Secondary Safety-Purge Flow
5. Broken lines represent the magnitude of the pressure fluctuations during steady state operation
6. Pressure Fluctuation During Drop-Out was ± 1.22 psi

Figure B.3-4

Ejector Wall Pressure PD - 71 vs Primary Chamber Pressure, $P_{sc} = 0$

NOTES:

1. Subsonic Turn Ejector System SST 2-1.14 - 16.7
2. Run No. D-275-LQ-29
3. Primary Fluid - Ambient H_2
4. Secondary Safety-Purge Fluid-Ambient N_2
5. Broken Lines Represent the Magnitude of the Pressure Fluctuations During Steady-State Operation.
6. Pressure Fluctuation During Drop-Out was $\pm .78$ psi

Figure B.3-5

Ejector Wall Pressure PD-71 vs Primary Chamber Pressure, $P_{sc} \neq 0$

NOTES:

1. Subsonic Turn Ejector System SST 2-1.14 - 22.7
2. Run No, D-266-LQ - 237
3. Primary Fluid - Ambient H_2
4. No Secondary Safety-Purge Flow
5. Broken Lines Represent the Magnitude of the Pressure Fluctuations During Steady State Operation
6. Pressure Fluctuation During Drop-Out was ± 2.3 psi

Figure B.3-6

Ejector Wall Pressure PD-55 vs Primary Chamber Pressure, $P_{sc} = 0$

A-23

NOTES:

1. Subsonic Turn Ejector System SST 2-1.14 - 22.7
2. Run No. D-266-LQ - 236
3. Primary Fluid - Ambient N_2
4. Secondary Safety-Purge Fluid - Ambient N_2
5. Broken Lines Represent the Magnitude of the Pressure Fluctuations During Steady-State Operation
6. Pressure Fluctuation During Drop-Out was $\pm .98$ psi

Figure B.3-7

Ejector Wall Pressure PD-55 vs Primary Chamber Pressure, $P_{sc} \neq 0$

A-24

B. AERODYNAMIC PERFORMANCE (cont.)

4. Steam Safety Purge

The ejector system must, at all times, exhaust the hydrogen gas so that it may be safely disposed of by burning. Air must not be allowed to mix with the hydrogen during this exhausting process. Under normal operating conditions, the primary ejector accomplishes this, and prior to start-up the air is replaced by nitrogen from the pre-fire ejector purge system located in the environmental cell.

A major malfunction such as main propellant line rupture or a turbine seizure could cause an instantaneous cessation of flow to the engine, and in turn collapse the established shock structure in the duct. Upon collapse of the shock structure, a large pressure differential exists between the engine compartment ($P_v \leq 1$ psia) and the atmosphere ($P_a = 12.8$ psia at NTS). This pressure gradient would force in air, mix it with the residual hydrogen in the duct, and create an explosive mixture. This surge of gas would also cause overpressurization of the engine compartment and separate the side shields. It was therefore necessary to investigate methods of preventing this backflow. A secondary purge system was devised whereby a series of peripheral nozzles was mounted at the end of the contraction cone aft of the elbow as a method of introducing the safety purge fluid.

The 10:1 area ratio nozzle was used for all tests except runs 158-161, which had the 25:1 nozzle installed.

The reference cell pressure, P_v , versus safety purge chamber pressure for SST 2 - 1.14 - 22.7 Ejector System is^o illustrated in Figure B.4-1. The reference cell pressure is the resulting back pressure obtained for a given safety purge chamber pressure when the primary nozzle flow rate, $\dot{W}_p$, is zero.

The simplified flow model is illustrated in Figure B.4-2. The arrows indicate the direction of flow after termination of nozzle chamber pressure. Because the pressure at Station 5 is more than twice the cell pressure, P_v , the flow will be choked at the minimum area during the greater part of the backflow duration. This minimum area is located at Station 2. The flow rate at Station 2 is

$$\dot{W}_2 = .528 P_{t_2} A_2 \sqrt{\frac{\gamma g m_2}{R_u .833 T_{t_2}}} \quad (1)$$

when the ratio of specific heats, γ is 1.4 and $M_2 = 1$.

Table B.4-1 compares the experimental and analytical values of flow rate into the environmental cell during backflow. $\dot{W}_v$ was determined from the measured rate of cell pressure increase, dP_v/dt . $\dot{W}_v^{\text{exp}}$ was the predicted flow rate at Station 2 based upon Equation (1) and the assumption that $P_{t_2} = P_{v_0}$. The safety purge flow rate, $\dot{W}_s$, was determined from the flow calibrated purge nozzles, safety purge chamber temperature and chamber pressure. The flow rate of air into the ejector exit was calculated, based upon the measured ambient pressure, ambient temperature, ejector exit static pressure and the assumption of one dimensional flow. A comparison of the predicted and experimental flow rates is given in Figure B.4-3.

The secondary safety purge flow rate is equal to the sum of the choked flow rate (97 lb/sec) required to fill the environmental cell ($\dot{W}_2$ in Equation (1)) in the event of an instantaneous termination of the reactor working fluid, and the flow rate (23 lb/sec) required to prevent penetration of 35 MPH air into the ejector. The momentum of the 35 MPH air must be balanced by the momentum of the gases leaving the ejector.

The safety purge fluid to be used is steam. The chamber pressure selected was 100 psia, to be compatible with the available water head and the pressure drop needed for stable operation of the steam generating system. The safety purge flow rate needed was determined from Equation (1), corrected for γ and a momentum balance with the 35 MPH air.

$$\dot{W}_s = .546 P_{t_2} A_2 \sqrt{\frac{\gamma g m_s}{R_u (.870) T_{t_2}}} + \frac{P_a A_{sd} V_a}{R_u} \sqrt{\frac{m_s m_a}{T_s T_a}} \quad (2)$$

where

$$\begin{aligned}
 P_{t_2} &= P_{v_o} = 8 \text{ psia (see following paragraph)} \\
 A_2 &= 1180 \text{ in.}^2 \\
 \gamma &= 1.3 \\
 g &= 32.2 \text{ ft/sec}^2 \\
 R_u &= 1545 \text{ ft lbs/mol}^\circ\text{R} \\
 m_s &= 20.2 \text{ lb/mol} \\
 T_s &= 1650^\circ\text{R} \\
 P_a &= 12.8 \text{ psia} \text{ —} \\
 A_{sd} &= 2130 \text{ in.}^2 \\
 V_a &= 51.3 \text{ ft/sec (35 MPH)} \\
 m_a &= 29 \text{ lb/mol} \\
 T_a &= 520^\circ\text{R}
 \end{aligned}$$

An iteration process was necessary to determine P_{v_o} since it is a function of the safety purge area ratio, A_{sd}/A_s^* . A good approximation of P_{v_o}/P_a as a function of P_{sc}/P_a and A_{sd}/A_s^* can be obtained from Fortini's analysis.¹

The secondary safety purge fluid for the ETS-1 Ejector System is steam with the following properties:

Ratio of specific heats	1.3
Molecular weight	20.2
Nozzle stagnation temperature	1650 ^o R
Nozzle stagnation pressure	100 psia
Flow rate	120 lb/sec ✓
Nozzle throat area	119 in. ²

¹Anthony Fortini, Performance Investigation of a Non-Pumping Rocket-Ejector System for Altitude Simulation, NASA TN D-257, December 1959.

NOTES:

1. Subsonic turn ejector system SST 2-1.14-25.2.
2. $(P_v/P_a)_o$ is the cell pressure (in atmospheres) obtained when the secondary safety purge is flowing and the primary chamber pressure P_{pc} is 0.

Run No.	Purge Fluid	Primary Fluid	P_{sc}/P_a	$(P_v/P_a)_o$	$\dot{W}_s$	$\dot{W}_{air}$	$\dot{W}_v \text{ exp.}$	$\dot{W}_v \text{ anal.}$
166	amb H_2	amb N_2	7.6	.77	.68	2.3	1.1	1.2
167	amb H_2	amb N_2	15.9	.56	1.42	0	.7	.9
168	amb H_2	amb N_2	9.3	.74	.83	1.3	1.1	1.2
169	amb H_2	amb N_2	13.5	.62	1.20	0	.9	1.0
172	amb H_2	amb N_2	13.8	.61	4.61	0	3.3	3.7
173	amb H_2	amb N_2	7.6	.77	2.54	3.0	5.1	4.6
174	amb H_2	amb N_2	11.4	.66	3.81	0	4.4	4.0
175	amb H_2	amb N_2	9.3	.72	3.11	1.3	4.7	4.3

Secondary Safety Purge
Test Results

Table B.4-1

NOTES:

1. Subsonic Turn Ejector System SST 2-1.14-22.7
2. Run No. D-266-LQ=166-169 & 172-175
3. $P_{pc} = 0$, No Primary Flow

Figure B.4-1

Reference Cell Pressure, P_{v0} , vs
Secondary Safety-Purge Chamber Pressure

Figure B.4-2

Simplified Model for Backflow Analysis

NOTES:

1. Subsonic Turn Ejector System SST 2-1.14 - 25.2
2. Run No. D-266-LQ-166 thru 169 and 172 thru 175

Figure B.4-3

Comparison of Predicted and Experimental

Flow Rate into Environmental Cell
(Safety Purge Requirements)

A-31

B. AERODYNAMIC PERFORMANCE (cont.)

7. Pre-Fire Ejector System Purge

The change in geometry of the ejector system from that previously reported¹ (AGC-2 configuration) did not change the method to determine the amount of nitrogen required to purge the complete ejector system of air prior to starting of the engine. The amount of nitrogen required to purge the system to a safe level (less than 4% by volume) is 1-1/2 times the volume of the complete ejector system including environmental cell as illustrated in Figure B.7-1. This amounts to approximately 1000 lbs if the cell is at one atmosphere during purge. Since nitrogen is relatively inexpensive, and safe operation of the ejector system must be assured, a safety factor of at least 2 is recommended in the amount of nitrogen used for purging. It is also recommended that the purging process take place over at least a 30 second period, to allow thorough mixing to take place. A checkout run at NTS to determine the O₂ content in various locations in the cell as a function of pre-fire purge flow duration is recommended.

During the previously reported¹ test program, it was noted that unless the purge ring nozzles directed the purge gas toward the top of the engine compartment, difficulty in purging this area would exist. The upward flow direction will permit a more efficient purging operation.

Additional consideration must be given to any hardware in the engine compartment that will act as a baffle or trap for the residue air. A suggested method of purging is illustrated in Figure B.7-2.

¹Analytical & Experimental Evaluation of Ejectors with 90° Turn for Use in ETS-1, AGC Report No. 2403, November 1962.

NOTES:

1. Turbine Exhaust Nozzles are Located 180° Apart
2. Keep the Turbine Exhaust Nozzle Exit within the Duct Inlet Diameter
3. The Turbine Exhaust Nozzles Should Have a Contraction Area Ratio of 2:1
4. The Turbine Exhaust Nozzle Feed Line Should be 6 Inches Diameter to Minimize Losses
5. The Turbine Exhaust Nozzles Should Have an Expansion Area Ratio of 4:1

Location of Supersonic Turbine Exhaust Nozzles
ETS-1 and ETS-2 for all 25:1 Nozzles

Figure B.5-1
A-33

NERVA
PROGRAM

NERVA EXHAUST SYSTEM (NES)

Date: 29 July 1963

Rev: 26 August 1963

NOTES:

1. Subsonic Turn Ejector System SST 2-1.14-22.7 Mod 2
2. Run No. D-266-LQ-361 Thru 365

3. Symbol	$\dot{W}_P$	$\dot{W}_T$	$\dot{W}_L$	P_{SC}	Remarks
•	1600°R H ₂	Amb H ₂	0	0	Nozzle Flows Full
○	1600°R H ₂	Amb H ₂	Amb N ₂	0	Nozzle Flow Separates
□	1600°R H ₂	Amb H ₂	0	0	Nozzle Flow Separates
---	NERVA design	NERVA design	1.0 lb/sec Amb N ₂	0	Independent of Separation

Figure B.5-2

Nozzle Separation with Turbine Exhaust,
Supersonic Turbine Exhaust Nozzles

NOTE:

1. Subsonic Turn Ejector System SST 2-1.14 - 22.7 Mod. 2

2. Run No. D-266-LQ 360 - 364

Symbol	$\dot{W}_p$	$\dot{W}_T$	$\dot{W}_L$	P_{sc}
□	1600°R H ₂	Amb. H ₂	0	0
○	1600°R H ₂	0	0	0

4. Turbine Exhaust Flow Rate, $\dot{W}_t$, Equals or Exceeds NERVA Requirements

Figure B.5-3

Performance of Subsonic Turn Ejector System
With and Without Turbine Exhaust Flow

6. Exhaust Plume Shape

One part of the analyses to determine the thermal radiation from the hydrogen exhaust flame is to establish a model to predict the flame shape. Hawthorne, Weddell, and Hottel have developed a model in which flame length is derived by applying the laws of conservation of mass and momentum and an equation of state along with the assumption that the flame shape is an inverted right circular cone (i.e., the angle spread of the flame is a constant.) The flame surface is defined as the surface on which combustion is 99% complete.

From continuity requirements it follows that:

$$A_f U X_N = \frac{P M_f A_f U X_N}{RT} = \frac{P M_f A_f U X}{RT X_o} \alpha = \rho_e A_e U_e = \frac{P_e M_e A_e U_e}{R T_e} \quad (1)$$

α = moles of reactants per mole of products

ρ = density

A_f = cross-sectional area of flame jet

U = velocity

X_n = mass fraction of exhaust gas counted as unreacted

P = pressure

M = molecular weight

T = temperature

X = mole fraction of fuel

X_N = mole fraction of exhaust gas counted as unreacted

Subscript

e = duct exit

f = exhaust gas

Assuming no external forces acting on the flames,

$$\rho_e A_e U_e^2 = A U^2 \quad (2)$$

$$\frac{\rho}{\rho_e} = \left[\frac{X}{X_e} + \frac{M_a}{M_f} \left(1 - \frac{X}{X_e} \right) \right] \frac{T_e}{T} \alpha \quad (3)$$

where M_a is the molecular weight of the surrounding fluid (air).

Assuming that the flame length is equal to a constant times the flame diameter ($L_f = k \cdot 2 r_f$) then Equations (1) through (3) may be solved for L_f in terms of L_f/D_{sd} as

$$\frac{L_f}{D_{sd}} = k \frac{X_e}{X_{sto}} \left\{ \left[\frac{X_{sto}}{X_e} + \frac{M_a}{M_f} \left(1 - \frac{X_{sto}}{X_e} \right) \right] \frac{T_f}{T_e} \right\}^{1/2} \quad (4)$$

where X_{sto} is the mole fraction of H_2 in the stoichiometric mixture, T_f is the adiabatic flame temperature, D_{sd} the diameter of secondary duct and k , a constant defining the angle spread of the flame.

An estimate of flame length was made from movies and a still photo taken of the hydrogen flame from the scale model system, indicating a flame length of 85 and 75 duct exit diameters respectively. Figure B.6-1 is a sketch of the hydrogen exhaust plume made from a still photo. Equation (4) predicts a L_f/D_{sd} of 93.7 for the conditions under which the test was conducted. The estimate of the flame length from the movies is subject to a higher degree of error and should not be viewed as experimental substantiation of the model but at the same time, the degree of agreement between calculated and measured flame length is encouraging. Since the flame length is predicted in terms of duct exit diameters, the value of flame length predicted by Equation (4) applied to the full scale system.

The exhaust plume illustrated in Figure B.6-1 is for SST 2-1.14-22.7 Mod. 1 Ejector System with safety purge fluid (nitrogen) but no turbine fluid. Mod 2 and the introduction of turbine exhaust fluid would have little effect upon the plume shape. The introduction of the full scale safety purge fluid (steam) would increase the emissivity of the plume but, according to the analysis presented, it should not affect the plume shape noticeably. If the ejector exit angle is increased or decreased, the plume centerline should increase or decrease by the same amount.

NOTES:

1. Subsonic Turn Ejector System SST 2-1.14 - 22.7 Mod. 1
2. Run No: D-266-LQ-348
3. Primary Fluid - 1600°R GH_2 , $P_{pc}/P_a = 40 - 45$
4. Secondary Safety-Purge Fluid - Ambient GN_2 - $P_{sc}/P_a = 18$
5. Ejector Exit Angle = 15°

Figure B.6-1
Hydrogen Exhaust Plume

7. Pre-Fire Ejector System Purge

The change in geometry of the ejector system from that previously reported¹ (AGC-2 configuration) did not change the method to determine the amount of nitrogen required to purge the complete ejector system of air prior to starting of the engine. The amount of nitrogen required to purge the system to a safe level (less than 4% by volume) is 1-1/2 times the volume of the complete ejector system including environmental cell as illustrated in Figure B.7-1. This amounts to approximately 1000 lbs if the cell is at one atmosphere during purge. Since nitrogen is relatively inexpensive, and safe operation of the ejector system must be assured, a safety factor of at least 2 is recommended in the amount of nitrogen used for purging. It is also recommended that the purging process take place over at least a 30 second period, to allow thorough mixing to take place. A checkout run at NTS to determine the O₂ content in various locations in the cell as a function of pre-fire purge flow duration is recommended.

During the previously reported¹ test program, it was noted that unless the purge ring nozzles directed the purge gas toward the top of the engine compartment, difficulty in purging this area would exist. The upward flow direction will permit a more efficient purging operation.

Additional consideration must be given to any hardware in the engine compartment that will act as a baffle or trap for the residue air. A suggested method of purging is illustrated in Figure B.7-2.

¹Analytical & Experimental Evaluation of Ejectors with 90° Turn for Use in ETS-1, AGC Report No. 2403, November 1962.

W = Mass
 R = Gas Constant
 T = Absolute Temperature
 P = Absolute Pressure
 Vol_{Cell} = Volume of Complete
 Ejector System

$$\text{Percent O}_2 = 20.9 e^{-\frac{\text{Vol N}_2}{\text{Vol Cell}}}$$

Where —

$$\text{Vol N}_2 = \frac{W_{N_2} R_{N_2} T_{\text{Cell}}}{P_{\text{Cell}}}$$

For Perfect Mixing

Figure B.7-1

Oxygen Content of Ejector System During Purge

NOTE:

1. All Dead Air Space Cavities Within the Engine Compartment (Not necessarily shown on this Schematic Drawing) Must be Purged with Nitrogen Prior to Flowing Hydrogen through the NERVA Engine

Recommended Location of
Pre-Fire Purge Nozzles

Figure B.7-2

A-111

C. HEAT TRANSFER EVALUATION

1. Ejector Wall Heat Transfer Coefficients

The heat transfer coefficients for various primary chamber pressures ($P_{sc} = 0$) are listed in Table C.1-I. Thermocouple locations are illustrated in Figure C.1-1. The regions of peak heating rates are shown to be independent of chamber pressure after the ejector has started. The heat transfer coefficients obtained, when not started, $P_c/P_a = 16$, show that the heating rates on the impingement side were generally lower but on the inside were considerable higher than they were for higher chamber pressures. The heating rates on the impingement side were still larger than on the inside of the elbow.

The heat transfer tests were run with the SST 2-1.05-82.5 ejector system. Enlarging the primary ejector exit (1.05 to 1.14) will not appreciably effect the shock system upstream of the expansion section and does not effect the pressure and mass distribution in the elbow as illustrated in Figures B.2-1 and B.2-2, and therefore, the heating rates will not change significantly. Enlarging the entrance will increase the heating rates in that region, but the heat transfer coefficients listed in Table C.1-I and illustrated in Figure C.1-2 are conservative in this region because no turbine exhaust fluid were introduced for these tests. The relatively cold turbine exhaust fluid will act as a film coolant in the entrance section.

It is therefore assured that the given heat transfer data applies to the latest ejector modification and can be used for coolant passage design.

Conversion of the scale model heat transfer coefficient data to the full scale condition required that a correlation be developed to interpret the test data. Since the local Mach number and mass flow-rate vary considerably along the ejector wall, it was not possible to obtain a direct correlation of the test data. Instead, the test data was converted to a form where a comparison could be made between the test data, and a turbulent pipe flow correlation, based upon the assumption that the shock structure in the ejector remained fixed.

Thus, it was assumed that the local mass flow rates throughout the ejector would vary as chamber pressure to the 0.8 power and a plot of $h_r/P_c^{0.8}$ should form a single curve. Figure C.1-2 illustrates the normalized heat transfer data for the impingement side as a function of L/D of the primary ejector. The normalized test data spread (3σ) was found to be $\pm 25\%$ for the tests run with heated nitrogen, and indicated good agreement with turbulent pipe flow correlation theory.

The heat transfer data generated during the test program were converted to the full-scale condition by the use of a turbulent heat transfer relationship, and used to obtain a first estimate of the heat flux and water requirements for the exhaust system. For this purpose, the upper 3σ limit of the test data for the impingement side of the duct was assumed to apply completely around the duct. This was somewhat conservative, but gave an upper limit for evaluating coolant water requirements. An additional design consideration was the possibility of a core failure producing a cloud of particles in the normally non-radiating gas that could increase the thermal load on the duct. Consequently, the system was evaluated for both a radiating, and a non-radiating gas.

When using hydrogen as the test fluid, the ratio of the duct wall resistance to the gas resistance to heat transfer (the Biot number) increases. When the correction factor is applied to the test data for this non-uniform instantaneous wall temperature and the different fluid properties are taken into account, the hydrogen test data falls within the $\pm 25\%$ normalized data spread of the nitrogen data.

The conversion of the scale model heat transfer coefficients to full scale values is the same as previously reported¹. An approximate conversion factor for determining full scale heat flux (in BTU/in.²sec) from the curve presented in Figure C.1-2 is 9.4×10^4 . This assumes a tubular construction stainless steel wall of approximately 0.09 inch thickness and a radiating gas (carbon particles in the gas). The conversion factor for a non-radiating gas is 6.9×10^4 .

These thermal conditions indicate that nucleate boiling will occur during the overload condition because of the radiation heat transfer, but that no boiling will occur during normal operation.

¹Analytical & Experimental Evaluation of Ejectors with 90° Turns for Use in ETS-1, AGC Report No. 2403, November 1962.

TABLE C.1-1

HEAT TRANSFER COEFFICIENTS FOR SUBSONIC TURN PRIMARY EJECTOR 2-1.05

TC No.	Run No. L/D	1400		1370		1370		1430		1440		1420		1320		1490	
		310		560		815		235		230		315		510		745	
		47		48		49		50		51		52		53		54	
		$h \times 10^5$		$h \times 10^5$		$h \times 10^5$		$h \times 10^5$		$h \times 10^5$		$h \times 10^5$		$h \times 10^5$		$h \times 10^5$	
TW - 1	.269	6.23	9.74	15.08	3.98												
2	.582	8.09	13.05	19.59	5.93												
3	.880	7.25	11.67	16.73	7.15												
4	1.214	6.11	10.09	14.75	8.20												
5	1.458	2.93	5.70	8.06	9.04												
6	1.721	2.61	4.72	6.75	8.99												
7	2.010	2.50	4.45	6.48	9.77												
8	.269	7.87	12.23	20.43	4.16											34.49	
9	.880	7.96	12.82	18.87	7.06											35.69	
10	1.458	3.01	5.57	7.94	9.58											17.69	
11	2.01	2.68	4.63	6.64	9.82											17.18	
12	2.46	6.35	10.43	15.62	10.35											32.11	
13	2.98	6.28	10.52	15.91	10.86											32.55	
14	3.29	5.05	8.48	13.00	10.79											25.81	
15	3.60	4.45	7.55	11.10	11.50											24.33	
16	3.92	3.70	6.38	9.10	11.67											21.13	
17	4.22	3.70	6.15	8.48	11.84											23.49	
18	4.55	5.40	8.74	12.64	11.54											28.40	
19	4.86	5.28	8.71	13.46	11.79												
20	5.18	4.87	8.24	12.40	12.10											25.53	
21	5.48	4.28	7.42	10.93	11.91											23.32	
22	5.82	3.99	6.80	10.16	12.41											22.09	

NOTE: Run No. 55 was with hydrogen gas, all others are with nitrogen gas.

T _c (°R)		1400	1370	1370	1370	1430	1440	1420	1320	1490
P _{pc} (psia)		310	560	815	235	230	315	510	745	665
Run No.		47	48	49	50	51	52	53	54	55
TC No.	L/D	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>
23	6.13	3.95	6.24	8.87	11.69					20.94
24	6.45	5.19	7.82	10.54	11.38					
25	6.76	5.28	8.47	12.55	11.14					29.79
26	7.08	5.93	7.74	11.29	10.37					22.91
27	7.39	7.18	8.06	11.70	11.10					24.17
28	7.71	7.53	7.53	10.63	10.27					
29	8.03	15.64	16.68	17.10	16.03					
30	8.34		10.34	14.13	10.23					
31	8.66	10.56	10.70	15.25	10.01					35.64
32	8.96	11.67	12.36	16.36	9.96					37.42
33	9.19	10.70	11.74	15.96	8.97					37.44
34	9.54									39.40
35	9.72	9.00	10.03	13.32	7.29					29.61
36	9.95	10.48	11.60	15.63	7.41					37.28
37	10.23	10.60	12.37	16.57	7.36					35.51
38	10.36	10.53	12.03	16.15	7.13					36.60
39	10.57	10.10	11.48	15.85	6.79					36.01
40	10.80	9.73	11.68	16.04	6.61					37.04
41	11.01	9.33	11.46	15.65	6.13					37.39
42	11.22	9.50	12.00	16.37	6.20					37.44
43	11.43	8.74	11.44	15.47	5.69					36.48
44	11.62		11.51	16.07	5.59					37.36
45	11.83	8.71								
46	12.28		12.35	16.54	4.90					54.81
47	12.43	7.88	13.94	18.99	5.21					41.96

NOTE: Run No. 55 was with hydrogen gas, all others are with nitrogen gas.

T _c (°R)		1400	1370	1370	1370	1430	1440	1420	1320	1490
P _{pc} (psia)		310	560	815	235	230	315	510	745	665
	Run No.	47	48	49	50	51	52	53	54	55
RC No.	L/D	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>
48	12.58	8.08	14.61	19.88	5.25					44.02
49	12.75	8.77	15.87	22.34	5.29					25.00
50	12.96	9.07	17.53	24.19	5.43					48.89
51	13.07	9.24	18.63	25.92	5.43					45.86
52	13.25	9.30								53.36
53	13.40		20.52	29.78	5.54					53.99
54	13.56	9.61	22.07	32.39	5.70					57.48
55	13.71	9.88	23.99	34.34	5.95					60.28
56	13.88	9.91								64.34
57	14.01		26.52	37.09	5.21	5.35	10.54	23.52	38.73	63.14
58	14.21	10.33	25.84	36.49	6.10	5.35	10.40	23.32	37.78	63.41
59	14.34	10.58								63.26
60	14.49		24.76	35.97	5.82	5.18	9.88	22.55	37.26	61.99
61	14.66	9.91	23.63	34.59	5.62	5.08	9.46	21.64	35.67	
62	14.79	9.16	24.71	.87	5.67	4.46	9.59	22.11	36.20	60.32
63	14.94	9.55	23.26	.47	5.43	4.24	9.10	20.78	34.69	59.18
64	15.14	9.11	9.02	12.88	8.05					55.48
65	15.30	5.62	21.14	20.32	5.25	3.99	8.32	19.03	31.57	53.45
66	15.45	8.19	19.64	19.88	5.12	3.76	8.00	18.02	30.27	
67	15.58	7.65	20.72	20.24	5.47	3.91	8.25	18.93	31.82	50.95
68	15.75	7.81	19.86	22.28	5.16	3.77	7.70	17.65	29.81	67.75
69	15.92	7.86	18.35	21.67	4.81	3.69	7.67	16.95	28.25	
70	16.50	7.52	14.68	6.57	2.70	4.08	6.44	13.49	22.21	40.78
71	16.71	6.14	14.72	5.01	3.05	4.17	6.56	13.63	22.63	40.11
72	16.93	6.40				4.29	6.73	13.41	22.68	40.88

NOTE: Run No. 55 was with hydrogen gas, all others are with nitrogen gas

T_c ($^{\circ}\text{R}$)		1400	1370	1370	1370	1430	1440	1420	1320	1490
P_{pc} (psia)		310	560	815	815	230	315	510	745	665
	Run No.	47	48	49	50	51	52	53	54	55
TC No.	L/D	$h \times 10^5$	$h \times 10^5$	$h \times 10^5$	$h \times 10^5$	$h \times 10^5$	$h \times 10^5$	$h \times 10^5$	$h \times 10^5$	$h \times 10^5$
73	17.15					4.23	6.75	13.64	23.66	40.59
74	17.26					4.35	6.66	13.09	22.31	40.07
75	17.47					4.69	7.27	13.51	22.53	40.31
76	17.67					4.66	7.01	13.22	22.09	37.15
77	17.88					4.56	6.88	12.79	21.16	37.05
78	18.11					4.77	7.31	12.99	21.53	36.06
79	18.24					4.13	6.08	11.18	18.30	28.47
80	18.44					4.69	7.13	12.18	19.97	32.82
81	18.64					4.42	6.53	10.60	17.45	25.37
82	2.66					8.12	6.36	9.68	15.50	
83	3.30					8.74	4.60	7.36	11.59	
84	4.14					8.83	3.39	5.49	8.80	
85	4.56					8.47	4.85	7.30	11.02	
86	5.18					9.85	4.73	7.70	12.28	
87	5.82					9.97	4.17	6.56	10.40	
88	6.44					8.77	5.02	7.44	11.21	
89	7.07					9.23	6.52	7.64	12.44	
90	7.71					8.53	7.50	7.06	10.95	
91	8.33					8.97	9.87	9.89	15.33	
92	8.95					8.67	11.36	11.80	17.51	
93	9.62					7.53	10.89	12.30	17.52	
94	9.83					6.86	10.67	11.63	17.24	
95	10.04					5.82	9.66	10.89	15.92	
96	10.25					6.32	9.99	10.94	16.22	
97	10.45					5.62	9.40	10.74	15.83	
98	10.58					5.85	9.75	10.92	16.39	

NOTE: Run No. 55 was with hydrogen gas, all others are with nitrogen gas

T _c (°R)		1400	1370	1370	1370	1430	1440	1420	1320	1490
P _{pc} (psia)		310	560	815	235	230	315	510	745	665
	Run No.	47	48	49	50	51	52	53	54	55
TC No.	L/D	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>	<u>h x 10⁵</u>
99	10.86					5.49	9.37	10.64	15.85	
100	11.08							7.91	18.29	
101	11.27					4.10	8.16	9.75	14.63	
102	11.48					4.65	8.34	10.27	15.41	
103	11.69					4.15	8.43	10.44	15.66	
104	11.91					3.59	7.38	9.83	15.35	
105	12.45					3.14	7.14	9.65	14.69	
106	12.76					2.29	5.96	8.36	12.91	
107	13.09					2.43	6.25	8.92	13.86	
108	13.41					2.61	5.25	8.07	12.71	
109	13.74					1.96	5.22	8.40	13.25	
110	14.40									
111	14.73					3.15	4.60	8.20	12.97	
112	15.05					1.62	3.14	5.37	8.64	
113	15.36					2.50	4.47	8.91	12.51	
114	15.69					3.03	4.58	7.82	12.64	
115	16.55							6.73	11.02	
116	16.74					3.10	4.33	7.27	11.75	
117	16.95					3.00	4.14	7.01	11.56	
118	17.17					3.46	4.58	7.54	12.50	
119	17.56					3.63	4.84	8.04	13.58	
120	17.77					3.75	4.99	8.44	14.23	
121	17.97							9.36	15.36	
122	18.17					3.65	5.80	9.34	15.32	
123	18.42									
124	18.63									

NOTE: Run No. 55 was with hydrogen gas, all others are with nitrogen gas.

T_c ($^{\circ}R$)		1360	1360
P_{pc} (psia)		695	695
		223	224
<u>TC No.</u>	<u>Run No. L/D</u>	<u>$h \times 10^5$</u>	<u>$h \times 10^5$</u>
TSW - 1	.41	17.14	16.46
2	.48		15.60
3	.56	15.20	15.17
4	.64	14.49	14.77
5	.80	14.12	14.16
6	1.27	13.59	13.14
7	1.74	13.35	12.90
8	2.21	12.78	11.85
9	2.68	12.38	11.57
10	3.18	12.16	12.19
11	3.65	12.29	
12	4.12	11.55	
13	4.59	10.89	
14	5.07	11.82	11.79
16	6.03	12.16	11.42
17	6.49	10.87	
18	6.97		10.64
20	7.91		10.46

SECONDARY EJECTOR		
THERMO-COUPLE	L	Δ
TSW 1	0.41	
TSW 2	0.48	
TSW 3	0.56	
TSW 4	0.64	
TSW 5	0.80	
TSW 6	1.27	
TSW 7	1.74	
TSW 8	2.21	
TSW 9	2.68	
TSW 10	3.18	
TSW 11	3.65	
TSW 12	4.12	
TSW 13	4.59	
TSW 14	5.07	
TSW 15	5.54	
TSW 16	6.03	
TSW 17	6.49	
TSW 18	6.97	
TSW 19	7.45	
TSW 20	7.91	
TSW 21	8.38	

PRIMARY EJECTOR			
THERMO-COUPLE	L	THERMO-COUPLE	L
TW 1	2.7	TW 63	14.94
TW 2	5.8	TW 64	15.14
TW 3	8.8	TW 65	15.30
TW 4	1.22	TW 66	15.45
TW 5	1.46	TW 67	15.58
TW 6	1.72	TW 68	15.75
TW 7	2.01	TW 69	15.92
TW 8	2.7	TW 70	16.50
TW 9	8.8	TW 71	16.71
TW 10	1.46	TW 72	16.92
TW 11	2.01	TW 73	17.15
TW 12	2.46	TW 74	17.26
TW 13	2.98	TW 75	17.47
TW 14	3.29	TW 76	17.67
TW 15	3.60	TW 77	17.88
TW 16	3.92	TW 78	18.11
TW 17	4.22	TW 79	18.24
TW 18	4.55	TW 80	18.44
TW 19	4.86	TW 81	18.63
TW 20	5.18	TW 82	2.66
TW 21	5.48	TW 83	3.30
TW 22	5.82	TW 84	4.14
TW 23	6.13	TW 85	4.56
TW 24	6.45	TW 86	5.18
TW 25	6.75	TW 87	5.82
TW 26	7.08	TW 88	6.44
TW 27	7.39	TW 89	7.07
TW 28	7.71	TW 90	7.71
TW 29	8.03	TW 91	8.33
TW 30	8.34	TW 92	8.95
TW 31	8.66	TW 93	9.62
TW 32	8.96	TW 94	9.83
TW 33		TW 95	10.04
TW 34	9.54	TW 96	10.25
TW 35	9.72	TW 97	10.45
TW 36	9.95	TW 98	10.58
TW 37	10.23	TW 99	10.86
TW 38	10.36	TW 100	11.08
TW 39	10.57	TW 101	11.27
TW 40	10.80	TW 102	11.48
TW 41	11.01	TW 103	11.69
TW 42	11.22	TW 104	11.91
TW 43	11.43	TW 105	12.45
TW 44	11.63	TW 106	12.76
TW 45	11.83	TW 107	13.09
TW 46	12.28	TW 108	13.41
TW 47	12.43	TW 109	13.74
TW 48	12.58	TW 110	14.40
TW 49	12.75	TW 111	14.73
TW 50	12.96	TW 112	15.06
TW 51	13.07	TW 113	15.36
TW 52	13.25	TW 114	15.69
TW 53	13.40	TW 115	16.55
TW 54	13.56	TW 116	16.74
TW 55	13.71	TW 117	16.95
TW 56	13.88	TW 118	17.17
TW 57	14.01	TW 119	17.56
TW 58	14.21	TW 120	17.77
TW 59	14.34	TW 121	17.97
TW 60	14.49	TW 122	18.17
TW 61	14.66	TW 123	18.42
TW 62	14.79	TW 124	18.63

NOTES:

- Δ ALL "L" DIMENSIONS ARE ALONG CENTERLINE OF PRIMARY EJECTOR AND ARE MULTIPLES OF D_2
- Δ ALL "L" DIMENSIONS ARE ALONG CENTERLINE OF SECONDARY SAFETY-PURGE EJECTOR AND ARE MULTIPLES OF D_5

Figure C.1-1

Thermocouple Locations
Subsonic Turn Ejector System
SST 2-1.05-22.7

NOTES:

1. Subsonic Turn Ejector System 2-1.05 - 82.5
2. Run No's
Primary Ejector: D-266-LQ-47, 48, 49, 53, 54
Secondary Ejector: D-266-LQ-223, 224
3. Fluid - Hot Nitrogen Gas
4. Points taken on Impingement Side of Elbow
5. Curve Shown is 3σ upper limit of Test Data

Figure C.1-2

Normalized Subscale Heat Transfer Coefficients

2. Exhaust Plume Thermal Radiation

Radiative heating from the hydrogen exhaust plume was estimated theoretically in order to determine the thermal environment of nearby hardware surfaces and structures. The theoretical model consists of two disks and introduces such parameters as disk parameters, distance between disks, and the geometric view factor. Other parameters of importance are the radiating disk temperature and its emissivity. Reradiation from the absorbing disk is neglected and the disks are separated by a non-absorbing medium.

Partial verification of the theoretical radiative heating rates thus obtained was made through an actual measurement of the emittance of the hydrogen flame from the scale model system. Steam was used as the safety purge fluid for these tests.

A measurement of the emittance of the flame (total power radiated per unit area) allowed heat transfer rates to be calculated. Since the principal emitting species in the flame is H_2O , the emitted radiation will be concentrated in the water band regions; and it is in those regions that atmospheric absorption is greatest. Consequently, a simple, wide-band radiometric measurement, from the distances required to avoid damage to the measuring instrument, needed to be corrected for attenuation. This correction was less than 10%.

The simplest method for determining the effect of attenuation requires knowledge of the flame temperature. The temperature could best be determined by measuring the spectral distribution of the flame radiation. However, this would be a major task, both in preparing a suitable instrument and in acquiring and reducing data. A sufficiently good estimate of the flame temperature was obtained by using narrow-band radiometric measurements.

Two groups of tests were run. One group was run without secondary safety purge. The emittance of the flame was $14,900 \text{ BTU/ft}^2 \text{ hr steradian}$ and the flame temperature was approximately 2700°R . Water was introduced into the nitrogen safety purge fluid for the second group of tests. The water turned to steam, which resulted in a higher emissivity of the flame. The emittance of the flame for these tests was $16,000 \text{ BTU/ft}^2\text{-hr steradian}$ and the flame temperature was approximately 2700°R .

An estimated radiation flux map for the sub scale model is presented in Figure C.2-1.

Since heating by radiation is proportional to the fourth power of the absolute temperature, thermal radiation from the full scale model will exceed that obtained in the test runs of the sub-scale model by the ratio of the flame temperature to the fourth power. The exhaust plumes, however, have the same shape and length to exhaust diameter ratio.

The temperature increase as a function of time of an object exposed to this thermal radiation, with the assumption that all the energy is absorbed and that the object is not cooled, is expressed by the following relationship.

$$\frac{dT}{d\theta} = \frac{(Q/A)_r}{\rho C_p t} \quad (1)$$

when

$\frac{dT}{d\theta}$ = rate of temperature rise in $^{\circ}\text{F}/\text{sec}$.

$(Q/A)_r$ = radiant heat flux from flux map in $\text{BTU}/\text{ft}^2\text{sec}$.

ρ = density of object in lb/ft^3

C_p = heat capacity of object in $\text{BTU}/\text{lb } ^{\circ}\text{F}$

t = thickness of object in ft.

Densities and heat capacities of selected materials are tabulated below.

	Aluminum	Stainless Steel	Concrete
$\rho - \text{lb}/\text{ft}^3$	173	500	144
$C_p - \text{BTU}/\text{lb } ^{\circ}\text{F}$	.18	.12	.16

Therefore, from Equation 1, and the preceding Table, the temperature rise of a stainless steel object 1/4 inch thick exposed to a thermal heat flux of $2 \text{ BTU}/\text{ft}^2 \text{ sec}$ is $1.6^{\circ}\text{F}/\text{sec}$.

It is recommended that areas of concern be checked out by the above method to see if any structure need be cooled.

NOTES:

1.

Symbol	Heat Flux (Btu/Ft ² -Sec)
□	13.2
△	11.9
○	2.49
◊	1.33
○	0.2 - 0.3
◆	13-15 Exp.
◆	4-5 Exp.

Figure C.2-1
Radiation Flux Map for Subscale
Subsonic Turn Ejector System

NOMENCLATURE AND SYMBOLOLOGY

drop-out	Minimum operating chamber pressure	GREEK LETTERS	
ETS-1	Engine Test Stand No. 1	α	Moles of reactants per mole of product
NES	NERVA Exhaust System	β	Turbine exhaust flow rate as a function of primary flow rate
NERVA	Nuclear Engine for Rocket Vehicle Application		
NTS	Nevada Test Site		
Operating pressures	Engine chamber pressures that provide the required environmental cell pressures resulting in nozzle flowing full		$\frac{\dot{W}_1 \sqrt{(T/m)_1}}{\dot{W}_p \sqrt{(T/m)_p}}$
primary ejector	The section of the ejector system between the environmental cell and the secondary ejector inlet	γ	Ratio of specific heats
		ρ	Density
pull-in	A sudden lowering of the environmental cell pressure to a minimum (start)	σ	Standard deviation
secondary ejector	The section of the ejector system between the secondary ejector inlet and the ejector system exit that is used for injecting the safety purge and ducting the gases outside the vault	SUBSCRIPTS	
start	A sudden lowering of the environmental cell pressure to a minimum (pull-in)	1, 2, 3, 4	Stations along ejector system
		a	Ambient or gas
		b	Bulk or backflow
		c	Chamber
		d	Duct
		e	Exit
		f	Flame or exhaust gas
		H ₂	Hydrogen
		i	Initial or inside
		l	Leakage
		N ₂	Nitrogen
		N	Unreacted exhaust gas
		O ₂	Oxygen
		p	Primary ejector conditions
		r	Recovery
		s	Secondary ejector conditions
		ST	Start
		STO	Stoichiometric mixture
		t	Total or stagnation conditions or time
		v	Environmental cell (engine compartment)
		v _o	Engine compartment reference pressure
		W	Ejector wall
		SUPERSCRIPITS	
		*	Throat or sonic conditions
A	Cross sectional area		
D	Diameter; for an ejector, internal diameter		
g	Gravitational constant		
h	Heat transfer coefficient		
k	Constant defining the angle spread of the flame		
L	Length, for an ejector, the length along the centerline		
M	Mach number		
m	Molecular weight		
P	Static pressure		
PD	Ejector wall pressure		
P _t	Total or stagnation pressure		
q	Heat Flux		
R _v	Universal gas constant		
r	Radius		
T	Temperature		
V	Velocity		
X	Mole fraction of fuel		
χ	Mass fraction of exhaust gas		