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MASTER

DESIGN AND SCALE MODEL TEST RESULTS
OF A SEVERELY MODIFIED RAO CONTOUR NOZZLE

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THESIS

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ABSTRACT

This thesis describes the design, selection and scale model test results of a contour design for a convectively-cooled, ground test nozzle extension which originates at an area ratio of 5:1 (termination point of main nozzle). Selection was based on the predicted ability of the contour design to duplicate the amount of heat transferred to the coolant (bulk temperature rise) of a reference Rao contour nozzle extension designed for flight conditions without inducement of flow separation at a chamber pressure of 450 psia. An 1/8 scale uncooled model was constructed using the selected contour (4° exit angle and 12:1 exit area ratio) with 40 pressure taps located along the divergent portion of the nozzle. Continuous wall pressure measurements were obtained up to a chamber pressure of 600 psia using nitrogen heated to 1500°R as the flowing fluid. Separation pressures as a function of chamber pressure were determined and compared with data of various authors. Agreement is shown in a few cases and the data ~~do~~ refute the conclusion of several authors that separation pressure is equal to a constant times the ambient pressure. Pressure taps were located in all four quadrants to monitor any asymmetric flow separation phenomenon; however, examination of ^{the} data did not reveal any such phenomenon. Based on examination of ^{the} data the selected contour incurred no flow separation at a chamber pressure of 450 psia and is capable of flowing full at an area ratio of 11.5 at a chamber pressure of 240 psia (55% of the rated chamber pressure of 450 psia) with only about a 3 degree deficiency in matching the bulk temperature rise of the reference nozzle extension.

TABLE OF CONTENTS

SECTION	PAGE
ACKNOWLEDGEMENT-----	i
ABSTRACT-----	ii
TABLE OF CONTENTS-----	iii
LIST OF TABLES-----	iv
LIST OF FIGURES-----	v, vi
NOMENCLATURE-----	vii
I. INTRODUCTION-----	
II. CONTOUR DESIGN AND SELECTION-----	
A. CONTOUR DESIGN-----	
B. PRESSURE PROFILE-----	
C. HEAT TRANSFER-----	
D. ^{CONTOUR} ^ SELECTION-----	
III. TESTING AND TEST RESULTS-----	
A. NOZZLE DESCRIPTION-----	
B. INSTRUMENTATION-----	
C. EXPERIMENTAL PROCEDURE-----	
D. TEST RESULTS-----	
IV. COMPARISON OF TEST RESULTS WITH PUBLISHED DATA-----	
A. DISCUSSION-----	
B. SUMMARY OF PUBLISHED RESULTS AND COMPARISON WITH TEST DATA-----	
V. CONCLUSIONS AND RECOMMENDATIONS-----	
REFERENCES	

LIST OF TABLES

TITLE	TABLE NO.
Contour Description	1
Contour E Tabulation	2
Contour F Tabulation	3
Contour G Tabulation	4
Contour H Tabulation	5
Record of Actual Final Contour Dimensions	6
Record of Actual Final Pressure Tap Locations	7
Tabulation of Pressure Tap Locations	8
Tabulation of Specific Heat Ratio for Full Scale and Scale Model Conditions	9
Tabulation of Various Authors' Nozzle Descriptions	10
Tabulation of Separation Pressure for each Area Ratio	11

LIST OF FIGURES

<u>TITLE</u>	<u>FIGURE NO.</u>
Contour Layout	1
Predicted Wall Pressure Profiles of Contours E, F, G, H and 70:1	2
Predicted Coolant Bulk Temperature Rise of Contours E, F, G, H, and 70:1	3
Predicted Pressure Drop of Contours E, F, G, H, and 70:1	4
Nozzle Design - 1/8 Scale	5
Chamber Pressure-Time Profile	6
Comparison of Specific Heat Ratio for Full Scale and Scale Model Conditions	7
Comparison of Predicted and Actual Wall Pressure Profile	8
Wall Pressure Distribution Test B-1	9
Wall Pressure Distribution Test B-2	10
Wall Pressure Distribution Test B-3	11
Wall Pressure Distribution Test B-4	12
Wall Pressure Distribution Test B-5	13
Wall Pressure Distribution Test B-6	14
Wall Pressure Distribution Test B-7	15
Wall Pressure Distribution Test B-8	16
Wall Pressure Distribution Test B-9	17
Wall Pressure Distribution Test B-10	18
Wall Pressure Distribution Test B-11	19
Wall Pressure Distribution Test B-12	20
Wall Pressure Distribution Test B-13	21
Wall Pressure Distribution Test B-14	22

LIST OF FIGURES (Cont'd)

<u>TITLE</u>	<u>FIGURE NO.</u>
Description of Flow Separation Region	23
Comparison of Test Data with Results of Various Authors	24
Comparison of Test Data with Results of Various Authors	25
Comparison of Test Data with Results of Green and Others	26
Comparison of Test Data with Results of Scheller and Bierlein	27
Comparison of Test Data with Probabilistic Results of Grant .	28
Comparison of Test Data with Results of Mager	29
Comparison of Test Data with Results of Ahlberg, Hamilton, Migdal Nilson [^] and	30

NOMENCLATURE

<u>SYMBOL</u>	<u>DESCRIPTION</u>	<u>UNITS</u>
$A/A_{cr}, f_s/f_t, A_e/A_t$	Area Ratio	
A_s/A^*		
C_g	Empirical constant in H_g equation	
C_p	Specific heat	BTU/lb-°F
D	Diameter of chamber	In.
H_g	Gas Side Heat Transfer Coefficient	BTU/ In. ² -sec-°F
H_L	Liquid Side Heat Transfer Coefficient	BTU/ In. ² -sec-°F
K	Empirical constant in Separation Equation	
k_f	Thermal conductivity of fluid	BTU/ sec-in.-°F
k_M	Thermal conductivity of metal	BTU sec-in.-°F
L	Axial length	In.
M_a, M'	Mach Number Upstream of Shock	
MAM	Molecular Weight-Arithmetic mean temp.	Lb/ Lb-mole
MFS	Molecular Weight-Free Stream temp.	Lb/ lb-mole
M_i	Initial Mach Number (upstream of shock)	
M_s	Mach Number Separation Point	
M_s^*	Characteristic Mach NO ^{NUMBER} at Separation	
M_1	Mach Number Upstream of Shock	
M_2	Mach Number Downstream of Shock	
N	Empirical Constant ^{IN} Separation Equation	

NOMENCLATURE (cont.)

P_a, P, P_o	Ambient Pressure	Lb/in. ² ABS
P_b	Pressure in Separated Region	Lb/in. ² ABS
P_c, P_N, P_t	Chamber Pressure	Lb/in. ² ABS
P_r	Prandtl Number	
P_s, P, P_i	Separation Pressure	Lb/in. ² ABS
P_w	Wall Pressure	Lb/in. ² ABS
Q	Heat Input to Surface	BTU/sec
$(Q/A)_i$	Local Heat Flux-Inside Surface	BTU/in. ² -sec
$(Q/A)_m$	Local Heat Flux-Metal Surface	BTU/in. ² -sec
$(Q/A)_o$	Local Heat Flux-Outside Surface	BTU/in. ² -sec
Re_f	Reynolds Number	
S.A.	Surface Area	In. ²
TAM	Temperature Arithmetic Mean	°F
T_B	Coolant Bulk Temperature	°F
T_C	Chamber Temperature	°R
T_E	Exit Temperature	°R
T_M	Metal Thickness	In.
T_o	Stagnation Temperature	°R
T_R	Recovery Temperature	°R
T_{wg}	Gas Side Wall Temperature	°F
T_{WL}	Liquid Side Wall Temperature	°F
T	Free Stream Temperature	°R
U_s	Separation Velocity	In./sec
U_s^*	Characteristic Separation Velocity	In./sec

NOMENCLATURE (cont.)

W_T	Weight Flow	Lb/sec
X	Longitudinal Distance	In.
Y	Radial Distance	In.

GREEK LETTERS

α	Empirical Constant-Separation Equation	
α_E	Exit Half Angle	degrees
γ	Specific Heat Ratio	
δ	Wedge Angle	degrees
ϵ	Area Ratio	
ϵ_s	Separation Area Ratio	
θ	Shock Angle	degrees
θ	Tangent Angle	degrees
μ	Viscosity	Lb/ In.-sec
ν_b	Kinematic Viscosity (ν_p) Evaluated at T_B	In. ² / sec
ν_w	Kinematic Viscosity (ν_p) at T_{WL}	In. ² / sec

SECTION I

INTRODUCTION

In many nozzle designs that operate in space or near space environments, it is necessary to ground test the nozzle without the expense of reproducing the vacuum conditions of space. In this thesis, a design is considered that attempts to reproduce the amount of heat transferred (coolant bulk temperature rise) in a convectively cooled nozzle extension that originates at an area ratio of 5:1 and terminates at an area ratio of 24:1. This nozzle extension is part of a reference configuration, a 70:1 area ratio Rao contour (Reference 18) nozzle assembly, which also consists of a main nozzle which terminates at an area ratio of 5:1 and an aft extension (uncooled) which originates at an area ratio of 24:1 and terminates at an area ratio of 70:1.

Duplicating the amount of heat transferred to the coolant of the nozzle extension during ground testing is the prime consideration since it is desirable to expose the main nozzle to the same thermal environment encountered during space operation (nozzle extension coolant is supplied to the main nozzle as coolant in a counter flow arrangement with respect to the main gas flow). An additional requirement is to maintain duplication of the amount of heat transferred to the nozzle extension at a minimum of 40% of rated chamber pressure. That is, full flow attachment must be attained at a minimum chamber pressure of 180 psia (40% of 450 psia the rated chamber pressure).

For ground testing the point of separation can be ~~determined~~^{estimated} by utilizing the separation pressure relationship recommended by various authors (References 2, 14, 17, 21).

$$P_s \approx .35 P_a \quad (1)$$

For an ambient pressure of 14.7 psia, the predicted separation pressure is about 5.1 psia, which corresponds to an area ratio of about 12:1 based on the pressure profile for the reference configuration (70:1 area ratio Rao contour nozzle) at a chamber pressure of 450 psia. This means that if the reference nozzle extension (which terminates at an area ratio of 24:1) is used for ground testing, separation would occur at about an area ratio of 12:1 and the heat transfer to the nozzle extension coolant is greatly reduced. To resolve this problem new ground test contours were designed.

Using an area ratio of 12:1 as the end point constraint for the ground test configuration, several contours ~~were designed~~^{were designed} which were turned severely (that is, from the basic Rao contour profile) into the hot gas stream. ~~were designed~~. Turning the contour into the gas stream (see Figure 1) allows the axial length of the nozzle extension to be ~~lengthened~~^{INCREASED} which in turn provides a greater surface area exposed to the hot gas stream. The surface area of the ground test nozzle extension ~~should be~~^{was designed to be} the same as the reference nozzle extension in order to duplicate the amount of heat transferred. Predicted pressure profiles were determined by a method of characteristics computer program and heat transfer analyses were conducted to determine the amount of bulk temperature rise obtained

for each contour design. Based on this information, one contour was selected and a scale model nozzle was constructed. Instrumentation was placed along the nozzle contour in order to determine the actual pressure profile and to determine at what chamber pressure and area ratio full flow attachment was established. In addition, instrumentation was placed circumferentially at several area ratios in order to determine if asymmetric flow separation occurred.

SECTION II

CONTOUR DESIGN AND SELECTION

A. CONTOUR DESIGN

In order to match the coolant temperature rise of the reference nozzle extension, several contours were designed as shown in Figure 1. Each contour's initial start point is at an area ratio of 5:1 and extends to an area ratio of 12:1, with a minimum exit angle of 4° and maximum of 24.13° . An angle of less than 4° would tend to give a contour which is too flat which then would result in possible radical movement of the separation plane. That is, the wall pressure in a flat or almost flat contour is nearly the same and any flow disturbance would cause the separation plane to move erratically up and down the contour since there is no increasing pressure gradient as you move upstream toward the throat. The maximum angle of 24.13° is that associated with the optimum 70:1 contour when truncated at an area ratio of 12:1.

An exit area ratio of 12:1 was selected as follows: According to Equation (1), the wall pressure at which flow separation occurs can be approximated. Since the modified contours will be tested at atmospheric back pressure (that is $P_a = 14.7$ psia) the resulting separation pressure is expected to be about 5.1 psia. Comparing this value with that given by Figure 2 for an optimum $\epsilon = 70:1$ Rao contour at $P_c = 450$ psia corresponds to an area ratio near 11:1. Because of uncertainty in the above relationship an area ratio of 12:1 was selected at the end point.

Using area ratios of 5:1 and 12:1 as upper and lower end points, several contours were designed of various lengths and exit angles within the prescribed envelope. Four contours of exit angles of $11^\circ 45'$, $7^\circ 15'$, $5^\circ 0'$, and $4^\circ 0'$ were designed as shown in Figure 1, with the 70:1 Rao contour for comparison.

~~In addition,~~ Table 1 lists the respective lengths and surface areas of each contour. Axial and radial coordinates as well as tangency angle were determined from the layout design and ^{ARE} tabulated in Tables 2, 3, 4, and 5.

B. PRESSURE PROFILE

Based on the coordinates as determined in the design layout, a method of characteristics computer program was used to determine the expected wall pressure distribution along the contour. The program is a numerical solution of axisymmetric, irrotational, isentropic, steady, supersonic flow of a perfect gas by the method of characteristics (Reference 32). A flow pattern or a characteristic network of left and right running Mach lines (characteristics) was calculated. The program uses axial and radial coordinates as well as tangency angle and nozzle throat radius and downstream radius as input. Output consists of pressure and temperature distribution along the contour wall (designated as upper boundary) and down the nozzle center (designated as lower boundary). This program is an axisymmetric isentropic program and therefore does not treat any flow disturbance (large pressure gradient) as a shock but continues to treat the solution isentropically. Therefore, a pressure distribution obtained by this program must be verified by other means.

The wall pressure distribution solutions for the four contours are presented in Figure 2. As can be seen Contour G and H immediately do not appear desirable due to the flat nature of the pressure distribution. Contours E and F appear more suitable even though an adverse pressure gradient is apparent and flow separation may occur at lower chamber pressures. However, Contour E and F are of longer length which is desirable for heat transfer purposes and therefore bear further consideration.

C. HEAT TRANSFER

In order to determine the amount of heat transferred to a convectively cooled nozzle section constructed of oval coolant tubes (CRES 347 mat'l) a convective heat transfer computer program (Reference 33) was used. The program predicts the increase in coolant bulk temperature rise for properties of liquid hydrogen as the coolant medium.

This program uses a heat balance across the coolant tube as follows:

The total rate of heat flow Q through the wall is

$$Q = \left(\frac{Q}{A}\right)_o = \left(\frac{Q}{A}\right)_M = \left(\frac{Q}{A}\right)_i \quad (2)$$

where

$$\left(\frac{Q}{A}\right)_o = H_G (T_R - T_{wg}) \quad (3)$$

with

$$T_R = [T_\infty + P_r^{1/3} (T_o - T_\infty)] \quad (4)$$

$$H_G^* = \frac{C_g}{1.644 D^{.2}} \left(\frac{U^{.2} C_p}{P_r^{.6} T_{AM}} \right) \left(\frac{4 W_T MAM T_\infty}{\pi D^2 T_{AM} MFS} \right)^{.8} \quad (5)$$

$$T_{AM} = \frac{T_\infty + T_{wg}}{2} \quad (6)$$

and

$$\left(\frac{Q}{A}\right)_M = \frac{k_M}{T_M} (T_{wg} - T_{WL}) \quad (7)$$

*As given by Bartz Equation, Reference 27.

and

$$\left(\frac{Q}{A}\right)_i = H_L (T_{WL} - T_B) \quad (8)$$

with

$$H_L^* = .0176 Re_f^{.8} P_{rf}^{.4} \left(1 + .01457 \frac{\sqrt{w}}{\sqrt{b}}\right) \frac{k_f}{D} \quad (9)$$

$$f = T = \frac{1}{2} (T_{WL} + T_B) \quad (10)$$

The coolant bulk temperature (T_B), the gas side wall temperature (T_{wg}) and the liquid side wall temperature (T_{WL}) are assumed and then the program iterates until consistent results are obtained. The procedure is continued along the contour using the previous stations temperatures as initial values.

Using liquid hydrogen as the coolant medium at a pressure of 910 psia and a temperature of 55°R and gaseous hydrogen as the propulsive medium at a chamber pressure of 450 psia and temperature of 4500°R, coolant bulk temperature rises were determined for gas side wall temperatures of 1000, 1200 and 1400°F. Figure 3 presents the change in bulk temperature rise as a function of gas side coolant tube wall temperature (Max) for each of the contours considered. Also, included for comparison is the 70:1 contour truncated at $\epsilon = 12:1$. The design point of $\Delta T_B = 30.8^\circ\text{F}$ for the 70:1 contour with end points of $\epsilon = 5:1$ and $\epsilon = 24:1$ can be matched at reasonable maximum gas side wall temperatures (T_{wg}) for only the E and F contour.

*As given by Hess and Kunz Equation, Reference 28.

Although it may appear desirable to choose the lower wall temperature case (Contour F), the pressure drop through the coolant system must be considered. Figure 4 presents pressure drop (ΔP) as a function of gas side wall temperature for each contour. As can be seen from the Figure, a pressure drop of more than 65 psi is obtained for a gas side wall temperature (T_{wg}) of 900°F for Contour F; whereas for Contour E at a maximum T_{wg} of 1200°F a pressure drop of 24 psi is obtained.

D. CONTOUR SELECTION

Based on the above heat transfer analysis and predicted gas side wall pressure distribution Contour E was selected as the desired contour that is capable of matching the bulk temperature rise of the reference nozzle extension. It is only left then to determine if Contour E is capable of performing at 40% chamber pressure (180 psia) without inducement of flow separation phenomena when flowing to atmospheric conditions. Using a separation pressure of 5.1 psia, it is estimated that separation occurs in the vicinity of an area ratio of 10.0 at a chamber pressure of 180 psia, however, tests must be conducted to verify the separation point since it is believed that equation (1) and hence the 5.1 psia separation pressure is not necessarily true for contoured nozzles.

When separation occurs in a nozzle, cool ambient air can be drawn up along the nozzle wall in the opposite direction to that of the tested mainstream flow. Therefore, if separation occurs prior to a chamber pressure of 180 psia a cooling effect is obtained along the nozzle wall downstream of the separation point provided reflected shock waves are not incident upon the nozzle wall. Reflected shock waves incident upon the nozzle wall downstream of the separation point will cause local enhancement of the heat transfer coefficient. Reference 29 indicates that at low area ratios the heat transfer coefficients are increased even above that of the throat due to the presence of multiple shock waves. However, this occurs near the throat and in

areas further downstream in the separated region the heat transfer coefficient is near zero and therefore heat transfer due to convection is negligible because of the cool air drawn up along the contour.

SECTION III

TESTING AND TEST RESULTS

A. NOZZLE DESCRIPTION

In order to verify the flow separation point, a 1/8 uncooled scale model as shown in Figure 5 was constructed of corrosion resistant steel (300 series) using the contour E design. Table 6 presents the calculated and actual measured X and Y coordinates for the entire nozzle using the nozzle throat as a base reference.

Monitoring of the desired static pressure distribution along the expanding portion of the nozzle wall was accomplished with a series of 0.062 inch diameter holes drilled at approximately one area ratio intervals (about 1/2 inch apart) starting at an area ratio of 3.5 and extending to the nozzle exit. The holes were drilled normal to the surface in each quadrant and at specific area ratios of 3.5, 4.75, 6.0, 7.0, 8.0, 8.75, 9.75, 10.75, 11.50 and 12.0 to 1 for a total of forty pressure locations.

Holes were also drilled in the chamber portion of the nozzle to monitor chamber pressure and temperature. Table 7 presents the calculated and actual measured X and Y coordinates for each pressure tap location in each quadrant and along the contour. By examination of the Y values in Tables 6 and 7 it can be seen that the contour radius is within 0.8% and the pressure tap locations are within 0.02 area ratio.

B. INSTRUMENTATION

The parameters of importance measured during the test were chamber pressure, chamber temperature and nozzle wall pressure at the various area ratios previously stipulated. In addition, the flow rate of the flowing medium (hot nitrogen) was also monitored.

For this test series Tabor pressure transducers were used. The maximum expected accuracy for the Tabor transducers used ^{WAS} ~~were~~ $\pm 0.5\%$ of full range. For the 0-25 psig transducers used, this amounted to ± 0.125 psig. However, each transducer is calibrated at the expected pressure reading prior to each test. Therefore, it is expected that the accuracy is ^{better} ~~less~~ than $\pm 0.5\%$.

In order that consistency be maintained in monitoring wall pressure, each pressure tap had a 1/4 inch diameter corrosion resistant steel (300 series) tube 12 inches long welded in place. Each pressure pickup line was then welded to a panel where the pressure transducers were mounted. Measurements were transmitted from the pressure transducers to oscillographs.

C. EXPERIMENTAL PROCEDURE

Data were collected for the nozzle exhausting to atmospheric pressure with hot (about 1500°R) gaseous nitrogen used as the primary fluid. A pressurization rate of approximately 20-30 psi/sec with dwell points at chamber pressures of approximately 200, 300, 400, 600 psia (see Figure 6) were used.

Due to limitations in the number of recording channels available, duplication of tests was required in order to accommodate all instrument locations. In order to maintain a correlation between tests, duplication of one specific area ratio pressure measurement was accomplished. Data were continuously recorded on oscillographs for the duration of each run. Fourteen runs were made in order to monitor all the required pressure locations. The tests were conducted in two main groups; the first group (runs B-1,3,5,8,10,12,&14) in which the chamber pressure reached a maximum of 400 psia with

dwel points at 200, 300 and 400 psia, and the second group (runs B-2, 4, 6, 7, 9, 11 and 13) which included wall pressure recordings at chamber pressures of from 400 to 600 psia. Particular pressure taps which were monitored for each test run are tabulated in Table 8. As can be seen, there is a repetition of pressure measurements in order to maintain consistency.

Hot nitrogen at 1500°R was chosen as the flowing medium since it more nearly simulates full scale specific heat ratios (see Figure 7 and Table 9) than that of H_2 at subscale conditions of 1500°R and is less expensive and easier to handle.

D. TEST RESULTS

Fourteen separate tests were made with various pressure taps monitored as previously described. Figures 9-22 present plots of the instrumented wall pressures that were recorded as a function of chamber pressure. Examination of each plot reveals high pressure peaks in the aft end pressure tap locations at low chamber pressures of about 160 psia. These pressure peaks occur in the separated flow region and are the result of shock waves incident upon the nozzle wall. These shock waves eventually disappear upon reattachment of flow to the nozzle wall as indicated by a sudden decrease in wall pressure to a minimum value followed by a sudden increase in pressure. For example, flow reattachment is attained at a chamber pressure of 236 psia at an area ratio of 11.5 for run B-1. It should be noted also that in some cases up to four pressure values are plotted for the same area ratio in each of the runs.

An attempt was made to determine if asymmetric flow separation occurs during any part of the nozzle operation. The importance of this phenomenon is that only partial heat transfer will occur, only at that part of the nozzle where attachment is maintained. In addition, this phenomenon is an important stress consideration since it may produce a side load and may also excite

the structural dynamic system. This phenomenon would be evidenced by a large pressure difference in one or more of the pressure readings with respect to the others at one particular area ratio. That is, at a given area ratio one or more pressure taps would approach the ambient pressure while the remainder would experience the particular wall pressure at that chamber pressure during full flow attachment.

As reported by McKenney (Reference 8) symmetric separation of the expanding fluid (dry nitrogen) occurred at pressure ratios (P_c/P_o) above 12 or about 196 psia for $P_o = 14.7$ psia. Below this value asymmetric flow separation was evident by spark shadowgraph which showed the expanding fluid attached to one side of the nozzle. Examination of all 14 runs did not indicate the phenomenon observed by McKenney. There were some slight deviations in wall pressure from one instrumentation tap to another but this was of the order of about 2 psia and may be due to calibration error of the instrumentation or the response of the transducer but most likely is due to the orientation of the separation plane (with its shock waves) as it varies abruptly and randomly about the nozzle axis and as it moves from the throat toward the exit plane. One reason that the phenomenon was not evident may be due to the stiffness of the nozzle. A thinner structure such as a tube bundle is much more flexible and has the capability of growth and contraction thereby changing shape (oval, triangular, etc.) which may influence or precipitate asymmetric flow separation.

Figure 8 presents actual pressure readings at various area ratios at a chamber pressure of 450 psia in comparison with those predicted by a method of characteristics analysis. It can be seen that there is good agreement between the different test runs and with that predicted.

Further examination of Figure 9-22 reveals that attainment of full flow is not apparent until a chamber pressure of about 426 psia is obtained. In fact full flow conditions at 40% chamber pressure level (180 psia) are met only at a maximum area ratio of 9.75, about 15.76 inches from the aft end of the nozzle, therefore losing much of the heat transfer surface area resulting in a bulk temperature loss of about 17°F. However, at an area ratio of 11.5 flow attachment is attained at a chamber pressure of about 240 or 55% level which is only 5.0 inches from the aft end with an expected resulting loss in bulk temperature of only about 3°F.

SECTION IV

COMPARISON OF TEST RESULTS WITH PUBLISHED DATA

A. DISCUSSION

Boundary layer separation is likely to occur if there is a pressure rise (adverse pressure gradient) in the main stream flow direction. It is less likely to occur if pressure is decreasing as the gas flows through a nozzle. However, if the velocity decreases along the nozzle surface and an adverse pressure gradient develops and pressure rises in the downstream direction, separation of the boundary layer occurs when the pressure gradient is of sufficient strength to cause the velocity profile to become tangent to a normal to the surface.

$$\tau \propto (\partial u / \partial r)_{\text{wall}} = 0 \quad (11)$$

The separation point for a two-dimensional boundary layer by definition occurs when the wall shear stress approaches zero. Therefore according to Equation (11) the velocity profile must terminate tangent to a normal to the wall.

At this point the isentropic expansion begins to break down with oblique shock waves (see Figure 23) originating at the nozzle wall. These shock waves cause thickening of the boundary layer and finally separation and will move downstream as the chamber pressure is increased and finally out of the nozzle if the chamber pressure is of sufficient strength to overcome the local pressure rise.

Several authors have theorized that flow separation occurs in a nozzle with a resulting static wall pressure as given by Equation (1).

$$P_s = K P_a \quad (1)$$

P_s = wall pressure at which separation occurs

P_a = ambient pressure

K = empirical constant with reported values
of .34 to .42

However, it is not believed that this relationship adequately describes separation in a contoured nozzle or in one modified such as that tested in this study. It is thought that a simple relationship as Equation (1) cannot describe the separation phenomenon since the wall curvature produces variations of the boundary layer characteristics as a function of travel along the nozzle wall. Therefore, it is necessary to determine how the test data of this study compare with relationships of other authors. A description of flow separation results (both theoretical and empirical) by various authors ^{is} ~~are~~ presented in the following pages and a comparison is made of test data from this thesis and data of other authors.

B. SUMMARY OF PUBLISHED RESULTS AND COMPARISON WITH TEST DATA

Various authors have attempted to correlate separation data. No single way of correlating separation data is acceptable, therefore the present results of this ~~study~~ ^{Study} are plotted in several ways in figures 24-30 for comparison with the results of various authors. Table 10 presents a tabulation of the various ~~authors~~ ^{Studies} discussed with a brief description of the type of nozzle tested with reference to plots (Figures 24-30) of their respective separation pressure results. Table 11 presents a tabulation of wall pressures at which separation began for the various area ratios monitored for each test of this analysis. Also included are the respective values for chamber pressure, ambient pressure and separation pressure combined into the respective parameters as required for comparison with that data of the authors mentioned.

Figure 24 (P_s/P_a versus P_c/P_a) presents data from ten different authors in comparison with data of this ~~analysis~~ ^{Study} and shows the absence of any particular trend or agreement. There may be a possible trend with that of Reference 8, however, the data of this analysis appear to be too scattered for any decisive conclusion. However, the comparison does refute the acceptance of $P_s/P_a = \text{constant}$ as previously determined by some authors. A brief description of the results of the authors included in Figure 24 follows.

Altman, Carter, Penner and Summerfield (Reference 2) indicate that in studies conducted with nitric acid-aniline as the propellant combination for rocket motors utilizing conical nozzles with half angles of 10°, 15°, 20°, and 30° at area ratios of 10 and 20 with pressure ratios (P_c/P_∞) from 11 to 25 it was found that

$$\frac{P_s}{P_\infty} = 0.36 \pm 0.02 \quad (12)$$

The above relation held for various mixture ratios and a nitrogen flow channel.

Fraser, Eisenklam and Wilkie (Reference 14) conducted tests on several conical and curved nozzles with cold air as the flowing fluid discharging to atmosphere with nozzle exit half angles varying from 5 to 30° for the conical nozzles and 1 inch and 1/2 radius of divergence for the curved nozzle. Separation data ^{were} ~~are~~ plotted in the form of P_s versus P_a and it ^{was} ~~is~~ concluded for the conical nozzles and curved nozzles flowing to atmosphere that the separation pressure ratio is a constant, that is

$$\frac{P_s}{P_a} \approx 0.36 \quad (13)$$

Values for this equation are presented in Figure 24. However, for the curved nozzles considered the separation pressure does not vary linearly with the ambient discharge pressure but varies with respect to the radius of divergence.

Summerfield, Foster and Swan (Reference 6) conducted tests on several conical nozzles with nitric acid and aniline as the propellant at chamber temperature of 3650°F with half angles and respective area ratios of 15°, 3.5; 10°, 10.0; 15°, 10.0; 20°, 10.0; 15°, 20.8 at pressure ratios of 14 to 25 with a back pressure of 14.1 psia. Separation data ^{were} ~~are~~ presented in a plot of P_c/P_0 versus separation area ratio (f_s/f_t) for the various configurations considered. The authors concluded that $P_s/P_a = 0.40$ at $P_c = 170$ and $P_s/P_a = 0.34$ at $P_c = 360$ independent of P_c/P_a , γ and ω .

McKenney (Reference 8) conducted tests on a two-dimensional conical nozzle with an exit half angle of 15° with an area ratio of 8.0. Dry nitrogen was used as the flowing fluid and tests were conducted at stagnation pressures ranging from 174 to 294 psia at constant back pressure of 13.1 psia. Separation data were presented in a plot of P_c/P_o versus f_s/f_t (separation area ratio) and also in a plot of P_s/P_o versus P_c/P_o . The author concluded that the 2-D nozzle exhibited behavior similar to separation behavior in actual 3-D nozzle tests and therefore concluded that the ratio of separation pressure to back pressure (P_s/P_o) is approximately constant and lies between 0.38 and 0.41.

X Ilsen (Reference 13) suggest^{ed} that conditions for separation are also influenced by (1) vibrational character of the flow due to perturbations in the chamber, (2) deformation of the divergent section due to mechanical vibrations and (3) deep separation or the ejector effect of the jet-contour combination which tends to make the separation point unstable. Ilsen indicated that the wall pressure at the separation point can be given by the semi-empirical equation:

$$P_s = \frac{N}{P_c^\alpha} \quad \text{where the empirical coefficients} \quad (14)$$

$N = 18-21$ depends on divergence of

the nozzle and ambient pressure

$$\alpha = 0.25$$

for the case when $P_a = 14.7$

$$P_s = \frac{20}{4 \sqrt{P_c}} \quad (15)$$

The results from this equation are plotted in Figure 24.

In addition the area ratio at which separation occurs is given

by

$$\epsilon_s = 0.1 P_c^{0.75} \quad (16)$$

Arens and Spiegler (Reference 16) conducted tests using a conical and two dimensional nozzles with exit half angles of 7° , 15° and 22° employing air as the flowing fluid ($\gamma = 1.40$). Data ^{were} ~~are~~ presented in the form of P_s/P_a versus M_s (Mach number of separation point) for various authors. Also included in the plot ^{were} ~~are~~ predictions from theoretical equations based on shock wave theory. These equations are based on the author's assumption that pressure rise must be sufficient to stagnate a characteristic velocity U_s^* in the boundary layer as suggested by Gadd (Reference 5). Gadd suggest^{ed} ~~s~~ a relation for determination of the shock pressure ratio required to cause separation of a turbulent boundary layer. The assumption made is that the pressure rise must be of sufficient strength to cause stagnation of the characteristic velocity U^* in the boundary layer. The author suggest^{ed} ~~s~~ a value of 0.60 for U^* , however, a value of 0.56 lends to better agreement with experimental data. The equations developed were:

$$M_s^* = \frac{M_s (U_s^*/U_s)}{\{1 + [(\gamma-1)/2] M_s^2 [1 - (U_s^*/U_s)^2]\}^{1/2}} \quad (17)$$

for $M_s^* < 1$

$$\frac{P_b}{P_s} = \left\{ \frac{1 + [(\gamma-1)/2] M_s^2}{1 + [(\gamma-1)/2] M_s^2 [1 - (U_s^*/U_s)^2]} \right\}^{(\gamma/\gamma-1)} \quad (18)$$

Assuming isentropic flow in the nozzle up to the separation point, the separation Mach number is given by ~~Equation 4~~¹⁶, Reference 16.

$$M_s^2 = \left[\frac{2}{\gamma-1} \right] \left[\left(\frac{P_c}{P_a} \right)^{\gamma-1/\gamma} \left(\frac{P_a}{P_s} \right)^{(\gamma-1)/\gamma} - 1 \right] \quad (19)$$

Substituting the above equation into equation 18 with $P_b = P_a$ an equation relating P_s/P_a is obtained.

$$\frac{P_c}{P_a} = \frac{P_c/P_a}{\left[\frac{(P_c/P_a)^{\gamma-1/\gamma} - (U_s^*/U_s)^2}{1 - (U_s^*/U_s)^2} \right]^{\gamma/\gamma-1}} \quad (20)$$

This equation with $\frac{U_s^*}{U_s} = .56$ is plotted in Figure 24 and in Reference 22.

Good agreement ^{WAS} ~~is~~ obtained with the above equations when compared with experimental data ^{of ARENS AND SPIEGLER} provided $U_s^*/U_s = 0.56$. Also included in ^{the} ~~in~~ Arens and Spiegler plot ^{WAS the} ~~is~~ theory of separation predicted by Mager (Reference 26), (REFERENCE 35). Page (Reference 11 and 12) and Sterrett and Emery ^{could} ~~can~~. The authors therefore concluded that nozzle separation ~~can~~ indeed be predicted by using data for the separation pressure ratio as a function of Mach number at the separation point.

Ashwood (Reference 17) discussed separation data obtained using a conical nozzle of exit half angle of 20° employing air as the flowing fluid. For design pressure ratios between 4 and 12, the author indicated that the limiting condition for initial separation at the nozzle exit ^{WAS} ~~is~~ given by:

$$\left(\frac{P_c}{P_a}\right)_{\text{Limit}} = \left(\frac{P_c}{P_a}\right)_{\text{Design}}^{0.604} \quad (21)$$

Further investigation revealed that a closer approximation fitting the data points ^{WAS} ~~is~~ given by

$$(P_c/P_a)_{\text{Limit}} = 1 + 1/3 (P_c/P_a)_{\text{Design}} \quad (22)$$

A plot of $(P_c/P_a)_{\text{Limit}}$ versus design pressure ratio is presented in ~~Figure 31~~ ^{IN REFERENCE 17} of Reference 17. Also included ^{are} ~~is~~ the results obtained by Eisenklam and Wilkie

(REFERENCE 14) which compares favorably with the authors data. The data of REFERENCE 17 ARE PRESENTED IN FIGURE 24.

Herbert and Herd (Reference 20) ~~have~~ plotted P_s/P_a versus P_c/P_a from various authors on data obtained using nozzles with exit half angles varying from 10 to 30°. Also included ^{was} ~~is~~ a theoretical prediction of the separation pressure as presented by Mager (Reference 26):

$$\frac{M_s}{M_1} = K^{1/2} \quad \text{where } K = 0.67 \quad (23)$$

This correlation when used in conjunction with the theoretical relation expressed by the authors

$$\frac{P_a}{P_s} = 1.05 + 0.05 M_1 \quad \text{for } \gamma = 1.4 \quad (24)$$

results ^{ed} in a curve which fits well within the scattered data presented.

The authors conclude^d that for nozzle exit angles of 10° or greater, there is no significant influence on the separation phenomenon because of divergence angle, area ratio, geometry (two-dimensional or axisymmetric) or the flowing fluid over range of γ from 1.2 to 1.4. When exit half angle is less than 5° a departure from the general correlations ^{was} ~~is~~ noted which is caused by increased pressure rise (recovery) in the mixing region and therefore the nozzle area ratio has some influence on separation.

Kalt and Badal (Reference 22) ~~have~~ plotted P_i/P_a versus P_c/P_a (where P_i is the pressure corresponding to boundary layer thickening and is generally referred to as the separation pressure in other empirical studies), from various authors on data obtained from nozzles using flowing fluids such as air, nitrogen and liquid propellants with various exit half angles, area ratios and back-pressures. The authors also include ^d data on solid propellant motors using a conical nozzle. Also included in the plot ^{WAS} ~~is~~ the correlation suggested by Arens and Spiegler (Reference 16) ~~Equation~~ (5)

$$\frac{P_s}{P_a} = \frac{P_c/P_a}{\left[\frac{(P_c/P_a)^{\gamma} - 1/\gamma - (U_s^*/U_s)^2}{1 - (U_s^*/U_s)^2} \right]^{\gamma/\gamma - 1}} \quad (25)$$

for various values of γ which show ^{ed} good agreement with the experimental data. The authors suggest ^{ed} an empirical equation

$$P_i/P_a = 2/3 (P_c/P_a)^{-0.2} \quad (26)$$

and include ^d it in the plot with good agreement. Results from this equation are presented in Figure 24.

Figure 25 (P_s/P_c versus P_a/P_c on log-log paper) presents data of four different authors in comparison with this ~~analysis~~ ^{study} and indicates a fairly good agreement with the curve drawn through the author's data except near $P_a/P_c \approx 0.10$ where test data begins to drift off. A brief description of the results of the four authors included in Figure 25 follows.

Bloomer, Antl and Renas (Reference 24) conducted tests on several conical nozzles with JP-4 and gaseous oxygen as propellants using nozzles of exit half angles of 15° , 20° , 25° and 30° with area ratios from 8 to 75/1 and pressure ratios from 35 to 840. Nozzle separation data was presented in the form P_s/P_c versus P_a/P_c on log-log paper with M_2/M_1 as a parameter for $\gamma = 1.2$ (see Figure 17, Reference 24). Also included on the plot ~~is~~ ^{was} data obtained from Campbell and Farley (Reference 3) and Foster and Cowles (Reference 7). Lines of constant P_{sep}/P_c ~~are~~ ^{were} included as parameters on the plot. The authors concluded that the data tend to gather along the curve of Mach number ratio of 0.85 and that separation occurs between pressure ratios of approximately 0.3 to 0.4.

Campbell and Farley (Reference 3) conducted tests on several conical convergent-divergent nozzles with heated air at 1200°F with half angles of 15° , 25° and 29° at area ratios of 10, 25, and 40 with pressure ratios up to 120. Separation data ~~are~~ ^{were} correlated by plots of P_s/P_N versus P_a/P_N (P_N is identical to P_c) on log-log plot with lines of constant Mach number ratios included ($M_a/M_s = .70$, $.75$ and $.80$). Most of the data ~~falls~~ ^{fell} on the $M_a/M_b = .76$ line. Separation data ~~are~~ ^{were} also presented in the form of P/P_N versus A/A_{cr} with values of P_a/P_c as parameters for 29° divergence angle nozzle. No particular separation correlation ~~is~~ ^{was} given except that the separation data of nozzle configurations considered tended to group at a Mach number ratio $(M_a/M_s) = .76$ or $.77$ and these data are plotted in Figure 25.

Foster and Cowles (Reference 7) conducted tests on several conical nozzles with red fuming nitric acid and aniline as the propellant at a chamber temperature of 3650°F with area ratios of 10.0 ($\alpha = 10^\circ, 15^\circ, 20^\circ, 30^\circ$) and 20.8 ($\alpha = 15^\circ$) at various chamber pressure ranging from 167 psia to 374 psia at back pressures of 14.1 psia. Separation data ^{were} ~~is~~ presented in a plot of P_c/P_o vs f_s/f_t , the area ratio at separation, and in a plot of P_c/P_o vs P_s/P_o for the various configurations considered. Conclusions reached by the authors are: (1) the curve of separation area ratio vs chamber pressure is nearly a straight line, (2) point of separation is insensitive to variations in nozzle divergence angle, propellant mixture ratio, gas temperature, adiabatic expansion exponent and nozzle length. Foster and Cowles attempt to correlate separation pressure of the various configurations considered by constructing a curve through the data points, however much scatter of the data points is evident. The data of Reference 7 is plotted in Figures 25 and 26.

Bloomer, Antl and Renas (Reference 23) also conducted tests on several contoured nozzles as determined by Rao (Reference 18) with JP-4 fuel and gaseous oxygen as propellants using nozzles of area ratio 16, 25, and 30 and pressure ratios from 35 to 450. Separation data ^{were} ~~are~~ presented in the form of P_w/P_c versus area ratio over the range of ambient pressures tested. The authors concluded that separation characteristics as applied to contoured nozzles agree with ^{those} ~~that~~ of conical nozzles investigated in Reference 24. The generalization made was that the Mach number ratio across the oblique shock wave occurring at the separation point is approximately equal to 0.85 in the range of the pressure ratios investigated at a γ of 1.2.

Figure 26 ($\frac{P_a - P_s}{P_c}$ versus $\frac{P_c}{P_a}$) presents the data of five authors plotted by Green (Reference 10) and the data of References 4, 12 and 15 in comparison with the test data of this ~~analysis~~ ^{study}. Test data from this ~~analysis~~ ^{study} does not lie on the curve drawn through Green's data points or through that of Reference 15 but appear to fall in line with that of Reference 4 and 12. A brief description of the results of the authors included in Figure 26 follows.

Green (Reference 10) indicated^d that P_s/P_a is not necessarily a true constant but may be a function of P_c/P_a (chamber pressure/ambient pressure). Green presents^{ed} a plot of P_s/P_a versus P_c/P_a based on experimental data for conical nozzles with exit half angle of 15° by investigators Scheller and Bierlein, Fleck, Johnson, Foster and Cowles and Elko and Stary, which showed considerable scatter. The data of the above investigators were replotted in the form of $\frac{P_a - P_s}{P_c}$ versus P_c/P_a (Reference 10 and Reference 1) which tends^{ed} to compress the data but allow^{ed} the data to be represented by a single curve which gives a good approach to obtaining a universal correlation in an effort to predict separation pressure. The data of References 10 and 1 are plotted in Figure 26.

Farley and Campbell (Reference 4) also conducted tests on several contoured (method of characteristics) nozzles with half angles ± 2.9 to 20.7° with unheated air as the flowing fluid with pressure ratios up to 130 at area ratios of 10, 15, 20 and 25. Separation data ~~are~~ ^{were} correlated by plots of P_a/P_s versus P_s/P_N (P_N identical to P_c) on semi-log plot with lines of constant Mach number ratio ($M'/M_s = .7, .75, .80$). Most of the data ~~fall~~ ^{were} on the $M'/M_s = .75$ line. Separation data ~~are~~ ^{were} also presented in the form of P_w/P_N versus A/A_{cr} with values of P_a/P_N as parameters for nozzle design Mach number

of 5.82, 5.02 and 6.85. No particular separation correlation ^{WAS} ~~is~~ given since the separation pressure-rise ratio was not uniquely associated with one particular Mach number ratio as was indicated by the conical data of Reference 3. This may be due to boundary-layer characteristics as indicated by the authors.

Page (Reference 11 and 12) presents ^{ed} ~~a~~ plot of $\frac{P_a - P_s}{P_c}$ versus $\frac{P_c}{P_a}$ (same coordinates as Green, Reference 10) using Green's curve and experimental data of Farley and Campbell (Reference 4) together with theoretical results predicted by Page in Reference 12 for $\gamma = 1.10$ and 1.667 . Theoretical prediction of separation by Page ^{WAS} ~~is~~ in good agreement with experimental data of Green, and Farley and Campbell as shown in Reference 12. The theory of Page is presented in Figure 26.

Roschke and Massier (Reference 15) conducted tests using a contoured nozzle designed by method of characteristics for constant $\gamma = 1.22$ at an area ratio of 55.0 and truncated to 20.3 with the resulting exit half angle of $12^\circ 50'$. Data were obtained using the decomposition products of hydrazine ($\gamma = 1.3$) and nitrogen ($\gamma = 1.4$) as the flowing fluids at atmospheric back pressure. Data were presented in the form of P/P_t (P_s/P_c) versus P_t/P_a (P_c/P_a). In addition data were compared to that compiled by Green (Reference 10) and ~~are~~ presented ~~in Figure 2~~ as $\frac{P_a - P_s}{P_c}$ versus P_c/P_a . Also included for comparison ^{WAS} ~~is~~ the theory of Page (Reference 11 and 12). The results of the authors data tend ^{ed} to diverge from that of Green and Page and this ^{WAS} ~~is~~ explained by the authors as being due to the difference in nozzle contours. Also included in their paper ^{WAS} ~~is~~ a plot of area ratio of separation (A_s/A^*) versus P_c/P_a for the data obtained. The authors conclude ^d that it is difficult to predict area ratio of separation since small changes in wall pressure are accompanied by large changes in area ratio and that separation tends to occur at smaller area ratios in contoured nozzles as compared to conical nozzles.

Figure 27 (P_s versus P_c on log-log paper) presents data of Scheller and Bierlein. Test data from this ~~analysis~~^{study} does not lie on the Scheller and Bierlein's curve but appears to branch off at a steeper slope.

Scheller and Bierlein (Reference 9) conducted tests using a conical nozzle of area ratio 16 corresponding to a pressure ratio of 200 with exit half angles of 5° , 15° , 25° and 35° . Data were obtained using unheated air as the flowing medium exhausting to atmosphere at chamber pressures varying from 70 to 635 psia. Separation data were presented in a log-log plot of P_c versus area ratio of separation (ϵ_s) and in a log-log plot of P_s (separation pressure) versus chamber pressure (P_c) with constant divergent angle as a parameter. The authors' data were also compared with data obtained by Summerfield, Foster and Swan (Reference 6) and by Green (Reference 10) but the comparison was not in good agreement. It was indicated by Scheller and Bierlein that the disagreement was mainly due to difference in physical size of the test pieces and the flowing fluid. Scheller and Bierlein concluded that no general correlation can be made regarding prediction of flow separation and that the acceptance of $P_s/P_a = \text{constant}$ as determined by Summerfield, Foster and Swan is not necessarily true since it was not confirmed by their experimental data; in fact, separation is governed by chamber pressure and nozzle divergence angle. The data of Reference 9 are plotted in Figure 26 and 27.

Figure 28 (P_c/P_a versus P_c/P_s) presents the mean and up to $\pm 3\sigma$ limit values of separation results as presented by Grant. ^{TEST from STUDY} Data of this analysis appear to fall mainly between the -1σ and $+1\sigma$ limits with the main portion of the data divided between the mean and $+1\sigma$ value. Therefore one would expect reasonable results using the mean value curve. Grant ~~has~~ concluded that flow separation cannot be predicted by 1-D gas dynamics since this theory assumes that the upstream flow is unaffected by ambient pressure, but in reality it is the boundary layer action which acts as the triggering device for separation. The previous theory that $P_s/P_a = \text{constant}$ ignored the boundary layer action and interaction between the gaseous wedge, the separated jet and the vortex region. Grant concludes ^d that one should first determine if separation is deep or shallow (deep separation is defined as that occurring deep inside the nozzle toward the throat and relationship $P_s/P_c \neq \text{constant}$) then proceed to use a plot of P_s/P_a versus Reynold's number for various Mach numbers if the Reynold's number is known or use a plot of P_c/P_a versus P_c/P_s (shallow separation) with the respective confidence limit desired.

Figure 29 (P_c/P_a versus P_c/P_s) presents the results of Mager (Reference 26). Fairly good agreement is obtained in comparison with test data of this ^{study} ~~analysis~~. The data show the proper trend but fall slightly below that of Mager.

Mager (Reference 26) suggests^{ed} that separation of a compressible turbulent boundary layer in the absence of surface friction combined with oblique shock approximations can be used to determine the pressure ratio across the separation plane.

$$P_s/P_i = 1 + \frac{\gamma M_i^2}{2} \frac{(1 - K)}{1 + [(\gamma - 1)/2] M_i^2} \quad (27)$$

$$K = 0.55$$

A theoretical correlation^{was} ~~is~~ also developed which expresses the pressure ratio across the separation plane for the case of free (plane) shock separation in a turbulent boundary layer in terms of P_s/P_i and M_i . The predicted results agreed fairly well with data of McKenney (Reference 8) for two-dimensional nozzle tests.

Figure 30 (P_c/P_a versus P_a/P_s) presents the data of Ahlberg, Hamilton, Migdal, and Nilson for three different configurations. ^{TEST} Data from this ~~STUDY~~ analysis falls mainly between the shortest and longest contoured nozzle curves; however, much of the test data show enough scatter that a conclusive result cannot be made. It appears the trend may be with the data of the longest contoured nozzle. The authors concluded that the nozzle pressure ratio depends only on the type of contour used which seems to be a valid point.

Ahlberg, Hamilton, Migdal and Nilson (Reference 34) ~~have~~ conducted tests on ten different truncated perfect nozzles with area ratios ranging from 6 to 36 and ranging in length to provide minimum surface area of maximum thrust nozzles. Tests were also conducted on conical nozzles of three different area ratios at exit half angle of 15°. All tests used cold air as the flowing fluid.

Separation data ^{were} ~~are~~ presented in a plot of P_a/P_s versus P_c/P_a . The authors indicate that scatter of some of the data is due to ^{the} ~~to~~ separation plane not being fully contained within the nozzle. Results obtained indicate^d that the nozzle pressure ratio P_c/P_a is independent of the nozzle area ratio and depends only on the type of contour used.

Arens (Reference 25) attempt^{ed} ~~s~~ to relate the separation pressure ratio of contoured nozzles ^{to} ~~with~~ separation Mach number. Experimental data for contoured nozzles obtained by Roschke and Massier (Reference 15), Ahlberg, Hamilton, Migdal, and Nilson (Reference 34) and Farley and Campbell (Reference 4) are plotted in Reference 25 as P_s/P_a versus M_s . Also included by the author ^{was} ~~is~~ the correlation for straight-walled conical nozzles suggested by Arens and Spiegler (Reference 16). The author conclude^d that the scatter of data ^{could be} ~~is~~ attributed to the range of pressure gradients prior to inducement of separation and to different geometries in the separated region. The data of the authors as presented by Arens are plotted in Figures 24 (Reference 16), 26 (References 15 and 4) and 30 (Reference 34).

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this thesis was to demonstrate that it is possible to design a contour for a ground test nozzle extension within certain constraints. The constraints for design of this new contour were: ⁽¹⁾ duplication of heat transfer to the coolant of the reference 70:1 Rao contour nozzle extension ^{which} ⁽²⁾ originates at an area ratio of 5:1 and terminates at an area of 24:1, ⁽³⁾ attainment of full flow attachment at 40% chamber pressure (180 psia), ⁽³⁾ contour to originate at an area ratio of 5:1 (where the main nozzle terminates) and terminate at an area ratio of 12:1 based on an expected separation pressure of 5:1 psia.

Contour E was selected as the ground test contour based on its ability to duplicate the heat transfer to the coolant of the reference nozzle extension. A test nozzle was constructed and pressure measurements were obtained along the contour for fourteen tests and separation data ^{were} ~~was~~ compared with data of several authors. Pressure measurements were recorded in various quadrants to determine if asymmetric flow separation occurs.

Examination of test data indicated that a contour can be turned into the gas flow stream without inducement of flow separation. Test data also indicated that full flow attachment is obtained at an area ratio of 11.5 at a chamber pressure of about 240 psia (55% of rated chamber pressure) with predicted matching coolant bulk temperature rise within about 3 degrees of the reference nozzle extension.

Test data also showed ^{good}~~the~~ reproducibility of predicted wall pressure profile of the selected contour (E) with that predicted by a method of characteristics computer program. In addition, reproducibility of wall pressure ^{data}~~from~~ from one test to another was in fairly good agreement.

Examination of test results did not reveal any asymmetric flow separation as noted by the duplication of wall pressure readings at the same area ratio. Prediction of asymmetric flow separation in a particular nozzle is a difficult task. A number of authors conclude that asymmetric separation occurs at very low values of the pressure ratio P_c/P_a . One correlation which showed that asymmetric separation occurs when P_c/P_a is less than 12 was not substantiated in this ~~study~~ ^{analysis} possibly due to the stiffness of the nozzle. Grant in Reference 19 ~~also~~ states that this result should be used with caution due to different boundary layer effects encountered in nozzles of different design. Grant also concludes that when the pressure ratio is close to the critical value (choke^d flow) parallel separation may occur close to the throat and since the separation point is sensitive to the lateral momentum contributed by the transient forces the possibility of separation becoming asymmetric is great. However, this was not observed in the scale model test of Contour E since no area ratio lower than 3.5 was monitored.

Ability to predict the pressure at which separation occurs was not consistently established as evidenced by the scatter of the data of this study with that of numerous other authors. Also test results ^{corroborate} ~~corroborate~~ the fact as presented by Grant and others ^{that} ~~the~~ P/P_a ^{is not} ~~is~~ constant but varies and is dependent on geometry and the fluid media ⁱⁿ ~~in~~. Best agreement was found with use of data presented by the following authors and in the following order of agreement.

- a. Figure 26, Reference 10 (Green's data) specifically that of Reference 4 (Farley and Campbell) and Reference 12 (Page).
- b. Figure 28, Reference 19 (Grant's data) specifically mean value curve.
- c. Figure 25, Reference 3 (Campbell and Farley), Reference 7 (Foster and Cowles), References 23 and 24 (Bloomer, Antl and Renas).
- d. Figure 29, Reference 26 (Mager) for $\gamma = 1.40$.

For further studies, it is recommended that additional tests be conducted on contours similar to contour E selected in this thesis. It may be of greater interest to construct these contours on a larger scale (full scale if possible) in order to locate more pressure taps which may help to reduce the amount of scatter in the data and to more precisely define the point of separation. More data may also help ^{in the development of a} ~~to arrive at a~~ simple correlation ^{for} ~~at~~ predicting the separation pressure for contoured nozzles. It is also recommended that additional testing be conducted to gain more knowledge on asymmetric flow separation. If possible tests should be conducted with a tube bundle nozzle to determine if asymmetric separation does occur in a less rigid structure.

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TABLE 1

CONTOUR DESCRIPTION

<u>CONTOUR</u> ⁷	<u>EXIT ANGLE</u> ¹⁰ <u>α_E (DEGREES)</u> ¹²	<u>AXIAL LENGTH</u> ¹² <u>L (INCHES)</u> ¹⁰	<u>SURFACE AREA</u> ¹² <u>S.A. (SQUARE INCHES)</u> ⁵	<u>EXIT AREA</u> ⁹ <u>RATIO</u> ⁵ <u>ϵ</u>
E	4	30.83	3806	12
F	5	26.49	2947	12
G	7.25	22.16	2349	12
H	11.75	17.83	1876	12
70:1 (Truncated)	24.13	13.57	1528	12
70:1 (Flight)	18.35	33.93	4809	2 1/4

Note all contour initiate at $\epsilon = 5:1$ for comparison

TABLE 2

CONTOUR E

³ STA	¹² LONGITUDINAL DIM. X (INCHES) ⁸	¹¹ RADIAL DIM. Y (INCHES) ¹⁰	¹⁰ AREA RATIO A_0/A_+ ⁵	¹³ TANGENT ANGLE θ (DEGREES) ¹¹
1	0	5.5680	1.000	0
2	0.0938	5.5696	1.0005	1.931
3	0.3742	5.5933	1.0091	7.725
4	0.4670	5.6074	1.0142	9.656
5	0.6508	5.6451	1.0279	13.519
6	0.8316	5.6951	1.0462	17.381
7	1.0087	5.7572	1.0691	21.244
8	1.0956	5.7926	1.0823	23.175
9	1.1812	5.8310	1.0967	25.106
10	1.2655	5.8723	1.1123	27.038
11	1.3484	5.9163	1.1290	28.969
12	1.4297	5.9631	1.1470	30.900
13	1.4310	5.9633	1.1470	30.996
14	2.7562	6.7762	1.4811	31.828
15	4.1314	7.6337	1.8796	32.104
16	5.5569	8.5246	2.3440	31.937
17	7.0268	9.4378	2.8730	31.614
18	8.5580	10.3676	3.4670	31.075
19	10.1393	11.3142	4.1290	31.435
20	11.7763	12.2607	4.8428	29.736
21	12.12	12.4504	5.00	29.65
22	12.80	12.7579	5.25	28.40
23	13.24	13.0581	5.50	27.15
24	13.84	13.3516	5.75	25.95
25	14.46	13.6387	6.00	24.70
26	15.09	13.9200	6.25	23.55
27	15.74	14.1956	6.50	22.40
28	16.41	14.4660	6.75	21.30
29	17.10	14.7315	7.00	20.20
30	17.835	14.9923	7.25	19.20
31	18.615	15.2486	7.50	18.25
32	19.41	15.5006	7.75	17.30
33	20.24	15.7486	8.00	16.40
34	21.09	15.9928	8.25	15.50
35	22.00	16.2333	8.50	14.65
36	22.93	16.4703	8.75	13.80
37	23.92	16.7040	9.00	13.00
38	24.95	16.9344	9.25	12.20
39	26.05	17.1617	9.50	11.40
40	27.19	17.3860	9.75	10.65
41	28.47	17.6075	10.00	9.90
42	29.74	17.8263	10.25	9.15
43	31.16	18.0423	10.50	8.40
44	32.61	18.2559	10.75	7.65
45	34.30	18.4669	11.00	6.90
46	36.00	18.6756	11.25	6.20
47	37.96	18.8820	11.50	5.50
48	40.35	19.0861	11.75	4.75
49	42.95	19.2861	12.00	4.00

TABLE 3

CONTOUR F

STA	LONG. DIM. X (INCHES)	RADIAL DIM. Y. (INCHES)	AREA RATIO A_e/A_t	TANGENT ANGLE θ (DEGREES)
21	12.12	12.4504	5.00	29.65
22	12.675	12.7579	5.25	28.60
23	13.23	13.0581	5.50	27.60
24	13.81	13.3516	5.75	26.60
25	14.40	13.6387	6.00	25.60
26	14.99	13.9200	6.25	24.65
27	15.61	14.1956	6.50	23.75
28	16.24	14.4660	6.75	22.80
29	16.88	14.7315	7.00	21.90
30	17.56	14.9923	7.25	21.00
31	18.27	15.2486	7.50	20.15
32	18.97	15.5006	7.75	19.25
33	19.70	15.7486	8.00	18.35
34	20.45	15.9978	8.25	17.50
35	21.24	16.2333	8.50	16.65
36	22.06	16.4703	8.75	15.80
37	22.93	16.7040	9.00	14.95
38	23.81	16.9344	9.25	14.15
39	24.77	17.1617	9.50	13.30
40	25.72	17.3860	9.75	12.50
41	26.78	17.6075	10.00	11.65
42	27.85	17.8263	10.25	10.85
43	29.02	18.0423	10.50	10.00
44	30.24	18.2559	10.75	9.20
45	31.615	18.4669	11.00	8.35
46	33.04	18.6756	11.25	7.50
47	34.63	18.8820	11.50	6.70
48	36.495	19.0861	11.75	5.85
49	38.161	19.2881	12.00	5.00

NOTE: Coordinates preceding $\epsilon = 5:1$ are included in Contour 'E' tabulation (Table 2)

TABLE 4
CONTOUR G

<u>STA</u>	<u>LONG. DIM. X (INCHES)</u>	<u>RADIAL DIM. Y (INCHES)</u>	<u>AREA RATIO A_o/A_t</u>	<u>TANGENT ANGLE θ (DEGREES)</u>
21	12.12	12.4504	5.00	29.65
22	12.67	12.7579	5.25	28.85
23	13.22	13.0581	5.50	28.10
24	13.78	13.3516	5.75	27.30
25	14.35	13.6387	6.00	26.55
26	14.91	13.9200	6.25	25.75
27	15.49	14.1956	6.50	25.00
28	16.06	14.4660	6.75	24.20
29	16.665	14.7315	7.00	23.40
30	17.29	14.9923	7.25	22.60
31	17.94	15.2486	7.50	21.85
32	18.59	15.5006	7.75	21.05
33	19.24	15.7486	8.00	20.25
34	19.905	15.9928	8.25	19.50
35	20.58	16.2333	8.50	18.70
36	21.29	16.4703	8.75	17.95
37	22.03	16.7040	9.00	17.15
38	22.79	16.9344	9.25	16.40
39	23.53	17.1617	9.50	15.60
40	24.40	17.3860	9.75	14.85
41	25.275	17.6075	10.00	14.05
42	26.15	17.8263	10.25	13.25
43	27.10	18.0423	10.50	12.50
44	28.10	18.2559	10.75	11.70
45	29.215	18.4669	11.00	10.85
46	30.305	18.6756	11.25	10.00
47	31.445	18.8820	11.50	9.15
48	32.70	19.0861	11.75	8.20
49	34.28	19.2881	12.00	7.25

NOTE: Coordinates preceeding $\epsilon = 5:1$ are included in Contour 'E' Tabulation (Table 2)

TABLE 5
CONTOUR H

<u>STA</u>	<u>LONG. DIM. X (INCHES)</u>	<u>RADIAL DIM. Y (INCHES)</u>	<u>AREA RATIO A_0/A_+</u>	<u>TANGENT ANGLE θ (DEGREES)</u>
21	12.12	12.4504	5.00	29.65
22	12.665	12.7579	5.25	29.20
23	13.21	13.0581	5.50	28.70
24	13.76	13.3516	5.75	28.20
25	14.30	13.6387	6.00	27.70
26	14.84	13.9200	6.25	27.20
27	15.375	14.1956	6.50	26.70
28	15.92	14.4660	6.75	26.15
29	16.475	14.7315	7.00	25.65
30	17.02	14.9923	7.25	25.10
31	17.60	15.2486	7.50	24.60
32	18.16	15.5006	7.75	24.00
33	18.78	15.7486	8.00	23.45
34	19.305	15.9928	8.25	22.85
35	19.89	16.2333	8.50	22.25
36	20.47	16.4703	8.75	21.60
37	21.10	16.7040	9.00	21.00
38	21.70	16.9344	9.25	20.35
39	22.33	17.1617	9.50	19.65
40	22.97	17.3860	9.75	19.00
41	23.64	17.6075	10.00	18.25
42	24.31	17.8263	10.25	17.55
43	25.04	18.0423	10.50	16.75
44	25.735	18.2559	10.75	15.95
45	26.49	18.4669	11.00	15.20
46	27.26	18.6756	11.25	14.40
47	28.075	18.8820	11.50	13.50
48	28.95	19.0861	11.75	12.65
49	29.95	19.2881	12.00	11.75

NOTE: Coordinates preceeding $\epsilon = 5:1$ are included in Contour 'E' Tabulation (Table 2)

TABLE 6

RECORD OF ACTUAL FINAL CONTOUR DIMENSIONS

X 6	Y 6	Y Actual 6	X 6	Y 6	Y Actual 6
.0000	.6833	.6838	1.6260	1.6036	1.6020
.0115	.6840	.6845	1.6297	1.6397	1.6366
.0230	.6846	.6882	1.7758	1.6749	1.6711
.0345	.6855	.6900	1.8532	1.7095	1.7057
.0459	.6869	.6919	1.9330	1.7433	1.7402
.0573	.6886	.6942	2.0153	1.7765	1.7737
.0688	.6904	.6960	2.1000	1.8092	1.8052
.0799	.6932	.6992	2.1903	1.8412	1.8372
.0920	.6962	.7020	2.2861	1.8727	1.8690
.1021	.6994	.7051	2.3837	1.9036	1.8995
.1130	.7030	.7085	2.4855	1.9341	1.9330
.1239	.7070	.7123	2.5900	1.9641	1.9630
.1346	.7114	.7162	2.7018	1.9936	1.9935
.1451	.7161	.7205	2.8160	2.0227	2.0230
.1554	.7212	.7252	2.9376	2.0514	2.0518
.1656	.7266	.7302	3.0641	2.0797	2.0799
.1756	.7323	.7355	3.1992	2.1076	2.1085
.1757	.7323	.7355	3.3392	2.1352	2.1356
.3385	.8322	.8368	3.4964	2.1624	2.1635
.5074	.9375	.9427	3.6523	2.1892	2.1885
.6824	1.0470	1.0532	3.8267	2.2158	2.2152
.8629	1.1590	1.1650	4.0048	2.2420	2.2418
1.0509	1.2732	1.2787	4.2123	2.2679	2.2655
1.2452	1.3894	1.3938	4.4211	2.2935	2.2905
1.4462	1.5057	1.5094	4.6618	2.3189	2.3150
1.6534	1.5290	1.5318	4.9553	2.3439	2.3389
1.8719	1.5668	1.5750	5.2716	2.3687	2.3650

TABLE 7

RECORD OF ACTUAL FINAL PRESSURE TAP LOCATIONS

Z	QUADRANT 1		
	X	Y	-E
1	1.0593	1.2770	3.488
2	1.4213	1.4884	4.738
3	1.7775	1.6706	5.989
4	2.1015	1.8059	6.975
5	2.4853	1.9297	7.964
6	2.8158	2.0224	8.747
7	3.3337	2.1350	9.748
8	3.9905	2.2393	10.729
9	4.6574	2.3214	11.525
10	5.2181	2.3650	11.962

QUADRANT 2		
X	Y	-E
1.0538	1.2832	3.522
1.4177	1.4924	4.763
1.7655	1.6703	5.970
2.0990	1.8056	6.920
2.4853	1.9331	7.992
2.8292	2.0230	8.753
3.3350	2.1350	9.742
4.0000	2.2114	10.744
4.6582	2.3205	11.516
5.2192	2.3657	11.769

QUADRANT 3		
X	Y	-E
1.0631	1.2848	3.530
1.4176	1.4894	4.744
1.7681	1.6703	5.970
2.0919	1.8020	6.945
2.4838	1.9303	7.959
2.8210	2.0215	8.740
3.3374	2.1335	9.735
4.0024	2.2405	10.736
4.6573	2.3197	11.508
5.2161	2.3638	11.950

QUADRANT 4		
X	Y	-E
1.0653	1.2860	3.537
1.4160	1.4907	4.758
1.7658	1.6684	5.953
2.0977	1.8021	6.945
2.4838	1.9239	7.957
2.8215	2.0204	8.750
3.3376	2.1332	9.732
3.9957	2.2393	10.724
4.6517	2.3211	11.522
5.2177	2.3648	11.960

TABLE 8
TABULATION OF PRESSURE TAP LOCATIONS

RUN NO.	B-1, B-2	B-3, B-4	B-5, B-6	B-7, B-8	B-9, B-10	B-11, B-12	B-13, B-14
QUADRANT	0° 90° 180° 270°	0° 90° 180° 270°	0° 90° 180° 270°	0° 90° 180° 270°	0° 90° 180° 270°	0° 90° 180° 270°	0° 90° 180° 270°
E							
3.50	X	X	X X				X
4.75	X	X		X X			X X
6.00		X			X X		
7.00		X				X X	
8.00							X X X X
8.75		X				X X X X	
9.75		X			X X X		
10.75		X		X X X	X		
11.50	X X X X	X	X X	X X		X	X
12.00		X	X X X				

RUN NO. →	B-1 B-2	B-3 B-4	B-5 B-6	B-7 B-8	B-9 B-10	B-11 B-12	B-13 B-14
QUADRANT →	0 90 180 270	0 90 180 270	0 90 180 270	0 90 180 270	0 90 180 270	0 90 180 270	0 90 180 270
€ ↓							✓
3.50	X	X	X X X				X
4.75	X X			X X X			X X
6.00		X			X X X		
7.00		X				X X X	
8.00							X X X X
8.75		X				X X X X	
9.75		X			X X X		
10.75		X		X X X	X X		
11.50	X X X X	X	X X	X X		X	X
12.00		X	X X X				

TABLE 38
~~FIGURE 14~~

TABULATION OF PRESSURE TAP LOCATIONS

TABLE 9

TABULATION OF SPECIFIC HEAT RATIO FOR FULL SCALE AND
SCALE MODEL CONDITIONS

FULL SCALE ¹⁰			SUB SCALE ⁹			
$P_c = 450 \text{ psia}$ ¹³			$P_c = 450 \text{ psia}$ ¹³			
$T_c = 4500^\circ\text{R}$			$T_c = 1500^\circ\text{R}$			
H_2			H_2		N_2	
ϵ	T_E ($^\circ\text{R}$) ²	γ	T_E ($^\circ\text{R}$) ²	γ	T_E ($^\circ\text{R}$) ⁴	γ
Cham. ⁵	4500 ⁴	1.275 ⁵	1500 ⁴	1.388 ⁵	1500 ⁴	1.357 ⁵
1.0	3580	1.315	1300	1.392	1300	1.367
1.11	2650	1.347	1170	1.394	1170	1.374
5	1800	1.381	644	1.401	644	1.397
12	1500	1.400	500	1.410	500	1.400

TABLE 10
TABULATION OF VARIOUS AUTHORS' NOZZLE DESCRIPTIONS

3 REF	3 FIG	6 AUTHOR ³⁰	7 TYPE OF NOZZLE CONTOUR	α	α E	PROPELLANTS	γ
2	24	Altman, Carter, Penner & Summer- Field	Conical ¹⁰	10, 20	10, 15, 20, 30	Nitric Acid- Aniline	1.26 ⁴
3	25	Campbell & Far- ley	Conical	10, 25, 40	15, 25, 29	Heated air Cold air	1.34 1.40
4	26	Farley & Campbell	Contour	10, 15, 20, 25	2.9 to 20.7	Cold Air	1.40
6	24	Summerfield, Foster & Swan	Conical	3.5, 10 20.8	10, 15, 20	Nitric Acid Aniline	1.22, 1.26
7	25, 26	Foster & Cowles	Conical	10, 20.8	10, 15, 20, 30	Nitric Acid Aniline	1.26
8	24	McKenney	2D-Conical	8	15	Dry N ₂	
9	27, 26	Scheller & Bierlein	Conical	16	5, 15, 25, 35	Unheated Air	
10	26	Green	Conical	-	15	Air Solid H ₂ -O ₂ RFNA-Aniline WFNA-Aniline	1.40, 1.28 1.28 1.23 1.23
11 & 12	26	Page	Theory	-	-	-	1.10, 1.667
13	24	Tlsen	Contour Conical	-	-	-	-
14	24	Fraser, Eisenklam & Wilke	Conical		10-20°	Dry Air	1.40
15	26	Roschke & Messier	Contour	20.3	12° 50'	Decomp. Prod. Hydrazine, N ₂	1.30 1.40

TABLE 10 (Cont.)

<u>REF</u>	<u>FIG</u>	<u>AUTHOR</u>	<u>NOZZLE CONTOUR</u>	<u>ϵ</u>	<u>α_E</u>	<u>PROPELLANTS</u>	<u>γ</u>
16	24	Arens & Spiegler	Theory	-	-	-	1.40
17	24	Ashwood	Conical	4-12	5,10,20,30, 50	Air	1.40
19	28	Grant	Theory & Exp.				
20	24	Herbert f Herd	Conical Contour	2.65-25 6.27-35.9	10 to 30 4-13	Air Air	1.2-1.4 1.40
21	24	Sutton	Theory	-	-	-	-
22	24	Kalt f Badal	Theory				
48 23	25	Bloomer, Antl f Renas	Contour	30		JP-4 GOX	1.20
24	25	Bloomer, Antl f Renas	Conical	42,50,75,60	10,15,20, 25,30	JP-4 GOX	1.20
26	29	Mager	Theory	-	-	-	1.10 1.667
34	30	Ahlberg, Hamil- ton, Migdal, f Nilson	Contour, Min Contour-Long Conical	6.27-19.25 12-35.9 6.33-18.9	7-13 4-6 15	Cold Air	1.40

32 levels
11 in
11 in
11 in

Start on 8 -
2 spaces, between each column.

85 spaces
+ 30 in below
115

TABLE 11
30 TABULATION OF SEPARATION PRESSURE FOR EACH AREA RATIO

E	Run ³ 4 No	Pc	PW (AT SEPARATION)													Pa-Ps 5 Pc
			5 0°	5 90°	5 180°	5 270°	5 Pa	6 Pc/Pa	5 Pa/Pc	5 Pa/Ps	5 Ps/Pa	5 Ps/Pc	6 Pc/Ps	6 Pa-Ps		
5	3.50	B-1	152.50	3.957			14.40	10.590	.0944	3.639	.275	.0259	38.539	10.443	.0685	
		B-2	242.40	6.530			14.40	16.833	.0594	2.275	.439	.0261	38.294	8.070	.0333	
		B-3	150.20	4.561			14.40	10.431	.0959	3.164	.316	.0303	33.004	9.849	.0656	
		B-4	154.90	4.819			14.40	10.757	.0929	2.988	.335	.0311	32.144	9.581	.0619	
		B-5	150.43	4.847			14.40	10.446	.0957	2.971	.337	.0322	31.036	9.553	.0635	
					4.416		14.40	10.446	.0957	3.261	.307	.0294	34.065	9.984	.0664	
						4.740	14.40	10.446	.0957	3.038	.329	.0315	31.736	9.660	.0642	
		B-6	172.23	5.645			14.43	11.936	.0838	2.556	.391	.0328	30.510	8.785	.0510	
					3.667		14.43	11.936	.0838	3.935	.254	.0213	46.967	10.763	.0625	
						3.720	14.43	11.936	.0838	3.879	.258	.0216	46.298	10.710	.0622	
		B-13	171.29		5.185		14.38	11.912	.0839	2.773	.361	.0303	32.036	9.195	.0537	
		B-14			4.082		14.38	11.912	.0839	3.523	.284	.0238	41.962	10.298	.0601	
7.5	4.75	B-1	152.50		3.515		14.40	10.590	.0944	4.097	.244	.0230	43.385	10.885	.0714	
						3.959	14.40	10.590	.0944	3.637	.275	.0259	38.519	10.441	.0685	
		B-2	218.40		5.200		14.40	15.167	.0659	2.769	.361	.0238	42.000	9.200	.0421	
						6.124	14.40	15.167	.0659	2.351	.425	.0280	35.663	8.276	.0379	
		B-7	186.61	4.581			14.43	12.952	.0773	3.149	.317	.0245	40.736	9.849	.0528	
		B-8	163.57	4.048			14.43	11.335	.0882	3.565	.281	.0247	40.408	10.382	.0635	
		B-13	179.74		4.136		14.38	12.499	.0800	3.477	.288	.0230	43.457	10.244	.0570	
						4.379	14.38	12.499	.0800	3.284	.305	.0244	41.046	10.001	.0556	
		B-14	137.49		3.141		14.38	9.561	.1046	4.578	.218	.0228	43.772	11.239	.0817	
						3.330	14.38	9.561	.1046	4.318	.232	.0242	41.288	11.050	.0804	
1.5	6.00	B-3	148.99		3.405		14.40	10.347	.0967	4.229	.236	.0228	43.756	10.995	.0738	
		B-4	159.90		3.705		14.40	11.104	.0901	3.887	.257	.0232	43.158	10.675	.0669	
		B-9	179.31	4.612			14.41	12.443	.0804	3.124	.320	.0257	38.879	9.798	.0596	
					4.603		14.41	12.443	.0804	3.131	.319	.0257	38.955	9.807	.0547	
						4.772	14.41	12.443	.0804	3.019	.331	.0266	37.575	9.638	.0538	
		B-10	151.42	4.083			14.41	10.508	.0952	3.529	.283	.0269	37.085	10.327	.0632	
					3.836		14.41	10.508	.0952	3.757	.266	.0253	39.473	10.574	.0698	
						3.946	14.41	10.508	.0952	3.652	.274	.0261	39.373	10.464	.0691	
4.5	7.00	B-3	150.20	3.780			14.40	10.431	.0959	3.809	.263	.0252	39.735	10.620	.0707	
		B-4	164.75	4.200			14.40	11.441	.0874	3.428	.292	.0255	39.226	10.200	.0619	
		B-11	171.29	4.572			14.38	11.912	.0839	3.145	.318	.0267	37.465	9.828	.0574	

TABLE 11 (CON'T)

	E	RUN. NO.	P _c	PW (AT SEPARATION)				P _a	P _c /P _a	P _a /P _c	P _a /P _s	P _s /P _a	P _s /P _c	P _c /P _s	P _a -P _s	$\frac{P_a - P_s}{P_c}$		
				0°	90°	180°	270°											
5	7.00	B-11	171.29			4.711	4.749	14.38	.11.912	.0839	3.052	.3276	.0275	36.359	9.669	.0564		
								14.38	.11.912	.0839	3.028	.3303	.0277	36.069	9.631	.0562		
		B-12	136.29	3.714		3.715	3.700	14.38	9.478	.1055	3.872	.2583	.0273	36.696	10.666	.0783		
								14.38	9.478	.1055	3.871	.2583	.0273	36.686	10.665	.0783		
5	8.00	B-13	178.53	5.001		5.081	5.065	14.38	12.415	.0805	2.875	.3478	.0280	35.619	9.379	.0525		
								14.38	12.415	.0805	2.830	.3533	.0285	35.137	9.299	.0521		
		B-14	138.70	3.993		3.958	3.998	14.38	12.415	.0805	2.839	.3522	.0284	35.248	9.315	.0522		
								14.38	12.499	.0800	2.857	.3501	.0280	35.705	9.346	.0520		
5	8.75	B-3	152.50	3.934		4.996	4.969	14.38	9.645	.1037	3.601	.2777	.0288	34.736	10.287	.0749		
								14.38	9.645	.1037	3.633	.2752	.0285	35.043	10.422	.0751		
		B-4	169.40	4.319		4.916	4.942	14.38	9.645	.1037	3.597	.2780	.0288	34.692	10.382	.0749		
								14.38	9.645	.1037	3.749	.2667	.0277	36.157	10.544	.0760		
5	9.75	B-3	172.03	4.368		4.999	4.965	14.40	10.590	.0944	3.660	.2732	.0258	38.765	10.466	.0686		
								14.40	11.764	.0850	3.334	.2999	.0255	39.222	10.081	.0595		
		B-4	176.88	4.594		4.942	4.942	14.38	11.912	.0839	2.964	.3374	.0283	35.303	9.528	.0556		
								14.38	11.912	.0839	2.878	.3475	.0292	34.285	9.384	.0548		
5	9.75	B-9	189.01			4.965	4.942	14.38	11.912	.0839	2.894	.3455	.0290	34.472	9.411	.0549		
								14.38	11.912	.0839	2.925	.3419	.0287	34.843	9.464	.0553		
		B-10	169.61			4.269	4.333	14.38	9.561	.1046	3.635	.2751	.0288	34.755	10.424	.0758		
								14.38	9.561	.1046	3.598	.2780	.0291	34.398	10.383	.0755		
5	9.75	B-9	189.01			4.999	4.965	14.38	9.561	.1046	3.597	.2780	.0291	34.389	10.382	.0755		
								14.38	9.561	.1046	3.749	.2668	.0279	35.842	10.544	.0767		
		B-10	170.82			4.363	4.333	14.40	11.947	.0837	3.297	.3033	.0254	39.384	10.032	.0583		
								14.40	12.283	.0814	3.135	.3190	.0259	38.502	9.806	.0554		
5	9.75	B-9	189.01			4.999	4.965	14.41	13.117	.0762	2.883	.3469	.0264	37.809	9.411	.0498		
								14.41	13.117	.0762	2.902	.3446	.0263	38.068	9.445	.04997		
		B-10	170.82			4.363	4.333	14.41	13.117	.0762	2.916	.3430	.0261	38.246	9.468	.0501		
								14.41	11.770	.0849	3.375	.2963	.0252	39.731	10.141	.0598		
5	9.75	B-9	189.01			4.999	4.965	14.41	11.770	.0849	3.326	.3007	.0255	39.144	10.077	.0594		
								14.41	11.854	.0844	3.303	.3022	.0255	39.152	10.077	.0598		
		B-10	170.82			4.363	4.333	14.41	11.854	.0844	3.303	.3022	.0255	39.152	10.077	.0598		
								14.41	11.854	.0844	3.303	.3022	.0255	39.152	10.077	.0598		

TABLE 11 (CONT.)

E	RUN NO	P _c	P _W (AT SEPARATION)				P _a	P _c /P _a	P _a /P _c	P _a /P _b	P _b /P _a	P _b /P _c	P _c /P _b	P _a -P _b	$\frac{P_a - P_b}{P_c}$			
			0°	90°	180°	270°												
10.75	B-3	213.25	4.493				14.40	14.809	.0675	3.205	.312	.0211	47.463	9.967	.0467			
	B-4	215.40	4.629				14.40	14.958	.0668	3.111	.321	.0215	46.533	9.771	.0454			
	B-7	225.23		4.782			14.43	15.608	.0641	3.017	.331	.0212	47.099	9.648	.0428			
					4.820		14.43	15.608	.0641	2.994	.334	.0214	46.728	9.610	.0427			
						4.834	14.43	15.608	.0641	2.985	.335	.0215	46.593	9.596	.0426			
	B-8	213.28		4.474			14.43	14.780	.0677	3.225	.310	.0209	47.671	9.956	.0467			
					4.368		14.43	14.780	.0677	3.304	.303	.0205	48.928	10.062	.0472			
						4.527	14.43	14.780	.0677	3.187	.314	.0212	47.113	9.903	.0464			
	B-9	250.85	5.015				14.41	17.408	.0574	2.873	.348	.0200	50.020	9.395	.0375			
					4.934		14.41	17.408	.0574	2.921	.342	.0197	50.841	9.476	.0378			
11.50	B-1	236.40	4.410				14.40	16.417	.0609	3.265	.306	.0187	53.605	9.790	.0423			
				4.458			14.40	16.417	.0609	3.230	.309	.0188	53.028	9.942	.0421			
					4.606		14.40	16.417	.0609	3.126	.320	.0195	51.324	9.794	.0414			
						4.525	14.40	16.417	.0609	3.182	.314	.0191	52.243	9.875	.0418			
	B-2	237.50	4.513				14.40	16.493	.0606	3.191	.313	.0190	52.626	9.887	.0416			
				4.596			14.40	16.493	.0606	3.133	.319	.0194	51.675	9.804	.0413			
					4.757		14.40	16.493	.0606	3.027	.330	.0200	49.926	9.643	.0406			
						4.681	14.40	16.493	.0606	3.076	.325	.0197	50.737	9.719	.0409			
	B-3	243.56	4.491				14.40	16.914	.0591	3.206	.312	.0184	54.233	9.909	.0407			
	B-4	235.08	4.641				14.40	16.325	.0613	3.103	.322	.0197	50.653	9.759	.0415			
	B-5	237.50	4.566				14.40	16.493	.0606	3.154	.317	.0204	48.903	9.834	.0414			
					4.706		14.40	16.493	.0606	3.060	.327	.0198	50.467	9.694	.0408			
	B-6	259.43	5.090				14.43	17.978	.0556	2.835	.353	.0196	50.969	9.340	.0360			
					5.172		14.43	17.978	.0556	2.790	.358	.0199	50.160	9.258	.0357			
	B-7	255.72	4.940				14.43	17.721	.0564	2.921	.342	.0193	51.765	9.490	.0371			
					4.965		14.43	17.721	.0564	2.906	.344	.0194	51.504	9.465	.0370			
	B-8	239.93	4.491				14.43	16.627	.0601	3.213	.311	.0187	53.425	9.939	.0414			
					4.707		14.43	16.627	.0601	3.066	.326	.0196	52.973	9.723	.0405			
	B-10	237.51	4.566				14.41	16.482	.0607	3.156	.317	.0192	52.017	9.844	.0414			
					4.532		14.41	16.482	.0607	3.179	.314	.0191	52.407	9.878	.0416			
	B-11	243.71			4.849		14.38	16.948	.0590	2.966	.337	.0199	50.260	9.531	.0391			
	B-12	234.05			4.605		14.38	16.276	.0614	3.123	.320	.0197	50.825	9.725	.0418			
	B-13	241.30			4.849		14.38	16.780	.0596	2.966	.337	.0201	49.763	9.531	.0395			
	B-14	232.85			4.581		14.38	16.193	.0618	3.139	.319	.0197	50.880	9.799	.0421			

TABLE II (CONT)

E	RUN NO	P _c	P _W (AT SEPARATION)				P _a	P _c /P _a	P _a /P _c	P _a /P ₃	P ₃ /P _a	P ₅ /P _c	P _c /P ₅	P _a -P ₅	$\frac{P_a - P_5}{P_c}$
			0°	90°	180°	270°									
12.00	B-3	404.12	7.413				14.43							6.417	
	B-4	426.65	6.775				14.40	29.628	.0338	2.125	.476	.0159	62.974	7.625	.0179
	B-5	402.40	7.230				14.40							7.150	
					7.230		14.40							7.170	
					7.229		14.40							6.571	
	B-6	427.43		6.479			14.43	29.621	.0338	2.227	.449	.0152	65.972	7.951	.0186
					6.552		14.43	29.621	.0338	2.202	.454	.0153	65.237	7.878	.0184
						6.944	14.43	29.621	.0338	2.078	.481	.0162	61.554	7.486	.0175

CONTOUR LAYOUT

FIGURE 1

FIGURE 2

PREDICTED WALL PRESSURE PROFILES OF
 CONTOURS ~~D, E~~, F, G, H AND 70:1
~~FIGURE 2~~

SYMBOL	α_E	L
D	24.13	13.57
E	4.00	30.83
F	5.00	26.49
G	7.25	22.16
H	11.75	17.83

FIGURE 4
 ΔP (PSI)

NOZZLE DESIGN - 1/8 SCALE

5.271 REF.

8.03

4.48

3.03

2.47

1.45

4.50 DIA

4.02 DIA

1.06

37°30'

.683 R

.342 R

45°

2.45 DIA

1.37 DIA

58°

.790

1.617

1.613

4.84L DIA

4.73L DIA

.002 TIR

-A-

Y

X

NOZZLE DESIGN - 1/8 SCALE

~~FIGURE 5~~

FIGURE 6

~~CHAMBER PRESSURE - TIME PROFILE~~
~~FIGURE 6~~

FIGURE 7

COMPARISON OF SPECIFIC HEAT RATIO FOR
FULL SCALE AND SCALE MODEL CONDITIONS

FIGURE 7

COMPARISON OF PREDICTED AND ACTUAL WALL PRESSURE PROFILE
 $P_c = 450$

0.612
 PRESSURE IS AREA RATIO

COMPARISON OF PREDICTED AND ACTUAL WALL PRESSURE PROFILE
 $P_c = 450$ PSIA

SYMBOL	TEST NO.
○	B-2
○	B-4
□	B-6
+	B-7
x	B-9
◇	B-11
△	B-13

COMPARISON OF PREDICTED AND ACTUAL WALL PRESSURE PROFILE

FIGURE 8

FIG 17

DESCRIPTION OF FLOW SEPARATION REGION

FIGURE 23

~~DESCRIPTION OF FLOW SEPARATION REGION~~

COMPARISON OF TEST DATA WITH RESULTS OF VARIOUS AUTHORS

FIGURE 25

COMPARISON OF TEST DATA WITH RESULTS OF GREEN AND ~~OTHERS~~ OTHERS

COMPARISON OF TEST DATA WITH RESULTS of Scheller AND BIERLEIN

SYMBOL	ϵ	SYMBOL	ϵ
O	3.50	$\triangleleft$	8.75
$\triangle$	4.75	∇	9.75
$\square$	6.00	+	10.75
$\diamond$	7.00	X	11.50
$\triangleright$	8.00	*	12.00

FIGURE 27

COMPARISON OF TEST DATA WITH PROBABILISTIC
RESULTS OF GRANT

SYMBOL	ϵ
O	3.50
Δ	4.75
$\square$	6.00
$\diamond$	7.00
$\triangleright$	8.00
$\triangleleft$	8.75
o	9.75
+	10.75
x	11.50
*	12.00

FIG 40

MAGER
8-1,4COMPARISON OF TEST DATA WITH
RESULTS OF MAGER

SYMBOL	ϵ
○	3.50
△	4.75
□	6.00
◇	7.00
▷	8.00
◁	8.75
○	9.75
+	10.75
x	11.50
*	12.00

COMPARISON OF TEST DATA WITH RESULTS
OF AHLBERG, HAMILTON, MIGDAL & NILSON

FIGURE 30