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NOZZLE ASSEMBLY TRADE STUDY

NERVA Program, Contract SNP-1

May 1970

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NERVA Program

Contract SNP-1

May 1970

L. A. Shurley

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I. INTRODUCTION

This trade study defines the NERVA nozzle assembly configuration arrived at through quantitative analyses included herein. As such, this document establishes a frame of references related to the design and operation of the NERVA engine and constitutes a technical point of departure for initiation of other subordinate studies and supporting data items, most of which are in the S-, R-, and T-series.

The necessary engineering in terms of thermal, fluid-flow, stress, and reliability analyses in support of the concept definition was performed. However, the prime components of the nozzle assembly are subject to further detailed analyses and optimizations.

In addition to feasibility-oriented aspects, considerations of facilities, payload, and mission operating costs were included whenever applicable. Inasmuch as more than one aspect related to concept definition is involved, each was treated as a separate sub-trade study so the influence of pertinent parameters could be more clearly identified.

II. SUMMARY

This document primarily concerns four major aspects defining the nozzle assembly, each constituting a sub-trade study in itself. Major aspects are considered those which, as a part of the overall configuration, have a direct relationship to engine operation, performance, and ability to meet requirements. These sub-trade studies and the results of each are as follows:

1. Determination of the nozzle-assembly terminal area ratio.
Result: Terminal area ratio of 100:1 was selected.
2. Determination of location of nozzle-extension attachment point.
Result: Attach the graphite extension to the cryogenically cooled portion of the assembly at an area ratio of 24:1.
3. Determination of location of the coolant inlet torus.
Result: Place the coolant inlet manifold so as to introduce the coolant into the subassembly at an area ratio of 24:1.
4. Selection of one-piece primary nozzle or two-piece (nozzle and skirt) cryogenically cooled subassembly.
Result: Incorporate into the system a one-piece cryogenically cooled nozzle.

In addition to the above configuration-oriented major items subject to optimization, certain ancillary design parameters were considered. Such parameters do not affect the engine operation directly but do influence the nozzle functional characteristics, primarily with respect to reliability.

These ancillary considerations and the resulting conclusions are given below:

1. Selection of internally fed or externally supplied nozzle-to-pressure-vessel mating flange and connecting-blot coolant.
Result: - Adopt internally fed cooling system.
2. Selection of oval vs U-tube construction aft of area ratio of 5:1.
Result: Adopt U-tube coolant-channel construction.
3. Selection of variable or constant-cross-section flow area for coolant inlet manifold.
Result: Adopt a constant-cross-section coolant-inlet manifold.
4. Examine the effect of coolant flow-rate swing as a function of demand by NSS at the start of life and the end of life.
Result: A penalty of approximately 40 psia of pressure drop through the nozzle as compared with a constant-coolant-flow-rate system exists.

Delineation of disciplines involved, consideration of influencing parameters, and justifications leading to each of the above selections are given with the respective sub-trade studies.

"Unless otherwise indicated in the Technical Discussion, results of reliability and safety analyses showed the same relative ranking of the different configurations; i.e., a concept considered to have the highest reliability also had the lowest hazard rating and vice versa. Therefore, a selection based on reliability considerations, per se, is also recommended for having the best safety rating."

III. SCOPE

A. OBJECTIVES

The objective of this trade study was to select an optimum nozzle configuration, primarily with respect to payload and engine reliability.

More specific objectives pertinent only to a particular aspect of the nozzle assembly are stated within the sub-trade study related to the evaluation of such parameter. Additional objectives were to establish design parameters for inclusion in design requirements sheets, requirements allocation sheets, and specifications.

B. FUNCTIONAL AND TECHNICAL REQUIREMENTS

All sections of this document pertain to the steady-state environmental extremes developed when

$$T_c = 4305^{\circ}\text{R (Max)}, \quad (\text{Ref 1})$$

$$P_c = 456 \text{ psia (Max)}, \quad (\text{Ref 2})$$

$$F = 75,000 \pm 2000 \text{ lbf}, \quad (\text{Ref 1})$$

$$I_s = 822 \text{ sec (nominal)} \pm 0.75\%, \quad (\text{Ref 1})$$

$$P_{in} \text{ (nozzle inlet pressure) } = 1220 \text{ to } 1335 \text{ psia}, \quad (\text{Ref 11})$$

$$T_{in} \text{ (nozzle inlet temperature) } = 59 \text{ to } 62^{\circ}\text{R}. \quad (\text{Ref 11})$$

It is recognized that nozzle inlet conditions may change as a function of future refinements of the system; however, it is believed that the conclusions resulting from this study would not be affected.

C. RESTRICTIONS

The scope of this study was limited to minimum length, maximum-thrust Rao nozzles up to an area ratio of 140:1. Also, this study was restricted to graphite composite as the material for the nozzle extension construction (Ref Technical Directive 70-13). Inasmuch as the chamber pressure has been previously optimized (Ref 2), no attempt was made to introduce this parameter as a variable subject to re-evaluation.

Design constraints adopted throughout this study, as listed below, are consistent with material limitations and reliability goals or result from previous evaluations. Thus, the maximum gas-side coolant-channel wall temperatures of 1500 and 1200^oF maximum mean wall temperatures were imposed to prevent metal fatigue, tube-wall buckling, or creep.

All coolant-channel designs were limited to coolant Mach numbers of less than 0.3. It was also assumed that tapered coolant channel walls were permissible.

D. TRADE-OFF FACTORS

Unless otherwise specified in the subsequent sub-trade studies sections, the following trade-off factors were used throughout this document.

TRADE-OFF FACTORS
FOR
NOZZLE-ASSEMBLY TRADE STUDY

	MISSION		
	<u>A-L-M</u>	<u>A-L-U</u>	<u>C</u>
$\frac{\Delta \text{ Inert wt}}{\Delta I_s}^{(1)}$	289 lb/sec	294 lb/sec	246 lb/sec
$\frac{\Delta \text{ Outbound Payload}}{\Delta \text{ Inert wt}}^{(1)}$	-2.80 lb/lb	-2.72 lb/lb	-2.90 lb/lb
$\frac{\Delta \text{ Inbound Payload}}{\Delta \text{ Inert wt}}^{(1)}$	-1.56 lb/lb	-1.58 lb/lb	-1.53 lb/lb
$\frac{\Delta \text{ Round Trip Payload}}{\Delta \text{ Inert wt}}^{(1)}$	-1.00 lb/lb	-1.00 lb/lb	-1.00 lb/lb
$\frac{\Delta \text{ Inert wt}}{\Delta P \text{ Nozzle}}^{(2)}$	-6.8 lb/psid	-6.8 lb/psid	-6.8 lb/psid
$\frac{\Delta \text{ Inert wt}}{\Delta T \text{ Rise}_{\text{Nozzle}}}^{(2)}$	+23.94 lb/ ^o R	+23.94 lb/ ^o R	+23.94 lb/ ^o R
$\frac{\Delta \text{ Extension wt}}{\Delta \text{ Surface Area}}^{(3)}$	0.01148 lb/in. ²	0.01148 lb/in. ²	0.01148 lb/in. ²

(1)_{Ref 3}

(2)_{Ref 4}

(3)_{Ref 5}

At the outset of this evaluation, the analysts assumed the weight per unit surface area of the nozzle extension to be the same for all assemblies and to be independent of the terminal area ratio. In retrospect, it would have been more realistic to assign a value about 5% lower than was used for the 70:1 assembly and one about 10% higher for the 140:1 assembly to compensate for the change in the moment arm and the side load generated by wall pressure integrated over the surface area.

IV. TECHNICAL DISCUSSION

A. MAJOR SUB-TRADE STUDIES

This section covers selection of an optimum nozzle-assembly configuration that best satisfies the requirements stated in Section I.B. As such, it constitutes an engine PDR item. To establish a technical justifiable position, variables within each option for each selection were quantified whenever possible. Thus, the process of selection, in addition to identification of what influences the engine operation or the system, includes evaluation of the extent to which the system may be affected.

1. Nozzle-Assembly Terminal-Area-Ratio Selection

a. Available Options

Recognizing that expansions below the area ratio of 70:1 would not meet the minimum performance requirement (I_s nominal - 0.75%) of 816 sec, and consideration of physical aspects which make area ratios larger than 140:1 unattractive, the scope of this investigation was narrowed down to options within area ratios ranging from 70:1 to 140:1.

b. Method of Evaluation

Emphasis was placed on identifying those parameters influencing selection of the terminal area ratio that lend themselves to quantitative treatment. The quantification was deployed whenever technical status permitted, although, in some instances, subjective quasi-qualitative techniques were resorted to. The influencing parameters examined within this section were as follows:

- Payload/area-ratio relationship
- Ground test operations
- Fabrication costs
- Relative reliability (subjective)

The sequence shown above is arbitrary and is not meant to indicate importance.

Analytical tools used to select a suitable area ratio for the nozzle assembly for the NERVA engine were theoretical shifting-equilibrium performance (Ref 6), frozen-equilibrium performance (Ref 7), attainable performance based on assessment of performance losses (Ref 8 and 9) and mission-oriented payload/specific-impulse relationships as delineated in Section I.D. Other sources and references are dispersed (for convenience) throughout the body of this document.

(1) Payload/Area-Ratio Relationship

Figure 1 graphically depicts specific impulse as a function of area ratio for both shifting and frozen equilibrium. In this analysis, it was assumed that the state of gases will be closer to frozen equilibrium than to shifting, and a numerical performance value of 2/3 of the difference between the two sets of states was assigned. Also shown is the magnitude of the expected attainable performance for the range of area ratios of interest. The dashed portion of the curve signifies that, at this time, there is an uncertainty in assessment of performance losses beyond an area ratio of 100:1 and that this portion of the curve should therefore be viewed as extrapolated. The magnitude of the suspected error is still being determined.

Table I identifies the categories contributing to the loss of performance and illustrates the extent to which some of the values have been revised, notably the divergence loss and the boundary losses comprising thermal effects and friction. These revisions reflect changes in the coolant channel design and attendant change in heat transfer rates.

NOZZLE ASSEMBLY TERMINAL AREA RATIO SELECTION
SPECIFIC IMPULSE VS AREA RATIO

HYDROGEN $P_c = 450$ PSIA, $T_c = 4250^\circ\text{R}$

REF: COMPUTER PROGRAM 166

FIGURE 1

NOZZLE ASSEMBLY TERMINAL AREA RATIO SELECTION

I_{sp} DERATING FACTORS
EXPRESSED IN TERMS OF % I_s LOSS

	$\epsilon = 100:1$	$\epsilon = 100:1$
NOZZLE EXIT LOSSES	0.48	0.64
BOUNDARY LAYER LOSSES	1.44	1.60
KINETIC LOSSES	0.43	0.20
VIBRATION	0.25	0.25
CONTOUR IMPERFECTION	0.25	0.25
TOTAL %	2.85	2.94
DATE	20 OCT 1969	13 FEB 1970
REF	7750:M0692	7750:M0793

TABLE 1

At least one more revision of the derating factors will be made to account for a 7% increase in heat transferred within the cryogenically cooled portion of the assembly as a result of accommodating the flow swing through the SSCS.

Applying the information thus developed and using trade-off factors listed in Section II.D., Figures 2 through 10 were prepared. Each of these figures shows the attainable payload gain (ordinate) as a function of area ratio (abscissa). The two scales at the top of each figure show the range of expected performance adjusted for losses discussed previously, and incremental gains in specific impulse. The right ordinate shows the equivalent gain in seconds of specific impulse, which is the net gain of attainable performance minus weight penalty computed as follows:

$$\Delta I_{s \text{ net}} = \Delta I_{s \text{ attainable}} - \frac{\Delta \text{Weight}(\text{inert mass factor})}{\text{Specific Impulse Factor}}$$

The block in each figure identifies the type of mission, specific impulse factor in lb payload/1 sec I_s , and the stage inert mass equivalency factor in lb payload/lb inert mass.

In all of the figures (2 through 10) it has been graphically indicated by the dashed portion of the curves that the indicated gain in payload beyond the area ratio of 100:1 is questionable. As previously stated, existence of error in computing frictional losses has been verified. Although its magnitude is still under assessment, it is believed that the shape of these curves past the area ratio of 100:1 is questionable. As previously stated, existence of error in computing frictional losses has been verified. Although its magnitude is still under assessment, it is believed that the shape of these curves past the area ratio of 100:1 should be flatter, thus making such area ratios less attractive.

In addition, examination of round-trip missions where outgoing and inbound payloads are involved, Figures 4, 7 and 10, show that, even within optimistically stated payload-area ratio relationship as explained above, there is very little motivation towards considering plans for area ratios higher than 100:1.

None of the figures (2 through 10) supply information relative to penalties associated with the length or weight of the interstage structure. This information is not available at this time because neither the boost vehicle or the construction of the interstage are identified and for this reason the penalties involved were not accounted for in constructing these graphs. However, no matter how small such penalties may turn out to be there will be an increasingly greater downgrading effect on the payload change towards higher area ratios which adds another element to the reluctance to recommend an area ratio higher than 100:1. Refinements in assessments to the nozzle extension construction weight would have lowered the gain of the equivalent specific impulse by less than 0.5 sec for the 140:1 area ratio assembly.

(2) Ground Test Operations

Not to be overlooked are relative complexities involved in ground test operations as a function of area ratio. Figure 11 shows envelope diameters, lengths, and static pressures at the wall of the exit planes for assemblies extending to area ratio of 70:1, 100:1 and 140:1. For operations for no flow separation duct pressures of 1.5 psia, 1 psia and 0.5 psia for area ratios of 70:1, 100:1, and 140:1 respectively would be required. It is doubtful that a single stage of steam injection could provide a duct back pressure of 0.5 psia, and from this point of view a significant increase in complexity in operation of ground test facility is expected.

NOZZLE ASSEMBLY TERMINAL AREA RATIO SELECTION
 NOZZLE PERFORMANCE FOR MISSION "A-L-M" *
 (2/3 FROZEN EQUILIBRIUM BASE REF) GRAPHITE COMPOSITE SKIRT EXTENSION

REF: MEMO 7410:0002

OPTIMUM CONTOUR NOZZLE AREA RATIO

FIGURE 2

NOZZLE ASSEMBLY TERMINAL AREA RATIO SELECTION
 NOZZLE PERFORMANCE FOR MISSION "A-L-M" *
 (2/3 FROZEN EQUILIBRIUM BASE REF) GRAPHITE COMPOSITE SKIRT EXTENSION

REF: MEMO 7410:0002

OPTIMUM CONTOUR NOZZLE AREA RATIO

FIGURE 3

NOZZLE ASSEMBLY TERMINAL AREA RATIO SELECTION

NOZZLE PERFORMANCE FOR MISSION "A-L-M" *

(2/3 FROZEN EQUILIBRIUM BASE REF) GRAPHITE COMPOSITE SKIRT EXTENSION

I_{sp} SEC (790.6) (803.0) (813.2) (813.5) (822.1) (824.8) (827.0)

REF: MEMO 7410:0002

FIGURE 4

NOZZLE ASSEMBLY TERMINAL AREA RATIO SELECTION
 NOZZLE PERFORMANCE FOR MISSION "A-L-U" *
 (2/3 FROZEN EQUILIBRIUM BASE REF) GRAPHITE COMPOSITE SKIRT EXTENSION

REF: MEMO 7410:0002

FIGURE 5

NOZZLE ASSEMBLY TERMINAL AREA RATIO SELECTION

NOZZLE PERFORMANCE FOR MISSION "A-L-U" *

(2/3 FROZEN EQUILIBRIUM BASE REF) GRAPHITE COMPOSITE SKIRT EXTENSION

NOZZLE ASSEMBLY TERMINAL AREA RATIO SELECTION
NOZZLE PERFORMANCE FOR MISSION "A-L-U" *
(2/3 FROZEN EQUILIBRIUM BASE REF) GRAPHITE COMPOSITE SKIRT EXTENSION

NOZZLE ASSEMBLY TERMINAL AREA RATIO SELECTION
 NOZZLE PERFORMANCE FOR MISSION "C" *
 (2/3 FROZEN EQUILIBRIUM BASE REF) GRAPHITE COMPOSITE SKIRT EXTENSION

REF: MEMO 7410:0002

NOZZLE ASSEMBLY TERMINAL AREA RATIO SELECTION

NOZZLE PERFORMANCE FOR MISSION "C" *

(2/3 FROZEN EQUILIBRIUM BASE REF) GRAPHITE COMPOSITE SKIRT EXTENSION

I_{sp} SEC (790.6) (803.0) (813.2) (818.5) (822.1) (824.8) (827.0)

ΔI_{sp} SEC 12.4 10.2 5.3 3.6 2.7 2.2
813.0 MIN REQD

NOZZLE ASSEMBLY TERMINAL AREA RATIO SELECTION
 NOZZLE PERFORMANCE FOR MISSION "C" *
 (2/3 FROZEN EQUILIBRIUM BASE REF) GRAPHITE COMPOSITE SKIRT EXTENSION

REF: MEMO 7410:0002-

NOZZLE ASSEMBLY TERMINAL AREA RATIO SELECTION
COMPARATIVE LENGTHS FOR OPTIMUM RAO CONTOURS AT
 $\epsilon = 70/1, 100/1, \text{ \& } 140/1$

REF: COMPUTER PROGRAM 447 1-12-70

FIGURE 11

In terms of facility costs and steam requirements also significant differences have been identified. Related information (Ref. 13) has been compiled and is shown in Table 2. While the steam requirements may be fairly realistic, the costs shown should be only viewed as relative, because lacking a detailed design study makes these estimates accurate no more than $\pm 25\%$.

(3) Fabrication Cost

As far as the fabrication aspects of the nozzle extension is concerned, the following was established:

	<u>AREA RATIO</u>		
	<u>70:1</u>	<u>100:1</u>	<u>140:1</u>
Surface Area (in ²)	23,500	40,000	64,000
Δ Area (in ²)	-16,000	Ref	+24,000
Fab Flow Time (months)	9*	10	12*
Cost Change %	-15*	Ref	+25*
Fab Equipment Cost Change %	No Estimate	Ref	+50*

*Signifies approximations.

This apparent attractiveness of a 70:1 area ratio assembly should be viewed with reservation because of the marginality of performance.

(4) Payload in Orbit Cost

140:1 area ratio nozzle assembly is excluded from quantitative consideration in this section because outgoing-inbound payload missions show no gain over a 100:1 assembly. One way payload delivery

NOZZLE ASSEMBLY TERMINAL AREA RATIO SELECTION

TEST CELL "C" COSTS & STEAM REQUIREMENTS FOR R-4 & R-5

TERMINAL AREA RATIO	70:1		100:1		140:1	
POWER LEVEL	40 %	100 %	40 %	100 %	40 %	100 %
FACILITY COSTS (\$ x 10 ⁶)	76.5	71.5	131.8	83.8	TOO HIGH TO ESTIMATE	105.6
STEAM FLOW REQD (LB/SEC)	3600	3200	8100	4100	>20,000	5800

TABLE 2

SOURCE: MEMO 7250:0226
DTD 18 FEBRUARY 1970

missions do show a gain, but because analytical uncertainties involved, a meaningful numerical comparison cannot be made. Thus, this comparison will be limited to 100:1 area ratio assembly with 70:1 area ratio assembly treated as a reference.

	<u>ONE WAY PAYLOAD</u> (A-L-M)	<u>ROUND TRIP PAYLOAD</u> (MISSION C)
ΔI_s (net)	6 sec	5 sec
Δ Payload	4800 lb	1200 lb
(1) 7 Flights/year	\$490/lb	\$490/lb
\$ Saved/Flight	\$2,450 K	\$590 K
\$ Saved/Year	\$17,200 K	\$4,130 K

In a 35 flights per year program at ⁽¹⁾\$288/lb payload about 3 times as much per year could be saved.

(5) Relative Reliability

Admittedly, the assessments of relative reliabilities of assemblies with area ratios ranging from 70:1 to 140:1 is qualitative. Certain failures attributed to causes shown in Figure 12 are associated with the surface area. The larger the size---the greater the chances of damage. Failures associated with loads are shown to be of greater probability for higher area ratios. This, however, is a subjective assessment assuming identical innate structural characteristics at this time. In reality, any one assembly can be brought to the same level of reliability by judicious manipulation of structure members such as the number of honeycomb cells, their size and web thicknesses.

(1) Ref 10

Nevertheless, the three discrete options for the selection of terminal area ratio were ranked relative to each other as to their respective capability to resist each mode of failure. The higher the number on the scale from 0 to 10 the greater the resistance to failure. The summation of all numbers given below is only indicative of relative reliability and as such may be a subject to challenge.

<u>Terminal Area Ratio</u>	<u>Ranking Points Sum</u>
70:1	36
100:1	28
140:1	21

On the above basis, unless more forceful arguments can be presented to the contrary, an assembly with a terminal area ratio of 70:1 should be adopted. A brief paragraph relating each mode of failure to effect on the system is given in the subsequent pages.

(6) Safety

No reasonable quantitative or qualitative relationships between safety and the terminal area ratio were found to exist.

c. Evaluation

(1) The foregoing discussions readily support incorporation of a 100:1 nozzle assembly into the NERVA engine. Such an assembly does meet the performance requirements while no strong basis against it can be established with respect to cost or reliability.

(2) The 70:1 area ratio assembly may be looked favorably upon from reliability and cost considerations, however, the barely

NOZZLE TERMINAL AREA RATIO

RELIABILITY AND SAFETY COMPARISON FOR
NOZZLE ASSEMBLY TERMINAL AREA RATIO

FAILURE MODES

1. Structural failure of nozzle extension.

a. Vibration

<u>70:1</u>	<u>Rel</u>	<u>100:1</u>	<u>Rel</u>	<u>140:1</u>	<u>Rel</u>
Lower vibrational loads because of higher natural frequency.	6	Natural frequency lower than 70:1, however, actual values are to be determined.	5	Highest vibrational loads.	4

System Effect: Loss of I₃ and thrust vector control problem if a large piece of the nozzle extension is removed.

b. Material Flaws

<u>70:1</u>	<u>Rel</u>	<u>100:1</u>	<u>Rel</u>	<u>140:1</u>	<u>Rel</u>
Smaller nozzle extension means less total possibility of material flaws due to smaller volume.	6	Increased volume slightly more subject to flaws.	5	Largest volume of material more subject to undetected material flaws.	4

System Effect: Same as Item 2a.

c. Internal Pressure Loads

<u>70:1</u>	<u>Rel</u>	<u>100:1</u>	<u>Rel</u>	<u>140:1</u>	<u>Rel</u>
Low pressure produces insignificant hoop stress.	4	Insignificant	4	Insignificant	4

System Effect: Same as Item 2a.

d. Bending loads amplified by destruct system attachment (during boost phase only).

<u>70:1</u>	<u>Rel</u>	<u>100:1</u>	<u>Rel</u>	<u>140:1</u>	<u>Rel</u>
Loads are lowest on 70:1 due to shorter moment arm and smaller exist diameter.	4	Ref.	3	Longest mement arm and largest exit radius produces greatest loads.	2

System Effect: Same as Item 2a.

e. Gimbaling Loads

<u>70:1</u>	<u>Rel</u>	<u>100:1</u>	<u>Rel</u>	<u>140:1</u>	<u>Rel</u>
Same as Item d.	4	Same as Item d.	3	Same as Item d.	2

2. Space flight damage due to impact with other vahicles.

<u>70:1</u>	<u>Rel</u>	<u>100:1</u>	<u>Rel</u>	<u>140:1</u>	<u>Rel</u>
Shortest length reduces probability of impact damage.	4	Ref.	3	Longest length increases probability of impact damage.	2

3. Meteriod Bombardment Damage.

<u>70:1</u>	<u>Rel</u>	<u>100:1</u>	<u>Rel</u>	<u>140:1</u>	<u>Rel</u>
Smallest surface area reduces probability	4	Ref	2	Largest surface area increases probability	1

4. Handling damage possibility.

<u>70:1</u>	<u>Rel</u>	<u>100:1</u>	<u>Rel</u>	<u>140:1</u>	<u>Rel</u>
Decreased weight and bulk decrease prob-ability of handling damage.	4	Ref.	3	Increased weight and bulk of longer nozzle increase probability of handling damage.	2

Reliability Totals:	<u>36</u>		<u>28</u>		<u>21</u>
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minimum attainable performance makes this concept unattractive, especially in view of costly flight operations.

(3) The 140:1 area ratio assembly appears to exceed the nominal performance requirements but other considerations, as listed below, made an assembly with 140:1 area ratio less attractive.

(a) There are uncertainties in prediction of attainable performance past area ratio of 100:1.

(b) There is no significant gain in allowable payload for missions requiring outgoing and inbound payloads.

(c) Penalties (if any) associated with interstage structure were not included and therefore the attainable performance shown tends to be optimistic.

(d) Costs tend to be higher.

50% increase in fabrication equipment.

25% increase per extension unit.

20% increase in fabrication flow time.

High costs of ground test facilities and testing.

(e) Operational complexities associated with testing at 0.5 psi duct pressure.

d. Recommendation

In view of the above evaluation, it is recommended that a 100:1 area ratio nozzle assembly be incorporated into the NERVA engine.

2. Nozzle Extension Attachment Location Selection

a. Available Options

To reduce this investigation to a reasonable scope the following criteria were adopted: investigate the effects of locating the interface between convectively cooled portion of the assembly and the graphite extension so that the R-series (R-1 in particular) could be tested without a diffuser with the primary nozzle flowing full at 100% power and treat such location as the lower area ratio limit. As the upper area ratio limit adopt dimensional restrictions imposed by ETS-1 facility. Thus, the alternatives exist any place between area ratio of 12:1 and 29:1.

b. Method of Evaluation

The following influencing parameters were examined for effects produced:

Gimbaling considerations in ETS-1.

Weight

Change in heat loss

Effect on equivalent I_s

Effect on nozzle ΔP and ΔT

Graphite Extension erosion

Interface flanges compatibility

Reliability

Cost

Hardware

Fabrication Equipment

Test Facility

Missions

Most of the items on the list were selected because of amenability to quantification. The exceptions are flange compatibility and reliability where only a lesser degree of exactness can be imparted at this time thus resulting in a more qualitative rather than quantitative comparison. In addition to analytical tasks listed in the previous sections, ΔP , ΔT - inert weight equivalency factors were used as defined in II.D.

(1) Gimbaling Considerations In ETS-1

Figure 13 shows the physical compatibility of the ground test configuration of the nozzle assembly within dimensional limitations of the ETS-1 facility. Three items invite attention. Number one, the internal duct diameter limits the area ratio of the nozzle assembly to 29:1. Number two, the 29:1 area ratio assembly affords no opportunity for gimbaling. Number three, a minimum gimbaling of $\pm 1/2^\circ$ becomes possible with an assembly limited to an area ratio of 24:1. Thus the location of the interface between the primary nozzle and the nozzle extension cannot be placed at an area ratio greater than 24:1.

(2) Effect on Nozzle ΔP and ΔT

Inasmuch as up to this point, it has not yet been established whether a single unit construction nozzle or a two piece nozzle and skirt subassembly should be incorporated into the NERVA engine, nor has it yet been established where the coolant inlet manifold should be located, it becomes necessary to consider both single and double pass

CRYO COOLED NOZZLE TERMINAL AREA RATIO SELECTION

NERVA FULL FLOW ENGINE
NOZZLE AND TEST
SKIRT EXTENSION

$A_e/A_t = 29:1$ (REF) NON-GIMBALLING

NASS DUCT COLLAR -
NON-GIMBALLING
TESTS

6.0-8.0" (REF)

NERVA FULL FLOW ENGINE
NOZZLE $A_e/A_t = 24:1$
ENGINE GIMBAL $\pm 1/2^\circ$

NASS DUCT COLLAR -
GIMBALLING TESTS

$2-1/2 \pm 1/2$

60.0" DIA
(INSIDE NOZZLE)

55.0" DIA REF
(INSIDE NOZZLE)

$2-1/2 \pm 1/2$

64.0" DIA
(INSIDE DUCT)

TOP OF EJECTOR
& EXISTING ETC.
BOTTOM SHIELD &
DOLLAR - TO DUCT
INTERFACE

BOTTOM SHIELD

NASS DUCT

ENGINE AND DUCT
CENTERLINE ON COMMON AXIS

REF: MEMO 7270:0410

82" DIA

FIGURE 13

coolant passage systems. The first assumes that the coolant inlet is located at the aft end of the cryogenically cooled assembly, the second assumed that the coolant inlet is located at area ratio of 5:1 directing the coolant aft first. The direction of flow is reversed at the interface with the nozzle extension and ducted through the coolant channels to the reflector inlet.

An exception to the above approach was made for the 12.5:1 nozzle where only the effects of a single pass arrangement were examined.

Table 3 is summary of results obtained. It is of interest to note that although a discrete coolant channel design was generated for each configuration to maintain identical hot gas side temperature profile, very little difference in ΔP was generated over the area ratio range of 16.5:1 and 24:1. Over this range a double pass coolant flow arrangement exhibits consistently higher pressure drop of 3 psid. Equally consistent is the change in coolant temperature rise, the double pass producing 6 - 7°R less temperature rise. Thus, there is an indication that approximately 1 psid pressure drop penalty produces 2°R change in coolant temperature rise. Such relationship appears as a very profitable trade in view of the fact that a break even trade is 3.5 psid per °R of temperature inlet into the turbine.

Table 4 is a tabulated summary of effect produced by all aspects herein considered. The nozzle assembly weight differences accounting for less mass in the cryogenically cooled portion and more mass in the graphite structure, resulting shield weight reduction, change in pressure drop and temperature rise, and change in thermal losses were all converted to allowable change in payload. If one takes a 24:1 area ratio nozzle as a reference, than it appears that a 16:1 area ratio would not offer an advantage. A very minimal gain of 140 lb of payload is shown for the 12:1 area ratio assembly. As insignificant as it may be it does,

GRAPHITE EXTENSION ATTACHMENT LOCATION

NOZZLE OPERATING PARAMETERS *

A_e/A_t	24:1 TWO PASS NOZ.	24:1 ONE PASS NOZ.	16:1 TWO PASS NOZ.	16.5:1 ONE PASS NOZ.	12.5:1 ONE PASS NOZ.
COMPUTER RUN NO., LOBE	036,065	072	035,064	071	066
ΔP NOZ. ASSY, PSI	111	108	114	110	95
P_{OUT} NOZ. ASSY, PSIA	1162	1165	1159	1163	1178
ΔT NOZ. ASSY	139	145	130	137	128
T_{OUT} NOZ. ASSY, °R	199	205	192	197	188
MAX T_{wg} , °F	1500	1501	1500	1499	1500
MAX T_{wg} , BARREL, °F	1306	1299	1318	1307	1321
MAX COOLANT MACH NO.	.23	.24	.21	.23	.21

* EXCLUSIVE OF SSC SWING EFFECTS

TABLE 3

TABLE
GRAPHITE EXTENSION ATTACHMENT LOCATION

FACTORS INFLUENCING PAYLOAD	LOCATION		
	$\epsilon = 24:1$	$\epsilon = 16:1$	$\epsilon = 12:1$
NOZZLE ASSY WEIGHT ①	REF	+85	+130
SHIELD WEIGHT	REF	+70	+150
NOZZLE ASSY PRESSURE LOSS ②	REF	-30	+260
NOZZLE ASSY TEMPERATURE RISE ③	REF	-540	-1140
THERMAL LOSS	REF	+160	+740
TOTAL ALLOWABLE CHANGE IN PAYLOAD	REF	-255	+140

- ① 1 LB INERT WEIGHT = 2.80 LB PAYLOAD (MEMO 7410:0002) (A-L-M)
- ② 6.8 LB INERT WEIGHT = 1 PSI ΔP ; 19 LB PAYLOAD/PSI ΔP (7860:0012)
- ③ 23.9 INERT WEIGHT = 1°R NOZZLE ΔT ; 67 LB PAYLOAD/°R NOZZLE ΔT (7860:0012)

however, constitute basis for preference in this direction before the effects of other elements were examined. It should not be overlooked, however, that para-ortho conversion phenomenon, although applicable to all cases under discussion, could compound the effect of lower turbine inlet temperature produced by the 12:1 nozzle to the point of marginality of energy available. In the foregoing discussion, no considerations were given to the potential effects that a flow swing through the SSCS may produce.

(3) Graphite Erosion

It is in general agreed that graphite reacts with hydrogen and that the rate of reaction is in some way proportional to temperature and pressure. Experimentations in this area were in most cases made at pressures two orders of magnitude higher than the 2-5 psia of interest and none at high hydrogen velocities. In order to gain more perspective in this field, a subscale experimental program was undertaken with the objective to simulate NERVA environment at the specimen's wall. Data of interest was in the range of:

Surface Pressure 2-5 psi, Hydrogen Velocity 15,000 - 25,000 ft/sec,
Surface Temperature 2000°R - 4000°R

The test results are shown in Figure 14. The plot shows that indeed the regression rate increases with increasing pressure. A detailed report on the subject will be issued at a later date relating all variables induced. Of significance here is the fact---aside from the effects of the scale factor---that over the range of conditions examined the graphite erosion should not be of major concern.

However, until the dissimilarities between the full scale and the 0.3 inch to 1.0 inch subscale specimens with respect to flow laminarization, turbulence, mass diffusion and heat transfer coefficients

GRAPHITE EXTENSION ATTACHMENT LOCATION GRAPHITE EROSION

○ FABRIC PARALLEL TO CONTOUR
 ▲ FABRIC PARALLEL TO CENTERLINE
 $P_c = 150 \text{ TO } 200 \text{ PSIA}$

$T_c = 4625^\circ\text{R}$
 $T_{\text{SPEC}} = 2000 \text{ TO } 4000^\circ\text{R}$

Figure 14 - Graphite-Extension Attachment Location, Graphite Erosion

are examined. The data should be viewed as very encouraging but not conclusive enough to enhance risks by recommending the attachment of the nozzle extension at an area ratio lower than absolutely necessary.

(4) Interface Flanges Compatibility

Without exception, all radiatively cooled devices used in nozzle constructions are subject to effects resulting from thermal environment. The closer to the nozzle throat the more severe is the environment and the induced effect. The first effect is the increase in wall temperature. In case of graphite, stipulating that even if the increase in erosion could be tolerated, the increase in temperature makes it more difficult to achieve a structurally compatible joint between the cryogenically cooled portion of the assembly and the graphite nozzle extension.

Admittedly, to date the thermal and structural compatibility between the two members was only examined at an area ratio of 24:1 and even here a fully satisfactory solution has not yet been obtained. While manageable temperatures in flanges on both sides of the interfaces to satisfy criteria pertaining to relative motion in the radial direction have been obtained, temperature gradients in the graphite flange continue to be a problem. Therefore, there is a great reluctance at this time to magnify these problems by moving the interface location to lower area ratios where the thermal gradients are going to be unavoidably greater.

(5) Relative Reliability

Here again a ranking method using a scale from 0 to 10 was used to establish if summation of all points could not contribute to selection of location of the interface between the cryogenically cooled nozzle and the graphite extension. Figure 15 shows graphically how the three examined locations rate relative to each other under the stipulated failures.

The summation of all rating shown below indicates that selection of cryogenically cooled nozzle extending to area ratio of 24:1 should be supported.

NOZZLE/NOZZLE EXTENSION
INTERFACE LOCATION

12.5:1	36
16.5:1	39
24:1	42

The above summation was extracted from an abbreviated mode of failure and effects analysis shown in the subsequent pages.

(6) Safety

From the safety point of view, assuming that a total loss of the nozzle extension is stipulated, a 24:1 residual area ratio would result in 6000 lb. of thrust reduction, which almost satisfies the minimum required. By contrast a 16:1 and 12:1 area ratios would result in thrust deficiency of 8,000 and 9,000 lb., respectively. An analogous situation exists if a partial loss of the extension is stipulated. A full length longitudinal crack 0.1 in. wide would produce a side force of approximately 150 lb. On the other hand, a damage extensive enough to produce 50% loss of extension's side wall would produce a loss of axial thrust ranging from 3000 lb. to 4500 lb. for attachment points at area ratio of 24:1 and 12:1 respectively. Assuming the unlikely extreme that the loss of axial thrust would be totally converted into the side thrust, a compensation of the thrust vector of 3000 lbs. for the 24:1 area ratio attachment case, 4000 lbs. for 16:1 attachment and 4500 lbs. for 12:1 attachment point would be required. The thrust vector control capability of 4000 lbs. compensation for thrust misalignment would be at best marginal with nozzle extension attached at area ratio of 16:1 and inadequate at area ratio of 12:1. On the basis, area ratios lower than 24:1 constitute safety hazards for flight personnel if the mission with the above thrust degradation could not be accomplished.

RELIABILITY AND SAFETY COMPARISON FOR
TERMINAL AREA RATIO OF CRYO COOLED NOZZLE

MODE OF FAILURE

1. Graphite nozzle extension erosion. Excessive erosion could lead to structural failure.

<u>12.5:1</u>	<u>Rel</u>	<u>16.5:1</u>	<u>Rel</u>	<u>24:1</u>	<u>Rel</u>
Approx. 70% more erosion than 24:1 joint.	1	Approx. 30% more erosion than 24:1 joint.	2	Lowest erosion rate of the three choices.	3

System Effect: Structural failure could cause loss of I_s and loss of thrust vector control.

2. Graphite structure failure due to boost and acceleration loads, and vibration.

<u>12.5:1</u>	<u>Rel</u>	<u>16.5:1</u>	<u>Rel</u>	<u>24:1</u>	<u>Rel</u>
As size of nozzle extension increases it becomes less capable of carrying induced loads.	2		4	Graphite structure most capable of carrying induced loads.	6

System Effect: Same

3. Coolant channel rupture.

<u>12.5:1</u>	<u>Rel</u>	<u>16.5:1</u>	<u>Rel</u>	<u>24:1</u>	<u>Rel</u>
Less chance of rupture due to shorter length of tube and lower tube radius produces lower pressure stress.	6		5	Larger radius of tube develops greater pressure across wall.	4

System Effect: Not Significant.

4. Weight C.G. moves aft resulting in higher nozzle bending loads.

<u>12.5:1</u>	<u>Rel</u>	<u>16.5:1</u>	<u>Rel</u>	<u>24:1</u>	<u>Rel</u>
Lowest bending loads C.G. forward as far as possible.	4		3	Highest bending loads. Excessive loads could cause coolant tube rupture and weld failures.	2

System Effect: Same

5. Nozzle to nozzle extension joint failure.

<u>12.5:1</u>	<u>Rel</u>	<u>16.5:1</u>	<u>Rel</u>	<u>24:1</u>	<u>Rel</u>
Maximum thermal Severity	5		4	Minimum thermal severity.	3

System Effect: Failure of joint would cause total failure of skirt extension. Resulting in loss of thrust (less than 20% less).

6. Nozzle fab difficulty.

<u>12.5:1</u>	<u>Rel</u>	<u>16.1:1</u>	<u>Rel</u>	<u>24:1</u>	<u>Rel</u>
Easier to fab, therefore, less change of fabrication and inspection errors which would degrade reliability due to nozzle quality (R_Q).	7		6	More difficult to fab.	5

System Effect: Nozzle failure could cause loss of I_s and thrust vector control.

Nozzle extension fab difficulty.

<u>12.5:1</u>	<u>Rel</u>	<u>16.5:1</u>	<u>Rel</u>	<u>24:1</u>	<u>Rel</u>
Most difficult to fab if nozzle extension starts at 12.5:1	5		6	Easiest to fab and inspect.	7

System Effect: Nozzle extension failure could cause loss of I_s out thrust vector control.

8. Lack of sufficient bulk temp rise to provide turbine energy.

<u>12.5:1</u>	<u>Rel</u>	<u>16.5:1</u>	<u>Rel</u>	<u>24:1</u>	<u>Rel</u>
Lowest bulk temp rise.	3		6	Highest bulk temp rise.	9

System Effect: Reduced turbine inlet temp reduces turbine operating margin calls for compensating TIP increase and thus increases pressure load on other components.

9. Max tube wall temp profile

<u>12.5:1</u>	<u>Rel</u>	<u>16.5:1</u>	<u>Rel</u>	<u>24:1</u>	<u>Rel</u>
T _{wg} 1321°F	3	T _{wg} 1307°F	3	T _{wg} 1299°F - Lower tube wall temp will reduce thermal fatigue buckling problem.	3

System Effect: Tube cracks and resulting coolant leakage could reduce I_s.

Reliability Totals:	<u>36</u>	<u>39</u>	<u>42</u>
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(7) Cost

Nozzle Assembly - Numerical evaluation of cost differences as a function of location of the interface between the cooled and graphite components was not made. However any differences could not be significant because the cost saved in a shorted cryogenically cooled component would shift to a longer graphite nozzle extension. This would be true of both the materials and fabrication time.

If any, the cost could be slightly higher for assemblies with interface at lower area ratios, but more because of a larger graphitization equipment that would be required rather than attributable to the fabrication process.

Test Facility Operation - Operational cost of the test facility are considerably affected by the steam requirements, and among other variables this one could be the most significant one.

The higher the test article exit pressure (lower area ratios) the less steam is required. Figure 16 shows that an assembly with terminal area ratio of 20:1 and a small graphite segment attached at area ratio of 16.5:1 could be operated at about \$1,000,000 less compared with a 25:1 area ratio assembly. A further reduction of area ratio could provide savings up to \$5,000,000. Before other elements of this analysis became examined it was predominantly the cost saving in the test facility operation that provided the motivation to go in this direction. Subsequent work, however, revealed that larger nozzle exit angles at lower area ratios in most likelihood would require facility modifications at a cost that would nullify saving envisioned for test assemblies with area ratio not larger than 16.5:1 and consume a significant portion of savings eliminated for testing assembly with area ratios less than 16:1.

NASS STEAM PLANT COST SAVINGS VS NOZZLE AREA RATIO

REF: NASS MEMO # 70-027 1-21-70

FIGURE 16

Missions - As it was pointed out before the net allowable payload changes with respect to a 24:1 cryogenically cooled assembly taken as a reference are (-) 255 lb. and (+) 140 lb. for 16:1 and 12:1 versions respectively. This, when equated to cost per pound of payload in orbit represents losses and savings illustrated below.

ONE WAY PAYLOAD TYPE MISSION
OPERATING COST CHANGE

Program	ASSEMBLY VERSION (A_e/A_t)		
	<u>24:1</u>	<u>16:1</u>	<u>12:1</u>
7 Flights/year	Ref	-\$885,000/year	+\$510,000/year
35 Flights/year	Ref	-\$2,500,000/year	+\$1,500,000/year

The change in missions' cost for a round trip type mission is considerably less dramatic as shown in the table below.

ROUND TRIP TYPE MISSION
OPERATING COST CHANGE

Program	ASSEMBLY VERSION (A_e/A_t)		
	<u>24:1</u>	<u>16:1</u>	<u>12:1</u>
7 Flights/year	Ref	-\$344,000/year	+\$200,000/year
35 Flights/year	Ref	-\$980,000/year	+\$590,000/year

Thus, it may be concluded that the combined cost of test facility operation, facility modification and missions provide no basis for adoption of a 16:1 area ratio for termination of the cryogenically cooled portion of the nozzle assembly. On the other hand, unless more important considerations dictate otherwise, adoption of a 12:1 nozzle could be supported on cost basis.

However, a subsequent review made, indicates that the reduction of heat transferred resulting from interface relocation from area ratio of 24:1 to 12:1 may not be as great. While the foregoing analyses were based on thermal loss reduction equivalent to 0.9 sec which was equated to 740 lb of payload gain (Table 4), a reassessment shows that 0.6 second of specific impulse loss may be a more realistic number. In terms of payload, this would be equivalent to 485 lb gain rather than 740. Should this be true, the total allowable change in payload for the 12:1 area ratio would be a reduction of -115 lb rather than the gain of +140 lb shown. This would produce a cost increase in mission costs rather than cost savings shown before the 12:1 area ratio cryogenically cooled nozzle.

c. Evaluation

(1) Nozzle/Nozzle Extension Interface Location at Area Ratio of 12:1

Selection of this location can be only supported on cost basis. Relative reliability assessment does not support it. Consideration of graphite susceptibility to erosion does not support it, and most important---17°R lower turbine inlet temperature compared with a 24:1 area ratio nozzle makes the 12:1 area ratio nozzle the least attractive. Reduction of turbine inlet temperature is very expensive in terms of payload and uncertainties with regards to para-ortho conversions dictate that risks involved should be avoided. Thus, the turbine inlet temperature is a very precious commodity and should be maximized if possible. Increasing the nozzle coolant exit temperature is possible at the expense of (1) pressure drop, and (2) loss of specific impulse caused by higher heat rejection rates. Either parameter, however, trades itself so as to favor maximization of turbine inlet temperature. This consideration is judged to outweigh the convenience associated with R-1 testing.

(2) Nozzle/Nozzle Extension Interface Location at Area Ratio of 16:1

Selection of this location cannot be supported by any discipline herein considered.

(3) Nozzle/Nozzle Extension Interface Location at Area Ratio of 24:1

Relative reliability assessment supports selection of cryogenically cooled nozzle extending to an area ratio of 24:1. Graphite erosion considerations make it desirable to attach the nozzle extension as far aft as possible. Desirability to maximize turbine inlet temperature supports this selection. Cost considerations do not favor this selection, but technical aspects, primarily the concern with energy availability at the turbine inlet are judged to be of greater importance.

d. Recommendation

Extend the cryogenically cooled portion of the nozzle assembly to area ratio of 24:1, and attach the nozzle extension at this interface.

3. Coolant Inlet Manifold Location Selection

a. Available Options

It already has been established that the cryogenically cooled portion of the nozzle assembly should be extended to area ratio of 24:1. This constitutes one location where coolant could be introduced into the nozzle. With this arrangement a single pass coolant flow from the aft end to the reflector plenum accomplishes the cooling function.

Any other location of the coolant manifold placement results in a double pass coolant path. Associated with a double pass are turning, crossover and manifold pressure losses. These could be offset by allowing higher wall temperatures to exist (less coolant temperature rise) compared with a single pass arrangement.

A practical lower limit in area ratio, as opposed to the 24:1 location, at which a torus could be located is one which allows for interchangeability between a flight configuration and a ground test simulator. The latter is a device which generates enthalpy change in the coolant equal to the flight model, but its contour is altered to preclude separation of flow during ground testing without a diffuser. It was determined that such substitution could be made without generating shocks in the nozzle by fairing the ground model contour into the flight contour at area ratio of 5:1.

Thus, the two extremes that will be examined and compared for locating the coolant inlet manifold are area ratio 5:1 and 24:1.

b. Method of Evaluation

Elements of potential influence and the selection of manifold location are listed below.

Nozzle Assembly Weight

Shield Weight

Nozzle Pressure Drop

Coolant Temperature Rise

Manufacturing Aspects

Nozzle Flange at the Nozzle Extension Interface

Payload

Reliability
 Cost
 Hardware
 Missions

Trade-off factors consistent with those used elsewhere in this document were used whenever applicable.

(1) Nozzle Assembly Weight

Inasmuch as it has not yet been established whether a one piece unit construction or a two piece nozzle and skirt should be selected, both versions will be examined for weight savings effectiveness.

Schematic rendition of options considered is shown in Figure 17. Weight comparison is given below.

<u>TORUS LOCATION</u>	<u>5:1</u>		<u>24:1</u>	
	<u>One Piece</u>	<u>Two Piece</u>	<u>One Piece</u>	<u>Two Piece</u>
Construction				
Manifold Weight Lb.	88	88	174	174
Flanges and Bolts	None	100	None	100

It should be remembered that the main reason why the location of area ratio of 5:1 is being considered is the desired interchangeability between a flight skirt and a ground testing simulator. Thus, a two piece assembly would be a logical choice with the manifold located at area ratio of 5:1. Admittedly the argument tends to be a weak one because it would appear to be profitable to accept manufacturing hardship for the sake of saving 100 lbs. of flange weight. On the other hand, locating the manifold at area ratio of 24:1 eliminates motivations

COOLANT INLET TORUS LOCATION

NOZZLE OPTIONS

5:1 JOINT WITH
TWO PASS SKIRT ONE PIECE TWO
PASS NOZZLE ONE PIECE SINGLE
PASS NOZZLE WITH OR WITHOUT
FLANGES

FIGURE 17

to provide for a two piece construction because of the expense in pressure drop and weight penalty of 100 lbs. Thus, the comparison reduces itself to a manifold location either at area ratio of 5:1 with a two piece nozzle and skirt construction or at area ratio of 24:1 with a one piece construction. The latter one is 14 lbs. lighter. Unless subsequent analyses show otherwise, Weight consideration favors locating the manifold at area ratio of 24:1.

(2) Shield Weight

(Ref 12) states that "...neither relocation of the torus nor replacement of the CRES 347 with graphite influence the shield."

Basis for the statement is that the larger hydrogen volume and increase in manifold mass when located at area ratio of 24:1 is offset by an increase in distance from the radiation source. The same applies to the flange at the interface between the nozzle and the nozzle extension.

(3) Nozzle Pressure Drop and Coolant Temperature Rise

The two parameters are so closely interrelated that it is not practical to consider them separately. Two basic design options constitute basis for comparison. If the nozzle with the coolant manifold located at area ratio of 5:1 (double pass) generates $X^{\circ}R$ of temperature rise with associated loss of pressure consumed by turning at the aft end, longer coolant flow path and the crossover manifold at the point of separation (area ratio 5:1) of the skirt from the nozzle, than there is a choice of designing a one piece nozzle with the manifold located at area ratio of 24:1 for the same temperature rise and saving in pressure drop, or designing for the same pressure drop by enhancing the heat transfer rates (higher coolant velocity) and thus generate more temperature rise in the coolant. Choosing the latter---there will be approximately 0.3 sec loss of

specific impulse resulting from the energy extracted from the hot gas. Numerical comparison of changes in nozzle pressure drop and coolant temperature rise is given below.

TORUS LOCATION	5:1	24:1		24:1
	<u>Two Piece</u>	<u>One Piece</u>		<u>Two Piece</u>
Pressure Drop	Ref	- 15 psid	No Change	No Change
Temperature Rise	Ref	No Change	+6°R	No Change
		(1)	(2)	

It is immediately evident that (a) locating the coolant inlet manifold to area ratio of 24:1 and retaining a two-piece concept (nozzle and skirt) offer no advantage over manifold location area ratio of 5:1; (b) locating the coolant inlet manifold to area ratio of 24:1 and adopting a single unit nozzle provides an opportunity to reduce the pressure drop or gain more temperature rise. Either one is an advantage over a 5:1 area ratio for manifold location. Which of the two combinations (marked 1 and 2) is more advantageous is not readily evident.

The foregoing establishes that pressure drop and temperature rise considerations provide basis for locating the coolant inlet manifold at area ratio of 24:1 as the preferred configuration.

(4) Manufacturing Aspects

Isolating the problem of selecting a most advantageous location for the coolant inlet manifold from consideration of one-piece versus two-piece construction aspects reduces the problem to consideration of coolant path in the vicinity of manifold location. Figure 18 shows a concept of flow introduction at area ratio 24:1. An inherent simplicity is evident. By contrast examination of Figure 19 and Figure 20 shows that two times as many coolant crossover slots would have to be machined, two manifolds

GRAPHITE EXTENSION ATTACHMENT LOCATION

GRAPHITE SKIRT EXTENSION JOINT COMPATIBILITY

TORUS LOCATION FOR
COLD 347 FLANGE

① CRES 347 NOZZLE

② AGCarb-101
SKIRT EXTENSION

TORUS LOCATION FOR
WARMER 347 FLANGE

FOR JOINT COMPATIBILITY $\sigma = (\overline{\alpha \Delta T})_1 = (\overline{\alpha \Delta T})_2$

METHOD OF COOLANT FLOW TRANSFER FROM SKIRT TO PRIMARY NOZZLE
ALTERNATE 1

FIGURE 19

METHOD OF COOLANT FLOW TRANSFER FROM SKIRT TO PRIMARY NOZZLE
ALTERNATE 2

FIGURE 20

formed and welded, more inspection functions to be performed. Associated with these intricacies are 432 (two for each coolant channel) potential flow stagnation points at the flow diversion plates. It is difficult to assign a complexity index number to these concepts. Qualitatively viewed, the complexity of coolant introduction at area ratio of 24:1 is less.

(5) Effect on Flange at the Nozzle/Nozzle Extension Interface

The compatibility of flanges on either side of the nozzle/nozzle extension interface depends to a large degree on temperature distribution in either flange. Temperature of one flange influences the temperature of the other. Some degree of control can be exercised by judicious manipulating of the location and selection of seal material. A simply stated principle of compatibility is to match radial motion in either member by controlling the change in temperature in one member with respect to temperature change in the other relative to the temperature at which the assembly was made. Thus, if coefficients of thermal expansions are not equal it could be stated that the relative motion of one member with respect to the other can be made zero if

$$(\alpha\Delta T)_{347} = (\alpha\Delta T)_{\text{Graphite}}$$

For the two materials, coefficient of expansion in steel is 5 times greater than that of AGCarb; thus, the temperature change in steel should only be 1/5 of that in graphite. It will be much easier to attain this condition if hydrogen contained in the coolant inlet manifold was available in the proximity. The concept of managing the temperature in the flange is illustrated in Figure 18.

Analyses performed to date indicate that in order to achieve and control the temperature within the flange of the nozzle

side of the interface, locating the torus at this location is almost mandatory.

(6) Relative Reliability

Six items were selected for ranking on a relative scale from 0 to 10. Figure 21 permits at glance to see how the locations of the coolant inlet manifold were rated. A brief paragraph related to each of the potential mode of failure is given. The reliability rating totals of 19 for the 5:1 area ratio location and 37 for the 24:1 area ratio location clearly identify the superiority of locating the coolant inlet manifold at area ratio of 24:1.

(7) Safety

Safety hazards or lack thereof are considered to be identical for both options.

(8) Payload

Four elements heretofore considered lend themselves to equating to change in pounds of payload in orbit. Trade-off factors used are consistent with those previously stated, but for convenience are also shown here. The four items here quantified and the equivalent change in payload are shown below.

COOLANT INLET TORUS LOCATION

RELIABILITY AND SAFETY COMPARISON FOR
COOLANT INLET TORUS LOCATION

MODES OF FAILURE

1. Coolant inlet manifold or attaching weld failure.

<u>Double Pass, Torus Located at Area Ratio other than 24:1</u>	<u>Rel</u>	<u>Single Pass, Torus Located at 24:1</u>	<u>Rel</u>
Failure to deliver required flow rate to reflector.	3	Same	3

System Effects: Thrust vector control problem. Loss of I_s . Fire hazard during
Ground Test.

2. Crossover manifold or attaching weld failure.

<u>Double Pass, Torus Located at Area Ratio other than 24:1</u>	<u>Rel</u>	<u>Single Pass, Torus Located at 24:1</u>	<u>Rel</u>
Failure to deliver required flow rate to reflector.	2	No crossover manifold. No possibility of failure.	10

System Effect: System effect same as above with double pass nozzle

3. Coolant channel transition joint failure.

<u>Double Pass, Torus Located at Area Ratio other than 24:1</u>	<u>Rel</u>	<u>Single Pass, Torus Located at 24:1</u>	<u>Rel</u>
Failure to deliver required flow rate to reflector.	2	No transition joint with U- tube design. No possibility of failure. One transition joint if oval tubes are used.- Rel = 4	10

System Effect: Thrust vector control problem. Loss of I_s .

4. Lack of sufficient turbine inlet energy.

<u>Double Pass, Torus Located at Area Ratio other than 24:1</u>	<u>Rel</u>	<u>Single Pass, Torus Located at 24:1</u>	<u>Rel</u>
Double pass flow arrangement results in pressure drop penalties, and less increase in temp rise available turbine inlet.	3	Less nozzle pressure drop (which may be converted to bulk temp rise) therefore, greater turbine inlet energy.	6

System Effect: Reduced turbine inlet energy reduces turbine operating margin and increases pressure load on other components.

5. Nozzle to nozzle extension joint failure.

<u>Double Pass, Torus Located at Area Ratio other than 24:1</u>	<u>Rel</u>	<u>Single Pass, Torus Located at 24:1</u>	<u>Rel</u>
Less controlability of temp distribution in nozzle flange. Higher temp gradient in the extension.	2	Flange stress ($\propto \Delta T$) can be equalized by location of inlet manifold.	4

System Effect: Ranging from external hot gas leak to partial loss of thrust in case of total joint failure.

6. Manufacturing complexity and NDT inspection complexity.

<u>Double Pass, Torus Located at Area Ratio other than 24:1</u>	<u>Rel</u>	<u>Single Pass, Torus Located at 24:1</u>	<u>Rel</u>
Crossover manifold increases brazing and inspection difficulty and more complex machining.	2	No crossover manifold simplifies construction.	4
Reliability Totals:	<u>19</u>		<u>37</u>

<u>Manifold Location</u> <u>Construction</u> <u>Influencing Factors</u>	<u>5:1</u> <u>Two-Piece</u> <u>Two-Pass</u>	<u>PAYLOAD CHANGE - LB</u>			
		<u>24:1</u>			
		<u>One-Piece</u>			
		<u>(ΔP Constant)</u>	<u>One-Pass</u>	<u>(ΔT Constant)</u>	
Pressure Drop, ΔP	Ref	Ref	No Change	-15 psi	+285
Temperature Rise, ΔT	Ref	6°R	+402	Ref	No Change
Flange Weight Δ	Ref	-100 lb	+280	-100 lb	+280
Torus Weight Δ	Ref	+ 86 lb	-240	+ 86 lb	-240
Shield Weight Δ	Ref	Ref	No Change	Ref	No Change
Heat Loss (I_s) Δ	Ref	0.3 sec	-240	Ref	No Change
NET PAYLOAD CHANGE	Ref		+202		+325

1 psi ΔP = 19 lb payload.

1°R ΔT = 67 lb payload.

1 lb. inert mass = 2.8 lbs payload

1 sec I_s = 809 lbs payload

It is evident that in terms of payload locating the coolant inlet manifold at area ratio of 24:1 is advantageous. What also became evident is that from the payload point of view it is more profitable to save pressure drop rather than trade it for temperature rise because the latter also causes a loss of impulse (0.3 sec). One may observe, however, that a very small error in the stipulated changes in hardware weight, produced pressure drop or temperature rise would either totally nullify or perhaps even reverse the outcome relative to preference in maintaining the same pressure drop or the same temperature rise. The problem is more germane to PFS and ultimately the decision will be made on this basis.

(9) Cost

(a) Hardware

There are not significant cost differences in the nozzle assembly that can be identified with location of the coolant inlet manifold. Because of relatively higher complexity associated with the manifold located at area ratio of 5:1, it is reasonable to expect this version to be somewhat more expensive.

(b) Mission

For simplicity, it will be assumed that the allowable payload increase for one way payload type missions is 300 lb and for the round trip mission 108 lbs.

This, when equated to cost per pound of payload in orbit represents savings as illustrated below.

OPERATING COST CHANGE

<u>Manifold Location</u>	<u>ONE WAY PAYLOAD</u>		<u>ROUND TRIP PAYLOAD</u>	
	<u>5:1</u>	<u>24:1</u>	<u>5:1</u>	<u>24:1</u>
Program				
7 Flights/year	Ref \$1,000,000/year		Ref \$ 370,000/year	
35 Flights/year	Ref \$3,000,000/year		Ref \$1,090,000/year	

Thus, a strong basis exists for locating the coolant inlet manifold at area ratio of 24:1.

c. Evaluation

Each element contributing to rendering a decision relative to selection of the coolant inlet manifold location examined, favors the location of area ratio of 24:1.

d. Recommendation

Place the coolant inlet manifold at area ratio of 24:1.

4. Selection of One-Piece Primary Nozzle or a Nozzle/Skirt Cryogenically Cooled Subassembly

a. Available Options

The title of this sub-trade study clearly states what the options are.

A one-piece unit construction of the cryogenically cooled nozzle is one interfacing mechanically with the pressure vessel on one end and at area ratio of 24:1 with the graphite nozzle extension on the other.

A two-piece subassembly would be comprised of a primary, cryogenically cooled nozzle interfacing with the pressure vessel on one end and interfacing at some location with a skirt on the aft end. The skirt would be extended to area ratio of 24:1 to interface with the graphite skirt extension.

The purpose of introducing a cryogenically cooled skirt into the system is to provide an opportunity to substitute this item with a simulator for R-1 testing---a system to be operated without a

diffuser and at the same time to retain no flow-separation capability. Thus, the separation plane between the primary nozzle and the skirt has to be such as to permit attachment of a simulator with a contour that generates a non-separating operation without shock formation at the simulator wall. It has been established that these conditions can be satisfied by changing contour beginning with area ratio 5:1. Thus all subsequent considerations will be related to this location.

b. Method of Evaluation

As in the previous section certain elements were selected for examination if and to what extent they may influence selection of either option under consideration. Should such elements point to the selection contrary to the objectives of R-1 system operation, then the effects of R-1 will be examined for acceptability of such effects. The purpose here, however, is to define an optimum configuration for the flight engine. Elements selected for examination are as follows:

Fabrication Complexity
Pressure Drop
Weight
Reliability
Effect on Payload
Cost

(1) Fabrication Complexity

The difference between the two options is the presence of flanges on flow crossover passages in the two-piece concept as shown in Figure 22. The flanges are used for transferring the coolant flow from the skirt to the primary nozzle. Should the final evaluation show that a two-piece concept is desirable, a design trade study will be

ONE PIECE VS TWO PIECE NOZZLE SKIRT
NOZZLE SKIRT JOINT

FIGURE 22

limited to evaluation of principle involved rather than design detail. The two surfaces on each side of the interface require a minimum of 32 finish to make the seals effective. Two major seals are required. One to preclude internal leakage of the coolant, the other to eliminate external leakage. In addition 72 seals are needed, one under each bolt head.

None of these would be required in one-piece nozzle construction. However machining and grooving operations of a longer one piece nozzle are envisioned to be more difficult.

Also, the two piece nozzle and skirt fabrication can be accomplished in parallel, while the one piece nozzle will require a longer fabrication time. It is difficult to quantify these differences. Therefore, a preference will be based on other factors.

(2) Pressure Drop

It has been previously established that a crossover manifold at coolant velocities associated with location of 5:1 causes approximately 15 psi of pressure loss. This penalty can be eliminated in a one-piece nozzle construction.

(3) Weight

It has been previously established that the weight of flanges and bolts is 100 lb. This penalty can be eliminated in a one piece nozzle construction.

(4) Relative Reliability

Seven modes of failures have been selected for ranking in comparing the two concepts. Figure 23 graphically depicts how a two-piece construction rates on a scale from 0 to 10 compared with a one

piece-nozzle. A brief paragraph addressed to each mode of failure along with stated effect on the system is given. On overall basis the one-piece unit nozzle was rated 3-4 times more reliable than a two-piece construction. This is reflected in reliability totals.

One-Piece Nozzle	61
Two-Piece Nozzle/Skirt	18

(5) Safety

There are some safety hazards associated with the two-piece construction. These have to do with potential external leaks. Such leaks, if developed during ground testing although may not jeopardize the safety of personnel, may cause a premature shutdown. This observation is believed to be applicable to the R-1 tests where a diffuser is not available.

(6) Payload

Combining the penalties in pressure drop and weight previously identified as to exist in the two piece construction, and equating these to payload, the following results:

Influencing Factors	<u>PAYLOAD CHANGE - LB</u>	
	<u>One-Piece Construction</u>	<u>Two-Piece Construction</u>
Crossover Pressure Drop (15 psid)	Ref	-200
Flange and Bolt Weight (100 lbs)	Ref	-200
TOTAL		-565

The disadvantage of a two-piece nozzle/skirt concept is evident.

:

ONE PIECE VS TWO PIECE NOZZLE

RELIABILITY AND SAFETY COMPARISON FOR
ONE PIECE VS. TWO PIECE NOZZLE

FAILURE MODE

1. Internal seal failure at flange connecting 2 piece nozzle sections. Will cause cold H_2 to enter hot gas stream

<u>One Piece</u>	<u>Reliability</u>	<u>Two Piece</u>	<u>Reliability</u>
No connecting flange no failure.	10	Failure to deliver required flow rate to reflector.	2

System Effects: Thrust vector control problem and loss of I_s .

2. External seal leakage at flange connecting 2 piece nozzle. Causes H_2 leakage to atmosphere.

<u>One Piece</u>	<u>Reliability</u>	<u>Two Piece</u>	<u>Reliability</u>
No connecting flange.	10	Same as above.	3

System Effects: Thrust vector control during space operation. Fire hazard during ground test. Loss of I_s .

3. Bolt Structural failure at connecting flange.

<u>One Piece</u>	<u>Reliability</u>	<u>Two Piece</u>	<u>Reliability</u>
No connecting flange.	10	1) One bolt failure causes internal and external leak. 2) More than one bolt failing results in loss of skirt. 3) Possible structural failure of nozzle caused by asymmetric thrust loads when bolts fail.	2

System Effects: 1) Same as above.
2) Significant loss of I_s caused by reducing ϵ from 100:1 to nozzle/skirt joint.
3) Catastrophic engine failure due to loss of skirt.

FAILURE MODE

4. Bolt seal failure causing external cold H₂ leak.

<u>One Piece</u>	<u>Reliability</u>	<u>Two Piece</u>	<u>Reliability</u>
No connecting flange.	10	Failure to deliver all H ₂ to reflector.	3

System Effects: Thrust vector control problem, loss of I_s. Fire hazard during ground test.

5. Structural failure of flange joint.

<u>One Piece</u>	<u>Reliability</u>	<u>Two Piece</u>	<u>Reliability</u>
No additional stress.	10	Flange joints add discontinuity stress to membrane stress and jacket wall.	2

System Effects: Loss of I_s. Possible catastrophic engine failure

6. Coolant leak at end cap braze joints.

<u>One Piece</u>	<u>Reliability</u>	<u>Two Piece</u>	<u>Reliability</u>
Two sets of end caps required.	5	Four sets of end caps required. Nozzle will not deliver required coolant to reflector if leakage occurs.	3

System Effects: Coolant injection into hot gas stream could cause thrust vector control problem and loss of I_s.

7. Excessive coolant channel wall temp near end caps.

<u>One Piece</u>	<u>Reliability</u>	<u>Two Piece</u>	<u>Reliability</u>
Same problem on both, however, half as many end caps in one piece nozzle.	6	Coolant stagnation at end caps causes unknown thermal effects in tubes near end caps. This thermal effect could lead to tube burnout and leakage of coolant into hot gas stream.	3

Reliability Totals: 61 18

(7) Cost

(a) Hardware

As previously stated, a two-piece nozzle construction requires more machining in the flange areas, whereas a one-piece requires more fabrication time. These differences and others such as tooling costs were expressed in dollars below.

HARDWARE COST COMPARISON
(CRES 347 NOZZLE)

	<u>5:1 Nozzle with 24:1 Skirt</u>	<u>24:1 One- Piece Nozzle</u>
Total Nozzle Fab Cost per Unit	\$ 352,000	\$ 448,000
Skirt Fab Cost per Unit	\$ 168,000	
Total Cost for 19 Nozzles	\$9,880,000	\$8,512,000
Additional Tooling for longer Nozzle		\$ 50,000
Skirt Tooling Cost	\$ 265,000	
R & M Tooling for Skirt	\$ 125,000	
Total Cost for 19 Nozzle Assemblies	\$10,270,000	\$8,562,000
Additional Skirt Extension Costs	Ref	Ref
Nozzle Cost Savings	Ref	\$1,708,000

This comparison shows that the unit costs of a one piece nozzle is approximately \$70,000 less expensive than a subassembly made up of a separate nozzle and skirt. The total savings of \$1,708,000 during the course of the program makes a one-piece nozzle construction very appealing.

(b) Mission

Payload loss of 565 lb associated with a

two-piece nozzle/skirt concept translates itself into dollar value as follows:

<u>PROGRAM</u>	<u>ONE WAY PAYLOAD</u>	<u>ROUND TRIP PAYLOAD</u>
7 Flights/year	-\$1,940,000/year	-\$690,000/year
35 Flights/year	-\$5,700,000/year	-\$2,020,000/year

Thus, this much savings can be realized by adopting a one-piece nozzle.

c. Evaluation

(1) Examination of manufacturing complexities did not provide quantitative basis for preference of a one-piece or a two-piece nozzle.

(2) From a pressure drop point of view a one-piece nozzle is superior. It could be operated at 15 psi less pressure drop than a two-piece subassembly, or such savings in pressure drop can be traded for increase in coolant temperature rise. Either approach provides more energy at the turbine inlet compared with a two-piece subassembly.

(3) One-piece nozzle is 100 lbs lighter than a two-piece version.

(4) Relative reliability and safety strongly favor a one-piece nozzle. A 3:1 advantage over a two-piece nozzle is indicated.

(5) Analyses have shown that payload considerations decisively favor a one-piece nozzle.

(6) A clear cut advantage, both in hardware cost and mission cost, of a one-piece assembly has been shown.

C

Thus, with the exception of inconclusive results pertaining to manufacturing aspects, quantitative evaluation shows an undisputed superiority of a one-piece cryogenically cooled nozzle.

d. Recommendation

Incorporate a one-piece nozzle into the system.

B. ANCILLARY STUDIES

C

In contrast with Section III.A. which dealt with the major aspects of the nozzle assembly configuration, each having to do with engine performance, weight, payload, etc., this section deals with nozzle design parameters which do not have a strong impact on how the engine works, but nevertheless cannot be completely divorced from the overall picture.

Also, while Section III.A. was Engine PDR oriented, this section is Component PDR oriented. Thus, each aspect herein considered is subject to a more detailed, separate quantitative design study which will be performed and published in due time.

The purpose here is to show how, rather to what extent certain design selections beneficial to the nozzle tend to benefit the system. For this reason, the discussions here will be qualitative in nature, as opposed to the quantitative treatment imparted to the major sub-trade studies.

C

Finally, because the requirements stated in Section III.B. are predominantly germane to the nozzle assembly configuration, requirements pertinent to the elements subject to consideration in this section will be so stated.

1. Nozzle-to-Pressure Vessel Flange and Connecting Bolts Cooling System

a. Requirement

(1) Dissipate, by convective cooling, heat generated by nuclear fluxes in the nozzle flange mating with the pressure vessel and in the bolts connecting the two members.

(2) Circumferential temperature distribution within the reflector inlet plenum shall be such as to provide a deviation from the mean temperature no greater than $+14$ and -11°R .

b. Problem

Determine optimum means of satisfying the requirement.

c. Available Options

Evaluation of choices will be limited to consideration of a cooling system similar to the one used in the XE assembly and an alternate described below.

(1) Cool the flange mating with the pressure vessel and the connecting bolts with coolant supplied through lines external to the nozzle assembly (XE version).

(2) Integrate cooling of the flange mating with the pressure vessel and the connecting bolts with the nozzle cooling circuit.

Figure 24 depicts the two systems. The picture on the left shows the nozzle coolant channels to be the source of coolant supply for the flange. The picture on the right (XE version) shows that an

NOZZLE - PRESSURE VESSEL FLANGE AND BOLT COOLING SYSTEM CONCEPT COMPARISON

INTERNAL COOLANT
FEED DESIGN

EXTERNAL MANIFOLD
COOLANT FEED

END VIEW OF
BOLT COOLANT SYSTEM

INTERNAL FEED
COOLING SYSTEM

EXTERNAL FEED
COOLING SYSTEM

external coolant supply is required to feed the manifold for distribution within the flange. Figure 25 shows cross sections of the two systems. It is readily evident that the internal feed provides more flange cooling passages and a greater redundancy in supplying the coolant to the bolts.

d. Evaluation

(1) Redundancy/Reliability

(a) Flange Passage Blockage

The external feed cooling system (XE type) provides one coolant passage into each bolt. A blockage of any one of these while may not cause a catastrophic failure, certainly will cause some temperature rise resulting in a potential loss of pretorque. Assuming that the passage was blocked completely, reverse flow of hydrogen from the reflector inlet plenum will provide a source of external leakage through an undertorqued bolt.

By contrast, the internal feed cooling system provides double the amount of coolant passages (two for each bolt), thus a blockage of any single one will be of no consequence. At the same time, inasmuch as coolant is extracted from each and every nozzle coolant channel, flow distribution in the flange channels remains unaffected.

(b) Coolant Supply Blockage

Unless the number of coolant supply lined feeding the external manifold was equal to the number of coolant passages in the nozzle, the reliability of the external feed system cannot be equal to the internal coolant feed system. Practical considerations place the limit on the number of external coolant supply lines ranging from 3 to 6,

each containing a flow control orifice. A blockage of any one of these will reduce the amount of coolant delivered to the flange by an amount ranging from 1/3 to 1/6---a significant percent. At the same time, a potential blockage of any of the coolant channels has neither been enhanced or reduced, nor the consequence of such event has been altered.

By contrast, if the coolant supply into the flange depends on the coolant flow through the nozzle coolant channels, a blockage of a coolant channel at the most can affect the coolant supply to the flange by less than 1/2 of a percent (there are 216 coolant channels in the nozzle).

Also internal feed coolant system as suggested, in the event of blockage of one nozzle coolant channel, would make a change of flow distribution in the flange imperceptible. This could not be said for the external feed cooling system.

(c) Loss of external coolant supply line.

This possibility represents a most significant mode of failure in terms of consequences. Approximately 20 lbs/sec of flow was calculated as lost externally in the event of line rupture. Resulting depletion of coolant in the nozzle and the pressure vessel mating flange can lead to catastrophic failure.

Thus, adoption of the internally fed coolant into the nozzle flange enhances the reliability of the engine without introducing deleterious effect otherwise.

(2) Manufacturing Aspects

No discernible differences in fabrication, flow time or cost have been identified.

(3) Flow Mixing at the Reflector Inlet

Relative to the requirement number (2)---In the externally fed coolant system, the coolant enters the flange at $60 \pm 2^{\circ}\text{R}$. The coolant dissipates the heat generated in the flange and bolt and in the process the coolant temperature is raised by about 17° to $77 \pm 2^{\circ}\text{R}$. The nozzle coolant discharge temperature is 210°R . Mixing takes place within the reflector inlet plenum and assuming no appreciable coolant maldistribution within the flange the requirement can be met.

In the internally fed coolant system, the coolant enters the flange at 163°R . Heat transfer from the flange to the coolant causes this circuit to discharge into the plenum at 180°R . The nozzle coolant discharge temperature is 203°R . The mixing process needs to be only as efficient as the ΔT of 23°R requires. By contrast elimination 133°R temperature difference is involved in the externally fed system.

Thus, there cannot be any question that the internal feed cooling system will more readily satisfy the flow mixing requirement.

e. Recommendation

On the basis of the foregoing comparison, it is recommended that an internal feed system for the nozzle-pressure vessel mating flange and bolt cooling be incorporated.

2. Nozzle Coolant Channels Construction Aft of Area Ratio 5:1

a. Requirement

None exists as to the type.

b. Problem

Provide a justifiable selection and incorporate in Data Items E-105 and C-002.

c. Available Options

The comparison below will be limited to two concepts. Additional concept, if any, will be considered under a separate design study.

(1) Concept one is based on oval or round tubular coolant channels, longitudinally brazed to each other and held together by external reinforcing hoop bands.

(2) Concept two is to extend the "U" tube construction to the nozzle/nozzle extension interface.

Figure 26 is a pictorial rendition of the two concepts under consideration.

d. Evaluation

The evaluation of the two concepts reduces itself to a "designer's choice" category. Engineering arguments generated to date do not provide a decisive support of one in preference of the other. It is hoped that a detailed study now in progress will provide a meaningful basis for confirming the herein expressed preference or provide sound arguments to the contrary.

SKIRT CONCEPTS
OPTIONS

OVAL TUBE

U-TUBE

FIGURE 26

(1) Weight

The "U" tube construction was found to be 55 lbs heavier than the oval type version.

(2) Reliability

The mode of failure analysis identifies four areas of significance where the two concepts differ.

(a) External, hot gas leakage is possible within the oval tube construction. If loss of tube-to-tube braze material is propagating the effects may range from generating small side thrust to catastrophic.

(b) Internal, Coolant Leakage - Possibility of pinhole leakage, although remote exist in both concepts. Loss of braze material between coolant channels is another source of internal leakage in the "U" tube construction. Because of self film cooling effect--- the consequence of this event is much less significant than loss of braze material in the oval tube construction.

(c) The oval tube construction requires tube splicing in the vicinity of area ratio 12:1 to 16:1. Thus, the aft end of the nozzle would have 432 tubes compared with 216 where splicing is not required.

Splicing is not required in the "U" tube version.

(d) In the oval tube construction, all transition points from "U" tube to oval at area ratio 5:1, at the tube splicing

point, transition to adapters at the aft flange involves either weldments or additional brazing area is contributing to degradation of reliability.

(3) Vibratory and Flow Separation Loads

No differences were found in capability to withstand vibration induced or flow separation induced loads. Either concept exhibits adequate structural characteristics.

Unless more in depth study will provide a cause for reversal, reliability aspects generate a preference for a "U" tube construction.

e. Recommendation

It is recommended that "U" tube construction of the nozzle be extended to the graphite extension interface.

3. Coolant Inlet Manifold Geometry

This item is subject to a detailed engineering study which will be completed and documented in support of Component PDR. The material presented here is only indicative of problems involved and provides a tentative selection. An in-depth study may provide basis for selection of a different geometry than the one presented here.

a. Requirement

Maintain coolant flow rate through the coolant channels within ± 5 percent of the $\left(\frac{\text{Total Coolant Flow Rate}}{\text{Number of Channels}}\right)$ value.

b. Problem

Select coolant inlet manifold geometry that gives most probability to satisfy the requirement.

Recognizing that grooves' machining, coolant channel fabrication, and assembly tolerances produce changes in impedance that results in flow rate distribution variation of 3.5% from the average (historical data), only 1.5% of coolant flow fluctuation can be allocated to a change in pressure differential driving force. Thus, the permissible circumferential distribution of pressure drop across the coolant channels cannot be allowed to be greater than 3.0% ($\Delta P = K (\dot{w})^2 / 2g z$) where:

$$\dot{w} = \text{lbs/in}^2\text{-sec}$$

$$g = 32.2 \text{ ft/sec}^2$$

$$z = \text{lb/ft}^3 \text{ (density)}$$

Thus, in a system of approximately 180 pounds pressure drop, the static pressure must be kept circumferentially constant within 5.4 psi. It follows then that the pressure distribution within the coolant inlet manifold must be maintained at 1400 psi (about) ± 5.4 psi.

c. Available Options

Figure 27 shows sketches of four coolant manifold shapes that can be considered for adoption in the NERVA nozzle. These include a constant cross section model, a tapered version for a controlled velocity profile, one shaped so as to eliminate pressure recovery which usually occurs someplace within 25 to 40 degrees from the inlet and one where velocity can be kept constant with no recovery.

COOLANT INLET TORUS GEOMETRY

OPTIONS

Figure 27 - Coolant Inlet Torus Geometry, Options

d. Evaluation

Admittedly, the tapered manifolds provide an opportunity for weight reduction. However, it may be difficult to tailor the taper effectively enough to maintain a pressure profile constant within 5.4 psi. On the other hand, a constant cross section geometry designed for entrance velocity not in excess of 150 ft/sec, if made large enough will behave like a plenum where neither the velocity effects or frictional effects are present. Thus, with such a geometry, a constant circumferential manifold pressure is more readily achievable.

At this time, this consideration is judged to be of greater importance than weight saving consideration.

e. Recommendation

In order to avoid jeopardizing the coolant channel reliability by excessive flow maldistribution, it is recommended that a constant cross section coolant inlet manifold be adopted in the nozzle assembly.

4. Effect of Nozzle Coolant Flow Rate Swing

This section within the intent of this document will be limited to consideration of technical feasibility and assessment of effects the coolant flow rate swing will have on the engine. A separate document treating this subject parametrically with respect to design variables inclusive of effects on reliability will be issued at a later date.

Reader should disregard communications or informations received prior to this date as related to feasibility of this approach.

Prior assessments were made on flow swing range which has been rendered obsolete and did not include considerations related to coolant channel buckling phenomena.

a. Requirement

Nozzle shall be designed to operate from 100% power to 60% power at coolant flow rates decreasing by 9.2 lb/sec at the end of life at 100% power and by 10.8 lb/sec at the end of life at 60% power from the respective values available at the start of life.

b. Problem

(1) Demonstrate the technical feasibility of achieving the requirement and identify associated penalties if any, or:

(2) Provide basis and technical justifications for deleting or altering the requirement.

c. Options Available

None exercised.

d. Feasibility and Effects Examination

In order not to jeopardize the reliability of the coolant channels, a design was generated for minimum coolant availability at the End of Life assuming 100% power and spec extremes.

This coolant channel geometry was then examined for increase in pressure drop resulting from higher coolant availability at the Start of Life at 100% power and for effects in terms of pressure drop,

temperature rise, maximum wall temperatures and coolant Mach numbers at other power levels. All pertinent information is listed in the attached table titled "Coolant Flow Rate Swing Effects Comparison". For the purpose of ease of scrutiny by the reader, elements constituting the most severe operating conditions or undesirable affects have been bracketed in this table.

As expected, the maximum gas side wall temperature at the nozzle throat of 1502°R occurred at 100% power at the End of Life when the coolant availability is reduced. Also as expected, the maximum pressure drop occurs at 100% power at the Start of Life when maximum coolant is available. With respect to the nozzle wall temperature at the throat at other power levels no inconsistencies were observed.

However, in the barrel portion of the nozzle, approximately 150°F wall temperature rise was noted. The computed values were reexamined, declared valid but unacceptable.

The noted temperature rise is a result of the coolant flow swing. While the coolant channels were designed with primary consideration of the throat zone allowing for 10% coolant flow degradation at 100% power, 25% degradation during throttling affects more the zone (barrel portion) where the resistance to heat transfer is governed to a lesser degree (compared with the throat region) by the gas side heat transfer coefficient and therefore the heat transfer rate is more sensitive to changes on the coolant side.

The wall temperature in the barrel section was declared unacceptable because an excess of 900° with 300° uncertainty in the mean wall temperature violates the non-buckling criteria.

COOLANT FLOW RATE SWING I CTS COMPARISON

<u>RUN</u>	<u>P_c</u>	<u>T_c</u>	<u>$\dot{w}_T$</u>	<u>$\dot{w}_c$</u>	<u>P_{in}</u>	<u>T_{in}</u>	MAX <u>$\bar{M}$</u>	MAX <u>T_{wg}</u>	<u>ΔP</u>	<u>ΔT</u>	<u>BARREL TEMP</u>	
											<u>MAX</u>	<u>MEAN</u>
LOBE090	456	4302	93.2	73.7	1330	62.0	.25	1502	140.3	141.0	1136	917
091	456	4302	93.2	82.9	1340	63.0	.27	1470	165.9	127.9	1087	821
092	364	4302	74.7	63.9	1200	63.0	.23	1401	115.2	140.1	1064	870
093	364	4302	74.7	54.3	1185	63.0	.21	1447	92.8	159.6	1131	947
094	273	4302	55.7	44.2	750	56.0	.26	1330	91.6	157.5	1061	907
095	273	4302	55.7	33.4	720	56.0	.25	1409	66.2	198.3	1191	1052
096	273	4302	55.7	44.2	930	58.0	.21	1331	74.8	160.1	1057	902
097	273	4302	55.7	33.4	910	58.0	.19	1414	53.1	199.6	1188	1049

A subsequent coolant channel geometry designed to maintain the coolant channel mean wall temperature in the barrel section at 900°F resulted in the nozzle pressure drop at the Start of Life at 100% power of 216 psid. No changes in wall temperature were introduced elsewhere. Thus, the basic feasibility to produce a design compatible with the stated requirement has been established.

The aspect of the associated pressure drop penalty posted will be examined on the engine level.

There are several options that will be examined separately in process of coolant channel design optimization, the minimum of which will be:

(1) Reduction of coolant channel wall thickness at the nozzle throat to reduce pressure drop.

(2) Increase of coolant channel wall thickness and thereby reduce the radius to thickness ratio to compensate for increase in wall temperature resulting from lower velocity accompanied by lower pressure drop.

(3) Reduction of coolant flow rate swing at 60% power and evaluate parametrically pressure drop saving on this basis.

e. Conclusions and Recommendations

(1) Feasibility to generate a nozzle design capable of satisfying the requirement of operating at specified coolant flow swing has been demonstrated.

(2) Because of pending investigation related to the coolant channel optimization, a recommendation for altering the requirement

cannot be made at this time. It is evident, however, that reduction of the coolant flow rate swing at 60% power will be beneficial up to 50 psi reduction in pressure drop penalty.

C. NOZZLE ASSEMBLY FOR R-1 TEST SERIES IN TEST CELL "C"

Consistent with Technical Directive 70-10, for the purpose of planning and this discussion, it is assumed that a diffuser will not be available for R-1 test operations.

This section is devoted to the review of recommendations made in preceding chapters in light of the above assumption. In particular, it will be examined how a flight configuration nozzle with a 24:1 area ratio may effect the R-1 system as compared with other possibilities.

1. Requirement

The R-1 nozzle assembly shall include a skirt simulator that provides for test conduction without flow separation at 40% power and higher and generates the same change in enthalpy of the coolant as the flight configuration without formation of shocks inside of the assembly.

2. Problem

a. Determine feasibility of a skirt simulator design to satisfy the requirement, or

b. Provide justification for deleting the requirement.

Relative to Problem (a), it would be desirable to provide a skirt simulator with imparting as little change as possible to the flight configuration. Thus, it was attempted to modify the contour beginning at

area ratio of 6:1. This resulted in a pressure profile as shown in Figure 28, Contour X. The positive pressure gradient up to area ratio seven is indicative of shock presence and results from a too rapid change in the contour turning angle. The same is true although to a lesser degree of the design designated as Contour E, for which the contour alteration was begun at area ratio of 5:1. Contour G is unsatisfactory because of lack of pressure gradient between area ratio of 6:1 and 9:1 which is indicative of potential flow oscillations seeking a gas dynamic equilibrium along the nozzle wall. In an attempt to adjust the contour, the nozzle wall turning angle change rate was over corrected and produced a similar phenomenon downstream of area ratio 9:1.

A compromise rendering the desired solution lies someplace between contour G and H. Additional iterations are required to define it. Each of the two contours, however, provides the desired enthalpy change in the coolant at area ratio of 11:1.

Thus, the feasibility to construct a skirt simulator has been established.

Relative to problem (b), it is necessary to evaluate other possibilities.

3. Available Options

Figure 29 is a pictorial rendition of options that will be considered. Option designated by I simply states that the flight configuration nozzle when fired into the atmosphere would separate at area ratio of 14:1. The point of separation was determined with the aid of Figure 30 where data on flow separation of gases of various isentropic expansion factors (otherwise known as gamma) was plotted. The consequences of separation will be discussed in the subsequent section.

WALL PRESSURE PROFILE IN NERVA SKIRT SIMULATOR

R-SERIES TEST OPTIONS

I - "E" CONFIGURATION
NO DUCT

II - "E" CONFIGURATION
WITH DUCT

III - SKIRT SIMULATOR
NO DUCT

FIGURE 29

MODIFIED FLOW SEPARATION CURVE
(Reference: Report No. 2024, Figure 5)

AFTC-TR-61-53
Aerojet Report No. 2024
Contract No. AF 33(616)-5552
June 1961

Option II shows that no-flow-separation condition, similar to engine testing, can be obtained with testing in a diffuser duct. Presence of the diffuser not only causes the nozzle to flow full but generates conditions suitable for inclusion in the R-2 and R-3 systems of the TPA development hardware.

A question can be asked what if a diffuser and scrubber are not available for the R-2 and R-3 series? Should not then a nozzle assembly be made available that satisfies the operational requirements and provide a meaningful test bed for the TPA testing? The answer is that a simplification such as a skirt simulator may provide (Option III) may cause bigger problems associated with 10 hours testing of R-2 and R-3 (each) at full power without a scrubber.

4. . Evaluation

Items for consideration:

a. Effects Induced by R-1 operation.

- (1) Reflector Inlet Temperature
- (2) Core Inlet Temperature
- (3) Nozzle Pressure Drop
- (4) Nozzle Flow Separation Loads

b. Test Data Value compared with the Engine Operation

c. Cost

- (1) Tooling
- (2) Test Hardware
- (3) Facilities

The table below gives a comparison of most of these items for the three options under consideration.

R-1 VS ENGINE OPERATION COMPARISON
(STEADY STATE CONDITIONS)

<u>PARAMETER</u> (1)	<u>OPT.I</u> <u>24:1 NOZZLE</u> <u>NO DIFFUSER</u>	<u>OPT.II</u> <u>24:1 NOZZLE</u> <u>WITH DIFFUSER</u>	<u>OPT.III</u> <u>11:1 SKIRT</u> <u>SIMULATOR</u> <u>NO DIFFUSER</u>
Nozzle ΔT_B	SOL 113°	SOL 127°	127°
Nozzle ΔP (psid)	SOL 160	SOL 180	SOL 180
Nozzle Max T_{wg}	1542°R	1500°R	1500°F
Reflector Inlet Temperature	-14°	Same	Same
Core Inlet Temperature			
With Turbine	-10°	Same	Same
No Turbine	+13°	+27°	+27°
Vibration & Flow Separation Loads	Highest	Lower	Lowest
Applicability of Data to Engine Reflector	APPL	APPL	APPL
Core	APPL	APPL	APPL
Nozzle	APPL	APPL	APPL
Cost			
Tooling	Ref	Ref	+90K
Facilities	Ref	Most	Ref

(1) Ref: Computer Runs LOBE 036, 065, 067

The values of bulk coolant temperature rise was given for coolant flow availability at the start of life. Additional 14°R of temperature rise will take place at the end of life. The coolant temperature rise posted for the flight configuration tested without the diffuser reflects the assumption that there will be no heat transfer past the separation plane.

In reality, some convective effect produced by combustion with atmospheric oxygen will take place in addition to radiation from the hot gas. Thus, the stipulated deficiency in temperature rise of 14°R is a pessimistic value. Consistent with this assumption, there will be an accompanying effect in the pressure drop through the coolant passage.

The coolant channel wall temperature at maximum heat flux location would be 1542°R compared with 1500°F in engine or ground test simulator configuration. This difference stems from lower cooling efficiency of the fluid at lower bulk temperature. This small difference is quite acceptable.

It is of interest to know what effects a nozzle with separating flow will have on the reflector inlet.

Should there be a TPA present, a lower temperature at the turbine inlet will result in a lower temperature outlet. If a TPA is not present, unless a heat exchanger was available, the energy equivalent to 27° of fluid temperature will have not been removed from the system, as shown for Options II and III. However, a separated nozzle is deficient in temperature at the reflector outlet by 14°R ; thus, the net difference at the core inlet would be an excess of 13°R . These differences in the fluid state points through the nuclear subsystem were considered of little consequence and were accepted by WEC.

In regards to vibratory and separation loads, it has been determined that neither the stiffness or flow separation is a problem as far as operation in engine-type facility is concerned.

Similar analyses for testing without a duct are still in process, but from the magnitude of loads established for the duct environment, it appears that loads about one order of magnitude higher in R-1 operation can be accepted.

At worst, additional reinforcements can be provided. Thus, these effects do not cause a concern.

The value of test data in terms of applicability for diagnostic and post test evaluation, in light of the small difference induced, was judged to be equal for all three of the options.

As far as costs are concerned, there would be no difference in the test article unit cost in any of the three options. However, a spare unit of the simulator configuration would be required in addition to a spare for the subsequent R-series test support.

Different, and therefore, additional tooling would be required to produce the simulator.

The biggest cost increased (not assessed) would be in the facility cost for option II where availability of a diffuser and scrubber was stipulated.

Thus, it does not appear that a flight configuration nozzle could not be used for R-1 testing.

A skirt simulator, however, although eliminates some thermodynamic and state points differences, which incidently were agreed to as acceptable, would be a two of the kind built, a prime and a spare. The spare in good likelihood would end up as an unused item that could not be applied to the support of the remaining reactor or engine development test program.

5. Conclusions

a. It is feasible to design a skirt simulator to satisfy the requirement.

b. A flight configuration nozzle assembly will not significantly affect the R-1 test operations and results. Therefore, justification for deletion of the requirement has been established.

6. Recommendations

Stated below in order of preference are recommendations relative to nozzle configuration and mode of R-1 test conduction.

a. Conduct an R-series in Test Cell "C" equipped with a diffuser and incorporate a 24:1 area ratio flight configuration nozzle into the test assembly.

b. Conduct R-1 tests in Test Cell "C" without a diffuser and incorporate a 24:1 area ratio nozzle, reinforced as required, into the test assembly.

c. Conduct R-1 test in Test Cell "C" without a diffuser using a 11:1 area ratio skirt simulator.

V. RECOMMENDATIONS AND CONCLUSIONS

The analyses and results stated throughout this document were based on technical information assembled from December 1969 through April 1970. Unless the technical variables involved change materially, these results are expected to be valid; it is, therefore, recommended that the following key features be incorporated into the NERVA nozzle assembly:

1. Nozzle assembly terminal area ratio of 100:1.
2. Extend the cryogenically cooled portion of the nozzle assembly out to an area ratio of 24:1, and attach the nozzle extension at this location.
3. Place the coolant inlet manifold at the area ratio of 24:1.
4. Eliminate the skirt and construct a one-piece cryogenically cooled nozzle.
5. Nozzle flange mating with the pressure vessel and connecting bolts cooling system integrated with the nozzle coolant channels flow circuit.
6. Extend U-tube coolant channel construction up to the interface with the nozzle extension.
7. Constant cross section area of the coolant inlet manifold.
8. Nozzle coolant channels designs for coolant flow rate swing.

Relative to R-1 system it is recommended that the requirement for a no-flow-separation nozzle be removed and a flight configuration nozzle with a 24:1 area ratio be used in all R-series tests.

VI. REFERENCES

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