FR-18323-2
CR-174953
1 JULY 1985

CONVOLUTED NOZZLE DESIGN FOR THE RL10 DERIVATIVE IIB ENGINE

FINAL REPORT

Prepared Under
Contract NAS3-22902
for
National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

Prepared by
Pratt & Whitney Aircraft
Government Products Division
P.O. Box 2691, West Palm Beach, Florida 33402

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SECTION I
INTRODUCTION

This document presents the results of a study for a convoluted nozzle design for the RL10-IIB engine. This study is part of an overall "Extendible Nozzle Tradeoff Study" conducted by Pratt & Whitney (P&W) for the NASA Lewis Research Center, in accordance with Technical Direction No. 1 to Contract NAS3-22902. The convoluted nozzle is a design which is proprietary to Bell Aerospace. This portion of the overall tradeoff study was conducted by Bell Aerospace under contract to P&W.

The convoluted nozzle was also compared to other nozzle configurations by P&W. The results of this comparison are provided in P&W report No. FR-18358-2 (NASA CR 174858).

SECTION II
DISCUSSION

The design of the convoluted nozzle for the RL10-IIB engine is an innovative approach for extendible nozzles. It provides for a lightweight nozzle configuration with specific advantages in packaging which allow for a larger nozzle within a given engine length. This is accomplished without the complexity of multiple, nested nozzle extensions. The Study Report for the Convoluted Nozzle Design is provided as-received from Bell Aerospace (Appendix A) and provides a description and analysis of this concept as it applies to the RL10-IIB engine.

Pratt & Whitney provided the nozzle interface requirements, nozzle contours, envelopes, etc. necessary for Bell Aerospace to conduct this study. The configuration and analyses produced by Bell Aerospace were not critiqued by P&W.

The study requirements for Bell Aerospace, as established by P&W, represent an attempt to provide information on the convoluted nozzle for a valid comparison between it and various other nozzle configurations to be evaluated in the Extendible Nozzle Tradeoff Study. As the overall nozzle tradeoff study was being conducted, P&W realized that these requirements may have unjustifiably penalized the convoluted nozzle configuration. For this reason, supplemental information was requested from Bell Aerospace. This information is included as received in Section 2.6. Pratt & Whitney also requested information for the addition of a gas-deployed skirt to the convoluted nozzle. This information is also included in Section 2.6. A discussion of this information is provided in the Extendible Nozzle Tradeoff Study final report P&W report No. FR-18358-2 (NASA CR 174953).

One particular configuration discussed in the Bell Aerospace study was not consistent with the other nozzle configurations that were studied, and was not included in the overall P&W nozzle tradeoff study. A discussion of this configuration is provided in Appendix A, Section 5.3. This configuration included the installation of a fairing, which involved a reduction in length of the RL10 primary nozzle by four inches. This and other modifications were not permitted for the other nozzles. Therefore, P&W adjusted the convoluted nozzle data to reflect a common base for comparison purposes. Hence, Bell Aerospace's mechanism for aft end installation of the convoluted nozzle was not considered in the overall nozzle tradeoff study. This does not have a major impact on the results of the study.

All other comments relative to the convoluted nozzle and the results of the overall nozzle tradeoff study are provided in P&W report No. FR-18358-2 (NASA CR 174953).

APPENDIX A
STUDY REPORT — CONVOLUTED NOZZLE DESIGN FOR THE RL10 ENGINE DERIVATIVE IIB

The following report was prepared by Bell Aerospace Textron for P&W in May 1985. It is provided here as-received.

Bell Aerospace TEXTRON
Division of Textron Inc.

Post Office Box One Buffalo, New York 14240

STUDY REPORT AND SUPPLEMENT

CONVOLUTED NOZZLE DESIGN FOR THE RL10-IIB ENGINE

Report No. 8881-933004

May 1985

Prepared for

PRATT & WHITNEY AIRCRAFT GROUP
West Palm Beach, Florida

Bell Aerospace TEXTRON

Division of Textron Inc.

Post Office Box One Buffalo, New York 14240

STUDY REPORT AND SUPPLEMENT CONVOLUTED NOZZLE DESIGN

FOR THE RL10-IIB ENGINE

Report No. 8881-933004

May 1985

Lee Carey

L.F. Carey
Project Mgr./Tech. Director

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1.0 INTRODUCTION

The Convoluted Nozzle is an otherwise conventional refractory metal nozzle extension that is formed with a portion of the nozzle convoluted (i.e., turned inside out) to stow the extendible nozzle within the length of the rocket engine. It has been successfully developed and characterized in technology and engineering development programs for the Minuteman Third Stage Motor and the Trident 1 (C4) Second and Third Stage Motors (References 1 through 4).

For these ballistic missile applications the Convoluted Nozzle (CN) was deployed by a system of four gas driven actuators. For spacecraft applications the optimum CN may be self-deployed by internal pressure retained, during deployment, by a jettisonable exit closure.

United Technologies Pratt & Whitney Aircraft Government Products Division (P&WA) has included the convoluted nozzle in a study of extendible nozzles for the RL10 Engine Derivative IIB for use in an early Orbit Transfer Vehicle (OTV). This study, requested by NASA Lewis Research Center, has evaluated four extendible nozzle configurations for the RL10-IIB engine. P&WA conducted the study of three configurations of the two position (i.e., nested) nozzle. This included a hydrogen dump cooled metal nozzle and radiation cooled nozzles of refractory metal and carbon/carbon composite construction respectively. P&WA subcontracted the study of the radiation cooled, refractory metal Convoluted Nozzle to Bell Aerospace Textron.

The following is the final technical report of the work performed under P&WA Contract 124211 during the period of 3 Aug. 83 to 31 Dec. 83 (Ref. Work Statement Para. 5.3, Study Report).

2.0 SUMMARY

The objective of this study was to generate and confirm the preliminary designs of Convoluted Nozzles for the RL10-IIB rocket engine and to produce sufficient engineering data to assess CN weight, performance, cost, operating characteristics and programatics (e.g., program risk and schedule).

The approach to this study is summarized in Table 2-1. The study began with a review of the CN design requirements specified by P&WA (see Section 4.0) and the design of the interface between the CN and the RL10-IIB engine. The design requirements, shown in Table 2-2 directed a study baseline CN exit expansion ratio (ε) of 205/1 and limited the maximum CN expansion ratio (to an extended length of 95 in.) to hold the engine length to 150 in. maximum. Three CN mount joint configurations were evaluated to arrive at a baseline interface with the engine.

TABLE 2-1. CN DESIGN STUDY APPROACH

- Requirements Review - Directed Baseline CN Exit ε = 205
- CN/RL10-IIB Engine Interface Study - Selected CN Mount Joint Design
- Deployed CN Thermal/Structural Analysis
- CN Self Deployment Analysis
- Actuator Deployment/Retraction Analysis of CN
- Scaled CN Self Deployed Design To ε = 303
- CN Weight and Performance Comparisons
- Cost Analysis - Baseline 205ε CN

TABLE 2-2. RL10-IIB ENGINE CN DESIGN REQUIREMENTS

Engine Thrust		15,000 lb
CN Thrust		1,300 lb
Engine Lengths		55 In. CN Stowed, 150 In. CN Deployed
Area Ratios		205ε Baseline, Max. ε at Max. Length
Nozzle Contours		Supplied By P&WA
Chamber Pressure		400 psia
Mixture Ratio		6.0
CN Static Pressures		0.87 → 0.21 psia
CN Service Life	Mission	1,500 Sec in 7 Firings
	Qual Test	9,000 Sec in 20 Firings
	Goal	36,000 Sec in 180 Firings

2.1 CN INTERFACE WITH RL10-IIB ENGINE

The first CN mount joint configuration was a light weight flange and thrust ring arrangement for installing the CN from the forward end of the engine. This configuration requires CN installation at the engine level before the engine is mated to the Centaur vehicle and therefore limits access to the engine for servicing on the vehicle.

Aft end installation of the CN on the engine in the vehicle was considered to be clearly desirable for engine servicing access on the vehicle and for best handling and shipping of the CN. The second mount joint configuration was therefore designed to provide aft end installation, but in a complicated fashion and at a considerable increase in mount joint weight. The third mount joint configuration incorporated a fairing to provide simple aft end installation at low weight and was therefore selected for the study baseline CN design. This mount joint consists of a stainless steel mount flange that is brazed to the RL10 primary nozzle, a titanium alloy thrust ring that is welded to the CN and a 4 in. long columbium alloy fairing as shown in Figure 2-1.

CN installation is accomplished by advancing the stowed CN over the RL10 engine (from the rear) until the thrust ring flange (with Grafoil static seal) meets and aligns with the mount flange on the primary nozzle. The CN is then sealed and secured to the primary nozzle by threading 80 bolts into nut plates on the mount flange shown in Figure 2-1. The fairing is then installed and secured by threading 20 flush head screws into the nut plates in the webs on the thrust ring. The purpose of the fairing is to hold the RL10-IIB engine exhaust gas boundary layer in place and smooth the gas flow across the large CN mount joint discontinuity required to provide for CN installation entirely from the aft end of the engine - after the engine has been installed (and serviced) on the

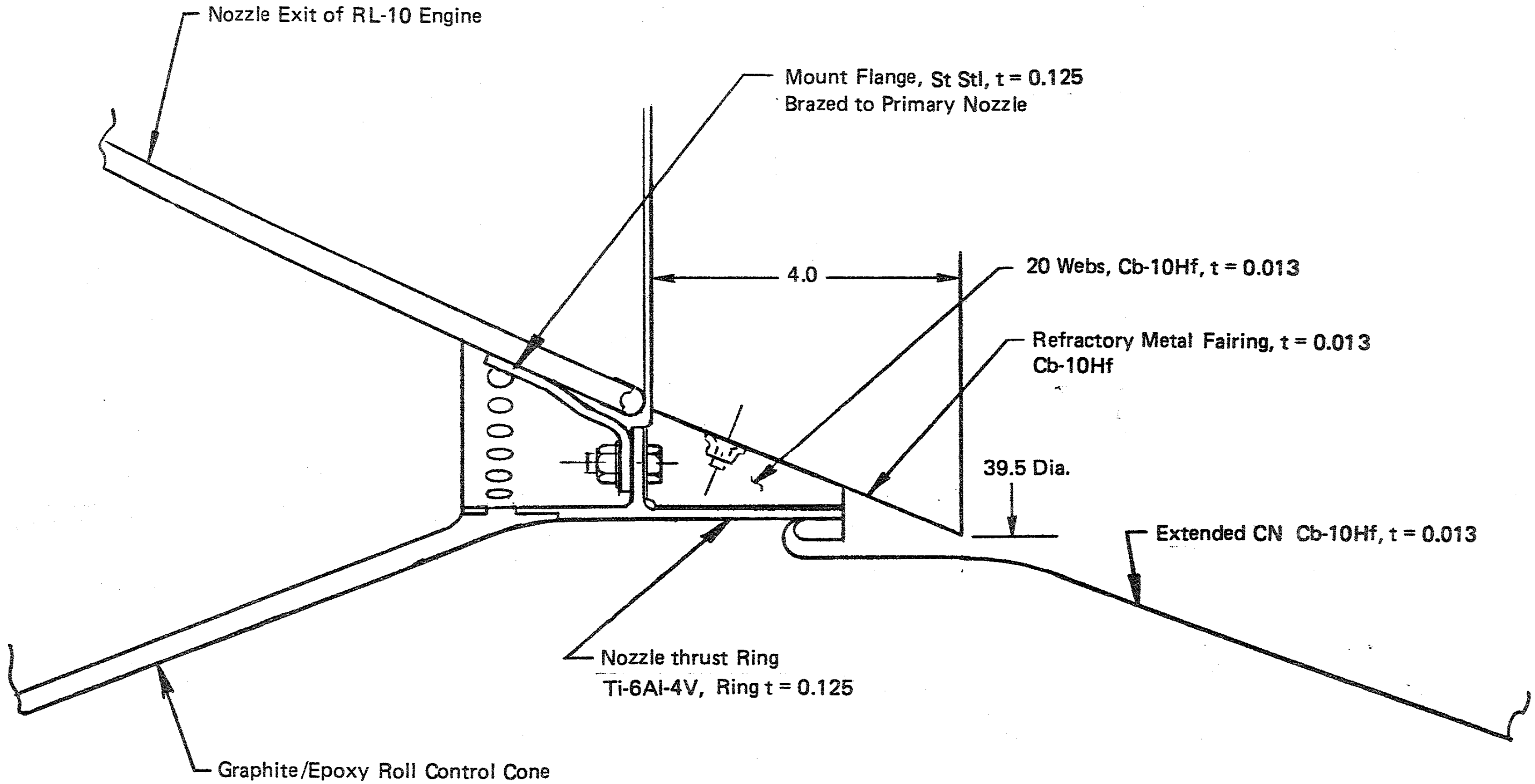


Figure 2-1. Convoluted Nozzle (CN) Mount Joint Config. No. 3A
Selected Study Baseline Design

Centaur vehicle. After the fairing is installed, the CN assembly is completed by attachment of the outer section of the 2 piece deployment cover with a nylon hinge cable.

2.2 BASELINE CN DESIGN, $\varepsilon = 205$

The study continued, as shown in Table 2-1, with the thermal/structural analysis of the deployed CN to confirm the design and define the minimum thickness of the nozzle that will be deployed by rolling inside out from a convoluted configuration to a rigid extension of the primary nozzle. The CN self deployment analysis was then conducted to define the optimum CN thickness profile, roll control structure requirements, deployment loads and deployment cover and subsystem requirements. By a process of design refinement and optimization during the course of these analyses, the conceptual design of the baseline 205 ε Convoluted Nozzle developed into the preliminary design shown in Figure 2-2.

The baseline 205 ε CN design consists of a modular assembly of convoluted nozzle, thrust/mount ring, roll control cone, warm gas generator, cover separation fuse and deployment cover of rubber impregnated nylon cloth as shown in the upper half of Figure 2-2. The RL10 engine is omitted from this figure to enhance clarity. Details of the thrust/mount ring interface with the RL10 engine are given in Figure 2-1 for the deployed CN configuration shown in the lower half of Figure 2-2.

Deployment may be initiated by 28 Vdc supplied to the igniter of the warm gas generator (solid propellant charge) by a single command discrete. The warm gas (T_c~2000°F) pressurizes the CN and flows out through the small apex vent of the cloth exit cover (sized to vent the CN during shuttle ascent to LEO). The CN starts rolling at an internal pressure of approximately 0.6 psia, continues rolling as the pressure rises above this value, and completes rollout at a pressure of approximately 2 psi in a burn rate/grain design controlled interval of approximately 7 sec. The gas generator burns out in 10 sec. (after consuming the design margin excess propellant) with the CN pressurized to approximately 2.6 psi. The pressure will then begin to decay by continued gas loss through the apex vent, dropping below 1.0 psi at 25 sec into the deployment sequence. The integral confined burning fuse is then ignited by 28 Vdc to burn away the nylon cloth cover attachment to the CN. The nylon cloth cover is then ejected by residual gas pressure in the CN to leave a simple, rigid refractory metal nozzle extension in place on the RL10-IIB rocket engine. This self deployment sequence is summarized in Table 2-3.

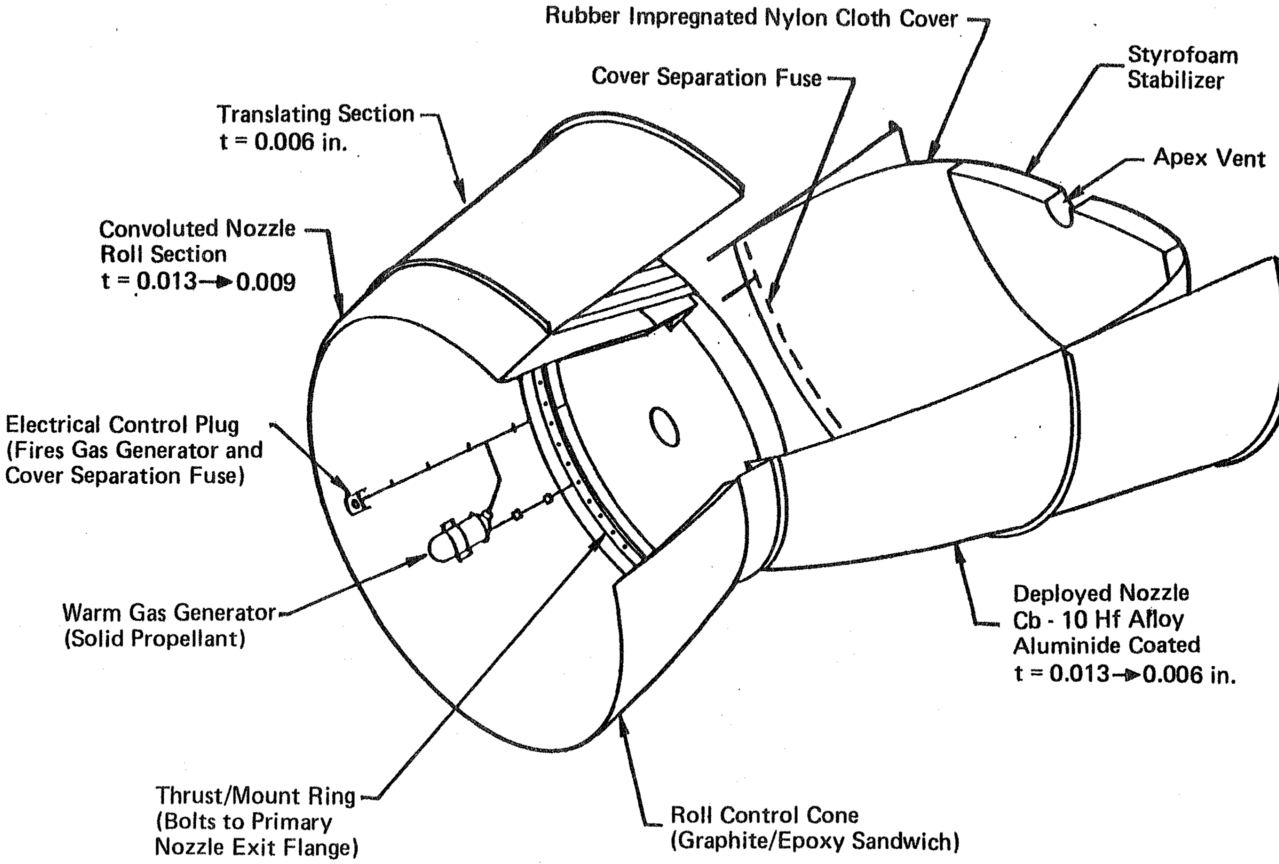


Figure 2-2. Baseline 205 ε CN Self Deployed System

TABLE 2-3. CN SELF DEPLOYMENT SEQUENCE

- 28 Vdc supplied to igniter of warm gas generator
- Warm gas pressurizes CN and flows out through small apex vent of cloth exit cover (sized to vent CN during ascent to LEO)
- CN starts rolling at an internal pressure of approx. 0.6 psia and completes rollout at a pressure of approx 2 psia in a controlled time interval of approx. 7 sec.
- Gas generator burns out at 10 sec (with CN pressurized to approx. 2.6 psia)
- 28 Vdc supplied to cover separation fuse at 25 sec or later (to permit CN pressure to decay below 1 psi)
- The fuse then burns away the nylon cloth exit cover attachment to the CN and the cover is ejected from the CN by residual gas pressure (from the warm gas generator burnout)
- The remaining CN is a simple rigid refractory metal nozzle extension that is ready for engine firing

The operating weight of this baseline 205 ε CN is 77.6 lb after deployment (and ejection of an 8.5 lb cloth cover) and the specific impulse gain is 16 sec. (i.e. 459.8 seq compared to 444 sec. for the standard RL10 engine operating at a mixture ratio of 5.0 with a fixed nozzle $\varepsilon = 57$). This CN is designed for a mission consisting of a single deployment to be followed by extensive firing use and reuse in space based OTV service of the RL10-IIB engine. The service life goal of 36,000 sec of operation in 180 firings is believed to be achievable with the columbium alloy and aluminide coating system selected for the Convoluted Nozzle (on the basis of successful application of this same alloy and coating system on the nozzle extension of the Apollo Service Module Engine and the LEM Descent Engine).

2.3 MAXIMUM PERFORMANCE CN DESIGN, $\varepsilon = 303$

The maximum performance increase obtainable with the Convoluted Nozzle (or any other nozzle extension) was determined by the deployed nozzle contour supplied by P&WA and the length limitation specified in the design requirements (Table 2-2). Layout studies showed that this contour would limit the expansion ratio (ε) to 303/1 within the 150 inch length limit for the engine with CN extended. In other respects this CN design is a scale up of the self deployed 205ε CN as shown by comparison in Figure 2-3.

The design features and operating characteristics of the maximum performance 303ε CN are identical to the 205ε baseline CN except for numerical details of dimensions, thicknesses and deployment pressures. After deployment and ejection of a 12.6 lb cloth cover, the operating weight of the maximum performance 303ε CN is 130.4 lb. and the specific impulse gain is 22 sec. The 303 ε CN therefore provides 6 more sec. of specific impulse than the 205 ε CN for a weight increase of only 53 lb. It was concluded that this 303 ε design is the maximum performance Convoluted Nozzle that can meet the design requirements of Table 2-2.

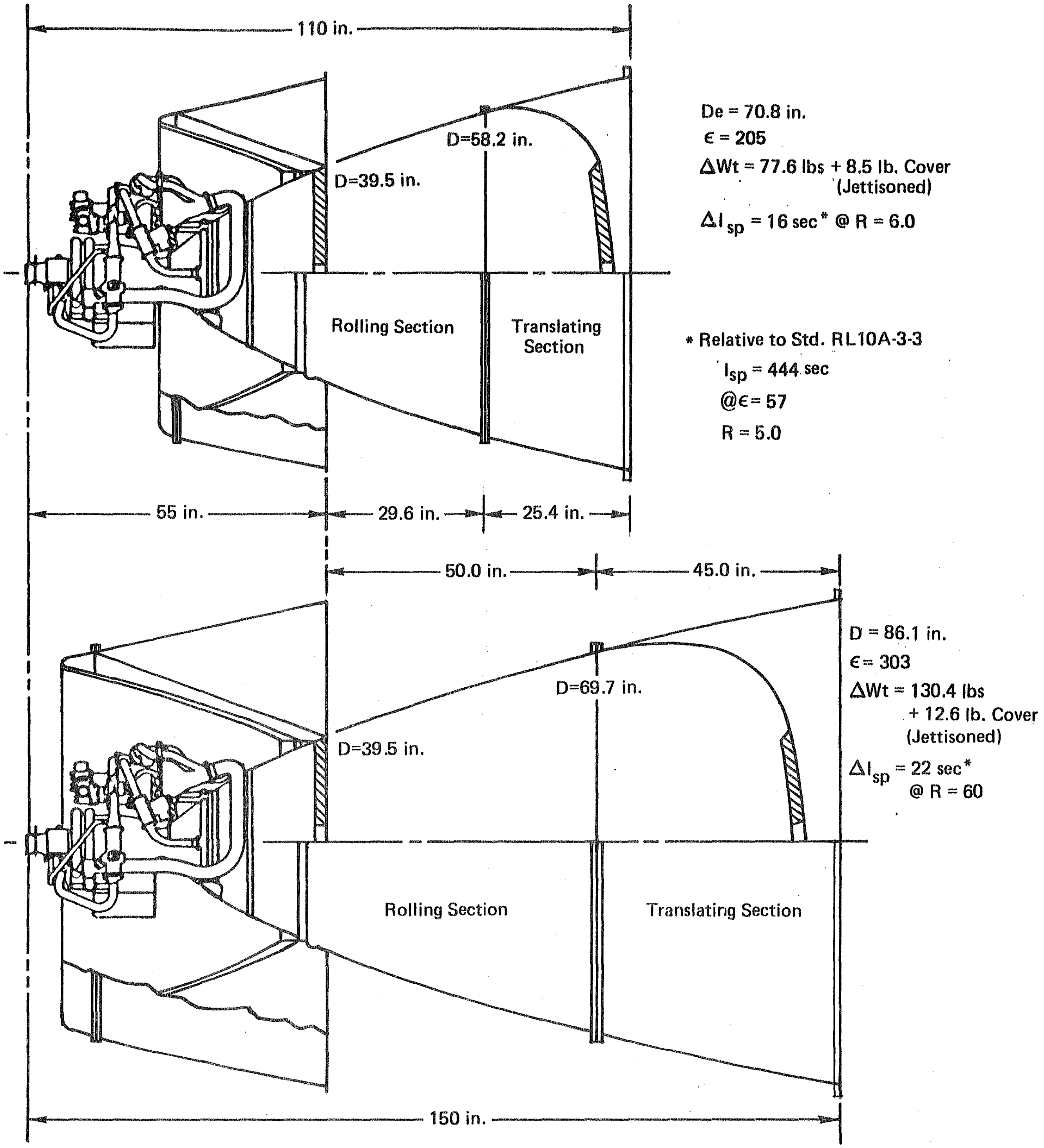


Figure 2-3. Max. Performance 303ϵ Convoluted Nozzle Self Deployed System

2.4 EXTENDIBLE/RETRACTABLE CN DESIGN, $\varepsilon = 205$

The extendible and retractable CN is a kit modification of the baseline 205 ε Convoluted Nozzle design to add nozzle retraction capability when required by the mission. The deployment cover and gas generator is replaced by a gas actuator kit as shown in Figure 2-4 for missions consisting of a single deployment followed by extensive firing use and then retraction (for OTV stowage in the Space Shuttle) in ground based OTV service of the RL10-IIB engine.

This extendible/retractable modification kit design was derived from the actuator deployment analysis of the CN. It consists of three double-acting gas actuators, deployment rings to distribute actuator forces on the CN shell, actuator brackets for trunnion mounting and an actuator support ring that forms a torsion box with the actuator support and roll control cone as shown in Figure 2-4. The torroid shaped torsion box is loaded in torsion by the eccentric actuator forces and no deployment loads are transmitted to the RL10-IIB engine. The CN shell, thrust/mount ring and mechanical interface with the RL10-IIB engine is identical to the baseline CN.

The working gas for deployment and retraction is hydrogen at turbine inlet pressure. The working gas is controlled by a 4-way solenoid valve (not shown in Figure 2-4) and 1/4 in. titanium gas lines to the extend and retract ports of the double-acting actuators. Gas flows in these lines only during a deployment or retraction cycle. The CN is deployed during the first few seconds of the first firing and then retracted during the last few seconds of the last firing of the mission. The deployed CN is free standing and does not require continued actuator pressure or mechanical detents to react the thrust produced by the CN. The feasibility of CN deployment and retraction during engine operation has been demonstrated by the Minuteman Third Stage Convoluted Nozzle (Reference 2).

The specific impulse gain of the extendible/retractable CN is the same as the baseline 205 ε CN but the installed and operating weight of this CN is 145.8 lb. This amounts to a weight increase of 68 lb to obtain the retraction capability. For this reason the actuator deployed version of the CN is recommended as a modification kit to be used only on those missions that require CN retraction.

However, missions requiring CN retraction are ground based and the CN can therefore be refurbished and reused. In the context of the CN life requirements (of Table 2-2) the only part of the extendible/retractable CN with limited life is the rolling section of the CN shell. Tests of small scale (5 in. dia.) Convoluted Nozzles have demonstrated up to 3 mission cycles of deployment and retraction but the reusability of the rolling section must be determined empirically for each CN design. It is estimated that the rolling section of the CN shell will have to be replaced for every second or third mission cycle of the extendible/retractable Convoluted Nozzle.

2.5 CONCLUSIONS

The Convoluted Nozzle design study for the RL10-IIB rocket engine was completed as planned (ref Table 2-1) and the numerical results are summarized in Table 2-4 for the 3 design cases studied. The cost analysis for the baseline self deployed 205 ε CN design, development and production indicates that all three designs are cost effective improvements in the RL10-IIB engine capability and that unit costs for CN flight

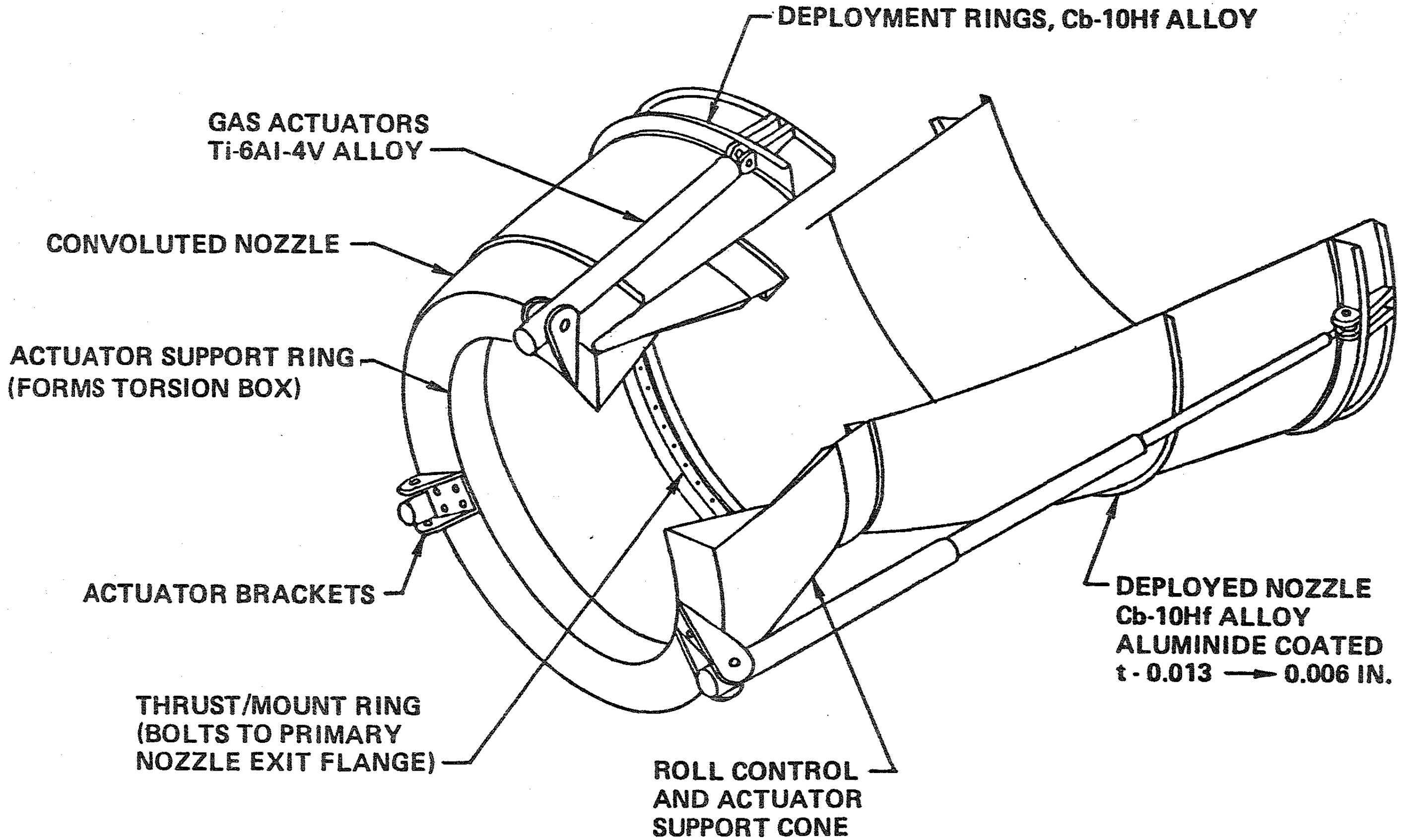


Figure 2-4. Alternate 205 ϵ CN Extendible/Retractable System

TABLE 2-4. WEIGHT AND PERFORMANCE COMPARISON

Convoluted Nozzle Size and Configuration*	Self Deployed CN Systems 205ε CN	Self Deployed CN Systems 303ε CN	Ext./Retractable 205ε CN
Primary Nozzle Mount Flange Ass'y			
Primary Nozzle	-9.6	-9.6	-9.6
CN Mount Flange	12.2	12.2	12.2
Fasteners (80 Bolts)	1.5	1.5	1.5
	4.1	4.1	4.1
Convoluted Nozzle Ass'y			
Fairing and Webs	2.9	2.9	2.9
Thrust Ring Flange	17.1	17.1	17.1
Roll Section	21.0	54.6	21.0
Translating Section	12.4	16.1	12.4
	53.4	90.7	53.4
Deployment Equipment			
Roll Control Cone	9.5	20.8	9.5
Deployment Rings	7.8	9.8	15.2
Gas Generator	2.8	5.0	-
Act. Support Ring	-	-	18.5
Actuators (3)	-	-	39.0
Act. Brackets (3)	-	-	3.1
Act. Gas Controls	-	-	3.0
	20.1	35.6	88.3
Max CN Operating Weight	77.6 lb	130.4 lb	145.8 lb
Specific Impulse Increase**	16 sec	22 sec	16 sec

* All CN's designed for simple aft end installation at the vehicle level.
** Relative to Std. RL10 engine I_{sp} = 444 sec at 57ε (with R = 5.0)

operations can be as low as $97,000 for the baseline CN. The conclusions derived from the study data are summarized in Table 2-5.

TABLE 2-5. CONCLUSIONS

- A low cost lightweight (77.6 lb after deployment) Convoluted Nozzle (CN) can provide an expansion ratio (ϵ) of 205/1 on the RL10-IIB engine.
- The 205 ϵ CN can be modified with a gas actuator kit to provide nozzle retraction capability when required by the flight mission
- The maximum performance CN for the RL10-IIB engine is a 303 ϵ design for a deployed nozzle/engine length limitation of 150 in. (approximately 6 more sec. ΔI_{sp} for approx. 53 lb more CN wt after deployment).
- All these options are cost effective improvements in the RL10-IIB engine capability.
- Enabling technology programs now can provide added confidence and make subsequent CN development a straight forward, short schedule program.

Bell recommends a low cost enabling technology program (or sequential series of programs) to produce the additional technical data base that is needed to enable high confidence/low risk entry into subsequent engineering development and operational use of the Convoluted Nozzle. The major elements of this work are given in Table 2-6.

TABLE 2-6. RECOMMENDED TECHNOLOGY PROGRAM(S)

- Material Property Tests at -300^{o}F: Tensile and Roll Strip Tests
- One Third Scale Self Deployment Evaluation Tests
- Reusability Tests: Deployment/Retraction Cycling
- Small Scale Fire Tests of Aluminide Coated Cb - 10 Hf Nozzle Extensions to Evaluate Life Potential

2.6 STUDY SUPPLEMENT

This supplement to the Convoluted Nozzle design study report was written to record the results of additional design studies conducted in response to suggestions of NASA LeRC and Pratt and Whitney Aircraft.

The additional design studies of the Convoluted Nozzle (CN) were conducted to define design options to improve the method of attaching the CN to the RL10-IIB Engine and to further increase the expansion ratio of the baseline 205 ϵ CN shown in Figure 2-2.

2.6.1 CN Mount Joint Design Simplification

To provide simple aft end installation of the CN at the vehicle level with minimum mount joint weight, the last 4 in. of the RL10 primary nozzle was replaced with a sheet metal fairing in the study baseline CN mount joint design (Figure 2-1). However, the resulting reduction in H_2 heating in the primary nozzle reduces the design margins in the expander cycle of the RL10 engine. Redesign of the CN mount joint was therefore suggested by NASA LeRC to retain current RL10 engine power margins.

The CN mount joint was redesigned to limit the change in the RL10 primary nozzle to the addition of a stainless steel mount flange, brazed in place near the end of the primary nozzle as shown in Figure 2-5. This mount flange mates with the CN thrust ring in lap joint fashion as shown in the figure.

CN installation is accomplished by advancing the CN over the RL10 engine (from the rear) until the thrust ring meets and aligns with the mount flange on the primary nozzle. The CN is then secured to the primary nozzle by threading 80 bolts into nut plates on the mount flange shown in the figure. The design incorporates a double static seal, including a rubber O-ring and a pressure loaded RTV rubber seal applied and cured in place.

This redesigned CN mount joint weighs 5.1 lb more than the faired design it replaces but it has the advantages of minimum change in the RL10 primary nozzle design and successful experience with similar lap joint designs on the C4 Trident Missile CN development program.

2.6.2 Increased CN Expansion Ratio

The CN design study was originally concerned with a baseline 205 ε CN design (for direct comparison with the 2 position nested cone nozzle) and a maximum performance 303 ε CN design that was limited by an engine length limitation of 150 inches with the CN deployed. These two convoluted nozzle designs are compared with each other in Figure 2-3.

P&WA suggested design options to increase the expansion ratio of both CN designs. A Gas Deployed Skirt (GDS) was added to the 205 ε CN to increase the expansion ratio to 274. The GDS and mating ring is secured to the exit lip flange of the CN by 150 bolts. The configuration of the baseline 205 ε CN is not changed.

The engine length limitation was increased to 165 inches with the CN deployed. This allowed the unused stowed CN envelope (see 303 ε CN design in Figure 2-3) to be used to increase the size of the stowed CN. The resulting deployed CN provides an expansion ratio of 330 with an engine length of 165 inches. In all other respects, the design is the same as the 303 ε CN shown in the figure.

The weight and performance of all the CN designs (with the redesigned mount joint) are summarized in Table 2-7.

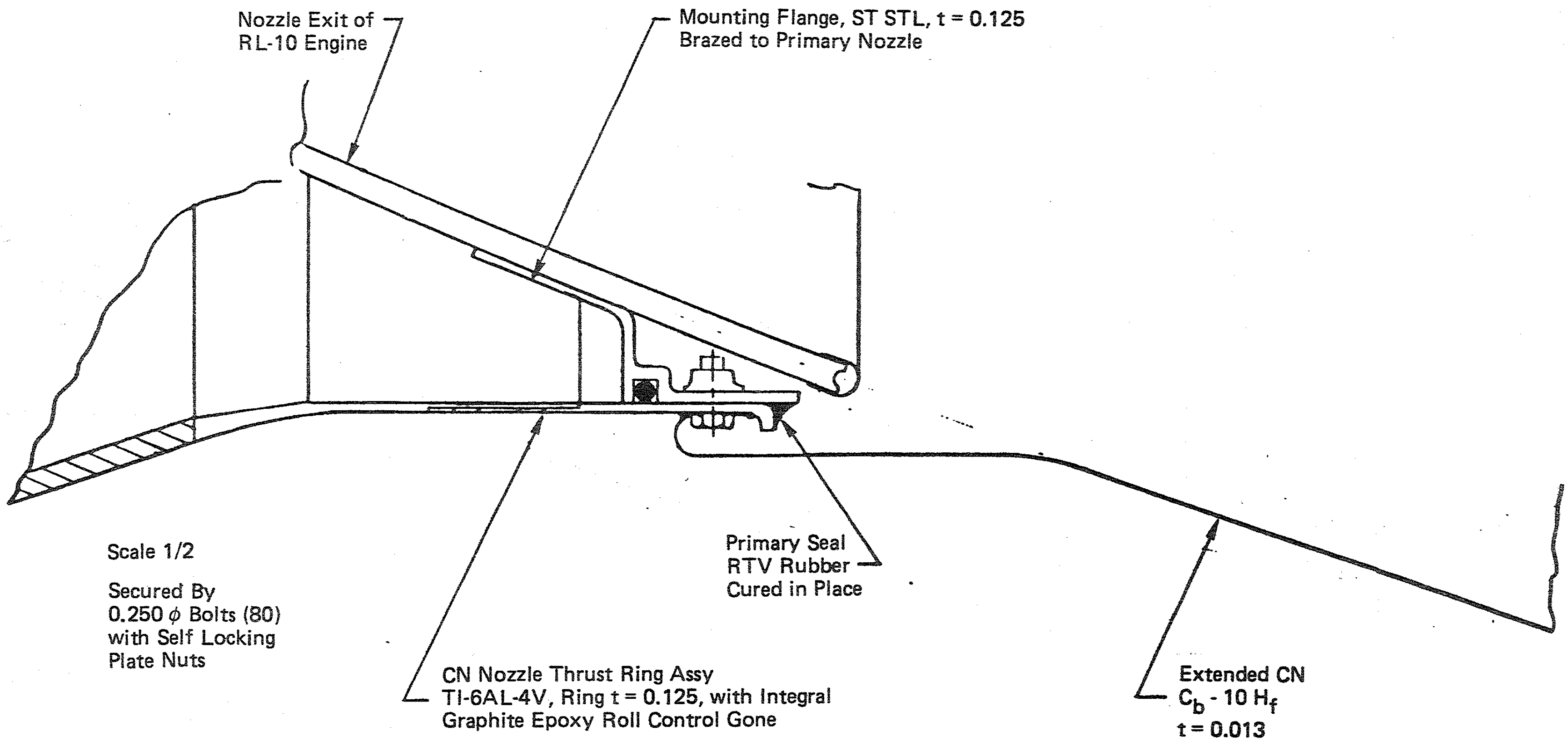


Figure 2-5. Convoluted Nozzle (CN) Mount Joint Config No. 4

TABLE 2-7. WEIGHT AND PERFORMANCE COMPARISON

CONVOLUTED NOZZLE SIZE AND CONFIGURATION*	SELF DEPLOYED CN SYSTEMS				EXT./ RETRACTABLE
	205 ε	274 ε	303 ε	330 ε	205 ε
PRIMARY NOZZLE MOUNT FLANGE ASS'Y					
CN MOUNT FLANGE	19.5	19.5	19.5	19.5	19.5
FASTENERS (80 BOLTS)	1.5	1.5	1.5	1.5	1.5
	21.0	21.0	21.0	21.0	21.0
CONVOLUTED NOZZLE ASS'Y					
THRUST RING	8.2	8.2	8.2	8.2	8.2
ROLL SECTION	21.0	23.1	54.6	60.5	21.0
TRANSLATING SECTION	12.4	13.6	16.1	20.2	12.4
	41.6	44.9	78.9	88.9	41.6
GAS DEPLOYED SKIRT	–	16.7	–	–	–
DEPLOYMENT EQUIPMENT					
ROLL CONTROL CONE	9.5	9.5	20.8	22.6	9.5
DEPLOYMENT RINGS	7.8	7.8	9.8	10.6	15.2
GAS GENERATOR	2.8	2.8	5.0	5.4	–
ACT. SUPPORT RING	–	–	–	–	18.5
ACTUATORS (3)	–	–	–	–	39.0
ACT. BRACKETS (3)	–	–	–	–	3.1
ACT. GAS CONTROLS	–	–	–	–	3.0
	20.1	20.1	35.6	38.6	88.3
MAX CN OPERATING WEIGHT	82.7 LB	102.7 LB	135.5 LB	148.5 LB	150.9 LB
SPECIFIC IMPULSE INCREASE**	16 SEC	20 SEC	22 SEC	23.5 SEC	16 SEC

*ALL CN'S DESIGNED FOR SIMPLE AFT END INSTALLATION AT THE VEHICLE LEVEL. (SEE FIGURE 2-5)

**RELATIVE TO STD. RL10A-3-3 ENGINE I_{SP} = 444 SEC AT 57 ε (WITH R = 5.0)

3.0 CONVOLUTED NOZZLE BACKGROUND

Bell, teamed with United Technologies Chemical Systems Division (UT-CSD), Thiokol, Hercules and Aerojet respectively, has conducted a series of evaluation test and development programs to fully establish the feasibility of this rolling metal nozzle extension for the C4 (Trident I) and Minuteman III motor applications (for Lockheed Missiles and Space Co. and the Air Force Rocket Propulsion Laboratory respectively).

3.1 ACTUATOR DEPLOYED CN

In the case of the C4 missile upper stage motor application shown in Figure 3-1, the deployment system consisted of four actuators (with warm gas generating integral charges in each) to drive deployment rings that are riveted to the exit of the CN. The actuators are bracket mounted to the CN roll control cone and the mount joint with the primary nozzle as shown in Figure 3-1. The CN is deployed by simultaneously firing the four actuator charges. The resulting synchronized actuator extension pulls the CN inside out by rolling the metal off the roll control conic surface. At the end of the CN deployment stroke (as shown in the lower half of Figure 3-1) the actuators lock on snap rings and the internal pressure becomes redundant. With this system the CN may be deployed before or after motor ignition. A test deployment of the C4 Third Stage (T/S) motor CN is shown in Figure 3-2 and, in the course of several CN development programs, convoluted nozzles have been successfully deployed by a variety of actuator systems as follows:

-	Hydraulic Actuators	-	2 Tests, 30 in. dia CN (C4 T/S)
-	N_2 Gas Actuators	-	4 Tests, 30 in. dia CN (C4 T/S) 5 Tests, 45 in. dia CN (MM III T/S)
-	Warm Gas Actuators	-	1 Test, 55 in. dia CN (C3 S/S) with 6 Internal Charge Actuators AP Propellant
	Total	-	18 Successful Tests

A test firing of the C4 Third Stage motor CN on the Thiokol/Hercules Third Stage motor is shown in Figure 3-3. This Ta-10W alloy CN operated successfully at 3200^oF for the 40 sec burn time of the motor. However in the course of several CN development programs, convoluted nozzles have been successfully fire tested with a variety of refractory metals and coating systems as follows:

-	Material Eval. Motors (43 sec Duration)	-	1 Nozzle, Cb-10 Hf, Silicide Coated 2 Nozzles, Cb-10 Hf-10 W, Silicide Coatings 5 Nozzles, Ta-10 W, Silicide, Velvet Black, ZrO_2, HfO_2 Coatings and Uncoated
-	Subscale Motors: (23 sec Duration)	-	1 Nozzle, Cb-20 Hf, Uncoated 2 Nozzles, TA-10 W - 2.5 Hf, Uncoated

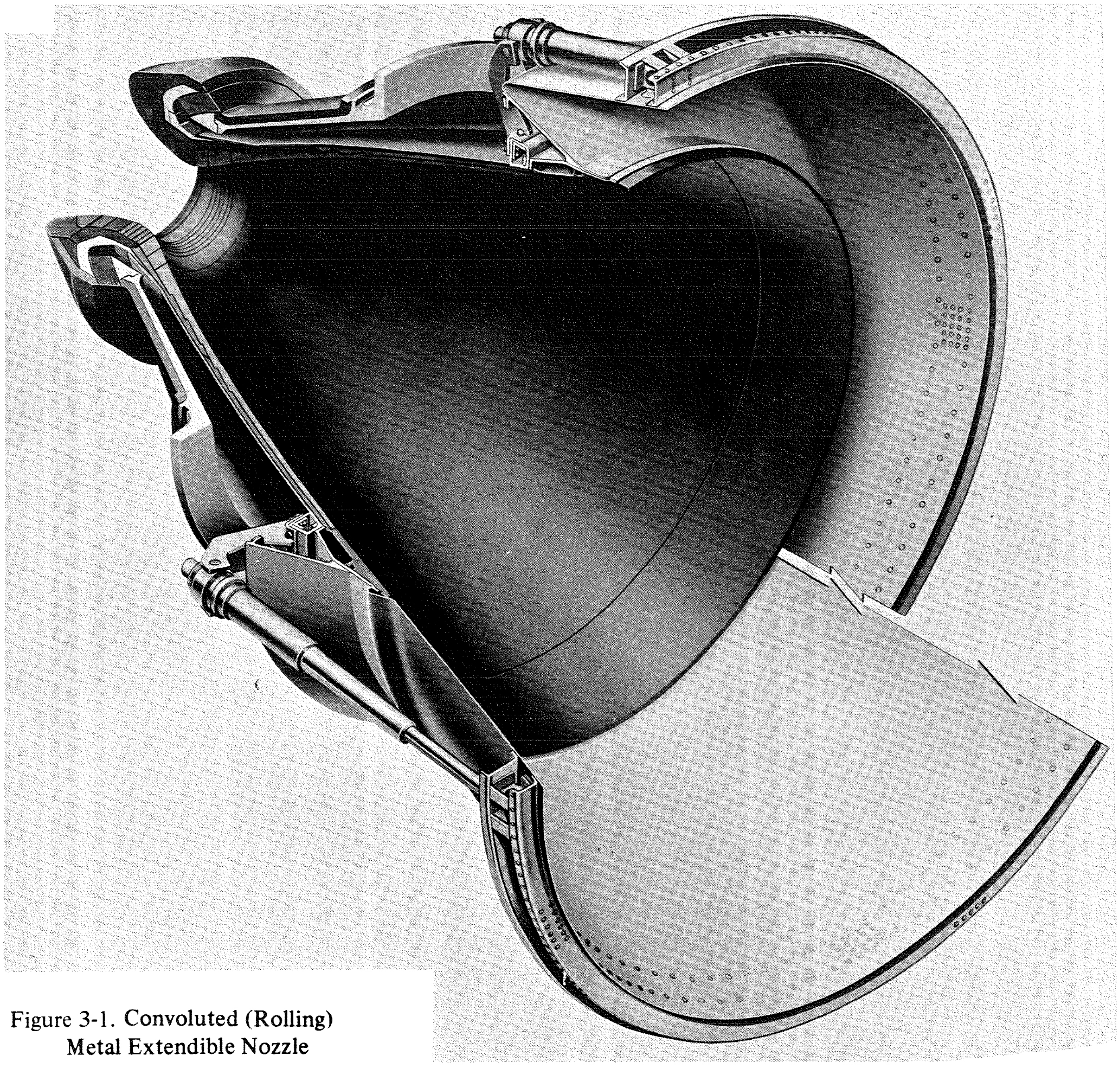
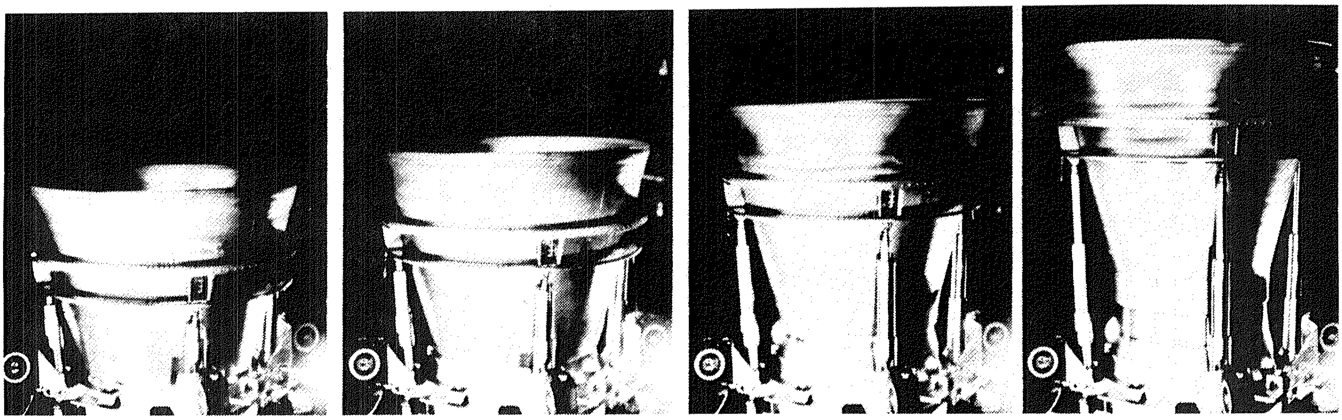


Figure 3-1. Convoluted (Rolling) Metal Extendible Nozzle



0.7 Seconds Action Time

Figure 3-2. Deployment Test of C4 T/S Convoluted Nozzle

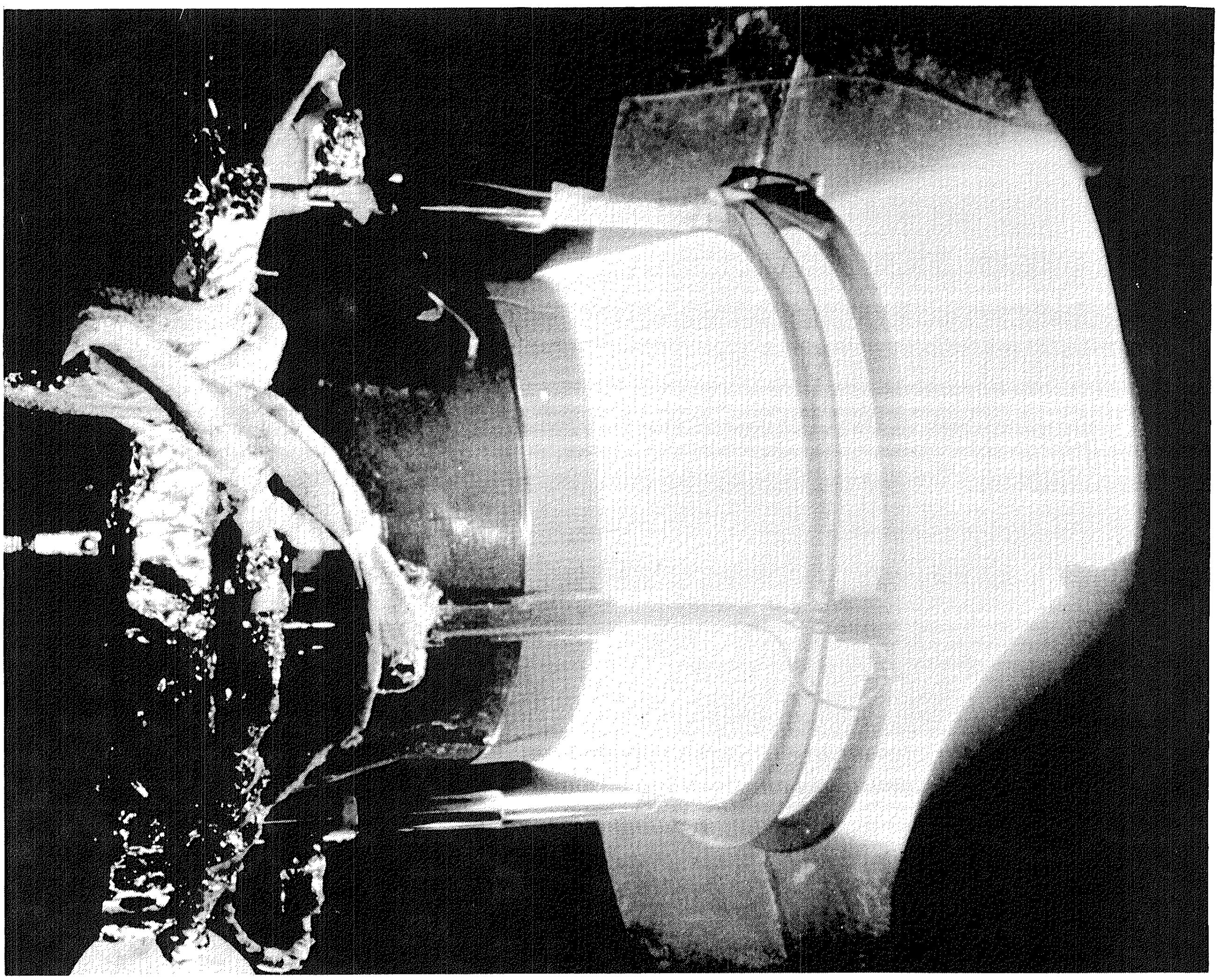


Figure 3-3. 30 in. Ta 10W Convoluted Nozzle Test Firing on C4 Development Motor (Altitude Test Cell J-5 at AEDC)

-	C4 T/S Motors: (54 and 40 sec Duration)	-	1 CN, Cb 10 Hf, Silicide Coated 1 CN, Ta-10 W, HfO_2 Coated and Uncoated Sections
-	MM III T/S Motors: (61 sec Duration)	-	3 CN's, Cb-10 Hf, Aluminide Coated
-	Total:	-	16 Successful Tests

3.2 SELF DEPLOYED CN

For space engine applications where extendible nozzle deployment can always be conducted before (or during) engine ignition, the optimum CN (i.e., max. ε/min. wt.) is usually the self deployed CN. In this configuration the CN exit is sealed with a low pressure cover of rubber impregnated nylon cloth. The convoluted nozzle is deployed to the fully extended position by internal pressurization to a low pressure level. This low pressure, acting over the large nozzle rolling section area, produces relatively large forces which roll the convoluted section through itself from the larger diameters to the smaller diameter. The deployment pressure requried is dependent on the CN thickness which is determined by the firing loads and temperature (i.e., the CN is not over designed for deployment pressure loads). The feasibility of this concept was demonstrated by six successful tests of 12 in. CN's (designed for the MM-III post boost axial engine). The final test of this series is shown in Figure 3-4.

This test with the background grid chart also gave some proof of the self alignment theory for the CN. Since the pressure required to roll the convoluted section is directly proportional to the roll through angle (i.e., between the rolled and unrolled portions) and inversely proportional to the local diameter, the nozzle is self aligning during deployment. For example, if one side should start to lead the opposite side because of material anomalies, it must roll the metal through a larger angle than the opposite side and would advance into a smaller local diameter, both requiring larger rolling forces than available. This would restrict the lead until the lagging side caught up and pressure rose to the value required to continue symmetrical rolling. The rolling forces required are not dependent on roll rate and the CN can be deployed as fast as the gas can be supplied.

The CN design shown in Figure 3-4 was a heavy weight test design incorporating a thick exit flange and mating ring to fasten the rubber impregnated nylon cloth exit cover manually with draw bolts. This was adequate for the feasibility demonstration objective.

3.3 CN FABRICATION AND PROGRAM DATA

In the course of these development programs convoluted nozzles were successfully fabricated by 1) rolling and seam welding, 2) power spinning and 3) shear spinning of columbium and tantalum alloy sheet metal. In addition to demonstrating these 3 basic methods of CN fabrication, the joining of CN elements by EB welding and by riveting was successfully employed.

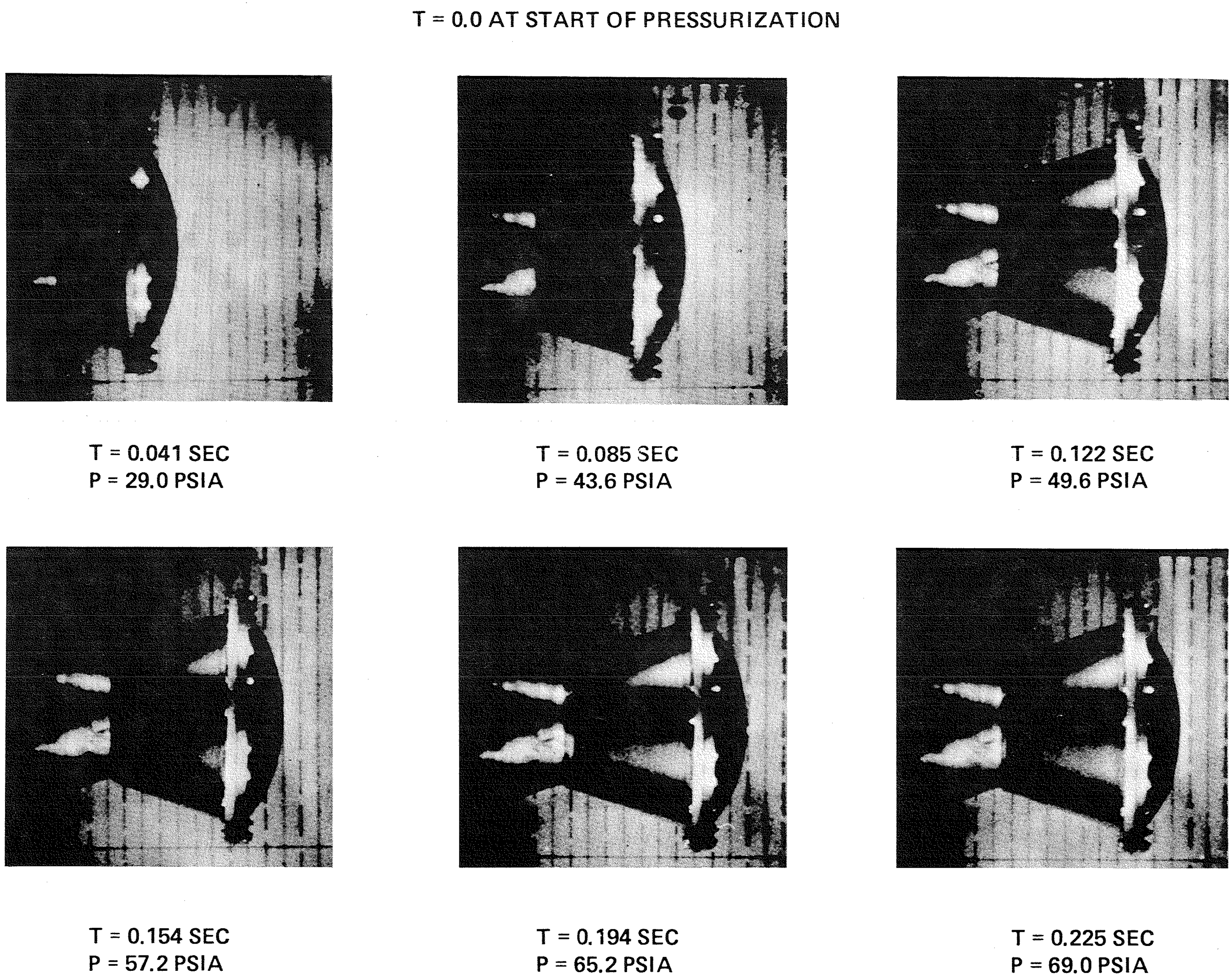


Figure 3-4. Convoluted Nozzle Deployment Test, S/N 7

The data from these programs and studies indicates that the convoluted nozzle concept can offer significant advantages in extendible nozzle design. These advantages include:

- High Performance
  - Maximum deployed expansion ratio and optimum contour

- Minimum Envelope
  - Minimum length packaging for short compact engines

- Low Weight
  - Self deployed, exit cover jettisoned

- High Reliability
  - Inherent reliability of simplicity, no moving seals, actuators or controls

- Low Cost
  - Simple. well proven fab methods

4.0 CN DESIGN REQUIREMENTS

The CN design study for the RL10-IIB engine was conducted on the basis of the following guidelines, ground rules and assessment criteria developed by P&WA in response to a request by NASA Lewis Research Center to evaluate extendible nozzle configurations for the RL10-IIB Derivative Engine.

4.1 GUIDELINES AND GROUND RULES

It was the P&WA objective to obtain sufficient, design and analysis, programmatics, development cost, production cost, risk assessment, performance and weight data to permit an evaluation of four configurations. The four configurations which will utilize identical contour and expansion ratio(s) that must be adaptable to the regeneratively cooled RL10-IIB Engine primary nozzle are:

1. Radiation-cooled nozzle extension of carbon/carbon-composite material.

2. Radiation-cooled nozzle of refractory metal material.

3. Radiation-cooled refractory convoluted metal nozzle extension.

4. Hydrogen dumped-cooled metal nozzle.

The RL10-IIB Engine with an extendible nozzle is intended for use in an Orbital Transfer Vehicle (OTV) carried into low orbit by the Space Shuttle. Engine length therefore is critical and the extendible nozzle length (excluding translation attachment) will not be permitted to exceed 55 inches (diameter is as required).

The basic extendible nozzle shall have an expansion ratio of 205:1. Performance comparison will be based on an OTV mission of 20,000 ft/sec delta velocity and the additional, ground rules provided in Section 4.2. To analyze this configuration, P&WA requires, conceptual designs, and preliminary structural and thermal analysis in addition to the weight cost, etc.

Additionally limited information is required (weight, sketches, cost, etc.) for a nozzle extension adaptable to an RL10-IIB Engine with an expansion of 280:1, with the same stowing constraints as the 205:1 expansion ratio nozzle. A recontoured primary engine nozzle is acceptable but the 55 inches overall stowed engine length must be maintained. Other expansion ratio(s) may be considered but the total primary engine with the extendible nozzle extended must be less than 150 inches.

The initial operational use for the OTV will be an expendable mission with up to 7 firings for approximately 1500 seconds total duration. Ultimately, however, the OTV is intended to be a reuseable vehicle with an engine life requirement of 180 firings and 10 hours. Nozzle extensions capable of meeting this requirement with a minimum of maintenance or replacement of parts will have an advantage.

A decisive consideration in the P&WA study will be, maintenance of the 1.0 reliability record of the RL10 Engine. Extensive ground test of the RL10 has been a significant contributor to this reliability.

The initial official qualification test for the RL10-IIB Engine with nozzle extension will be 20 firings and 9000 seconds. The preceeding development program should provide high confidence of success leading to the qualification test.

For expendable operational use, the secondary nozzle is extended prior to engine firing, and will never be retracted. For reuseable missions, the secondary nozzle would be retracted (nonfiring) prior to restowing in the Space Shuttle payload bay. This could occur up to 20 times. For this reason, it would be P&WA's intent to translate the extendible nozzle after each qualification and acceptance test firing. If this is not acceptable, for a particular extendible nozzle configuration, alternative qualification and acceptance test firing plans should be provided.

Ground test of high ratio nozzles is difficult since nozzle exit pressures must be very low to assure full expansion within the nozzle. For this trade-off study a modified E-6 stand at P&WA was selected.

In this stand the engine is mounted in vertical attitude and enclosed in an altitude chamber connected to a steam exhaust diffuser system. A steam ejector is used to evacuate the altitude chamber and the engine exhaust system, prior to engine start and to maintain simulated space conditions during ignition, acceleration and steady state operation. During rapid engine deceleration such as shut-down or abort, the pumping action of the diffuser stops at about 65% engine thrust and pressure spikes can be expected.

At this condition, a 5000 lb forward axial and a 1000 lb side load at 25 to 50 Hz will be exerted on the primary engine nozzle extension system. This load will decay rapidly to less than 10% in under 0.1 second.

The diffuser entrance is 74 inches in diameter and located 5 inches from the nozzle exit. Minimum steady state altitude pressure is 0.6 psia and the nozzle radiates to the 10 feet diameter chamber wall having a maximum temperature of 140^{o}F.

Test facilities also affect nozzle cooling characteristics as compared to space environment; compromises in design due to these thermal affects should be identified.

Each RL10 Engine is fired three times through a rigorous acceptance qualification test. With the engine operational record in mind, requirements for altitude acceptance qualification test of production nozzle extensions should be addressed.

A description and operation of the 205:1 and the 280:1 expansion ratios nozzle extensions deployment systems are required. The system components to be evaluated for integrity and reliability include: sealing techniques between primary and secondary nozzle, actuators, brakes, locks, tracks and drive mechanisms, in the retracted and translating modes. Due to the extremely low exhaust pressure required, comments relative to ground test of the high expansion ratio nozzle configuration are solicited.

This study is also to provide development and manufacturing background of the proposed extendible nozzle concept (or similar applicable configurations) to support an extendible nozzle system selection for the RL10-IIB Engine. Any supporting information or suggestions i.e., experience with similar designs or technology type test programs which could eliminate or reduce risks should be identified. (Note: this was covered in the preceding Section 3.0 in Convoluted Nozzle background.)

4.2 GROUND RULES AND ASSESSMENT CRITERIA

The RL10-IIB Engine specifications that affect or drive the design of the extendible nozzle are given in Table 4-1 and Figures 4-1 through 4-5.

TABLE 4-1. GROUND RULES AND ASSESSMENT CRITERIA

Full Thrust (lb)	15,000
Primary Nozzle:	Regeneratively cooled
Extendible Nozzle Constraints:	Maximum stored length 55 inches, excluding the translating attachment* which may extend 8 inches above the gimbal plane at 3 locations.
Extendible Nozzle Type:	Optional
Engine Contour Baseline:	Supplied by P&WA
Area Ratio of Engine with nozzle extended:	
1) Baseline:	205:1
2) Option:	280:1**
Mixture Ratio(s):	Useable for both 5:1 and 6:1
Chamber Pressure (psia):	400
Propellant Type:	Hydrogen-Oxygen
RL10-IIB Engine Free Stream Temperatures:	
1) For Mixture Ratio 5:1:	See Figure 4-1
2) For Mixture Ratio 6:1:	See Figure 4-2
RL10-IIB Engine Free Stream Pressures:	
1) For Mixture Ratio 5:1:	See Figure 4-3
2) For Mixture Ratio 6:1:	See Figure 4-4
RL10-IIB Estimated:	
Weight (lb)	327

* Applies only to configuration 1, 2 and 4 (Para. 4.1). The CN does not require this local increase in envelope.

** Recontoured primary nozzle acceptable, maintain 55 inches overall stowed engine length. Other expansion ratio(s) may be considered. The exersize of this option yielded a deployed expansion ratio of 303:1 with a total length limitization of 150 in. (and therefore the 280:1 CN was not designed).

The estimated maximum allowable loads due to gimbal actuation and degrees of gimbal are:

Maximum allowable actuator loads (lb):	2640
Maximum pitching acceleration (Rad/sec^2):	1
Maximum yawing acceleration (Rad/sec^2):	1
Gimbal angle (degrees):	∓ 4
Maximum actuator shock load:	2640 lb with a minimum time interval of 2 sec. between successive shocks

The estimated center of gravity for the RL10-IIB Engine without secondary and translating mechanism is: (See Figure 4-5)

Axial (x), nozzle (inches)	26.0
Horizontal (y), (inches)	1.0
Vertical (z), (inches)	2.2

System Life

1) Baseline:	Expendable for up to 1500 seconds of operation and a total of 7 burns.
2) Optional:	Reuseable with an engine/system life of 180 firings and 10 hours.

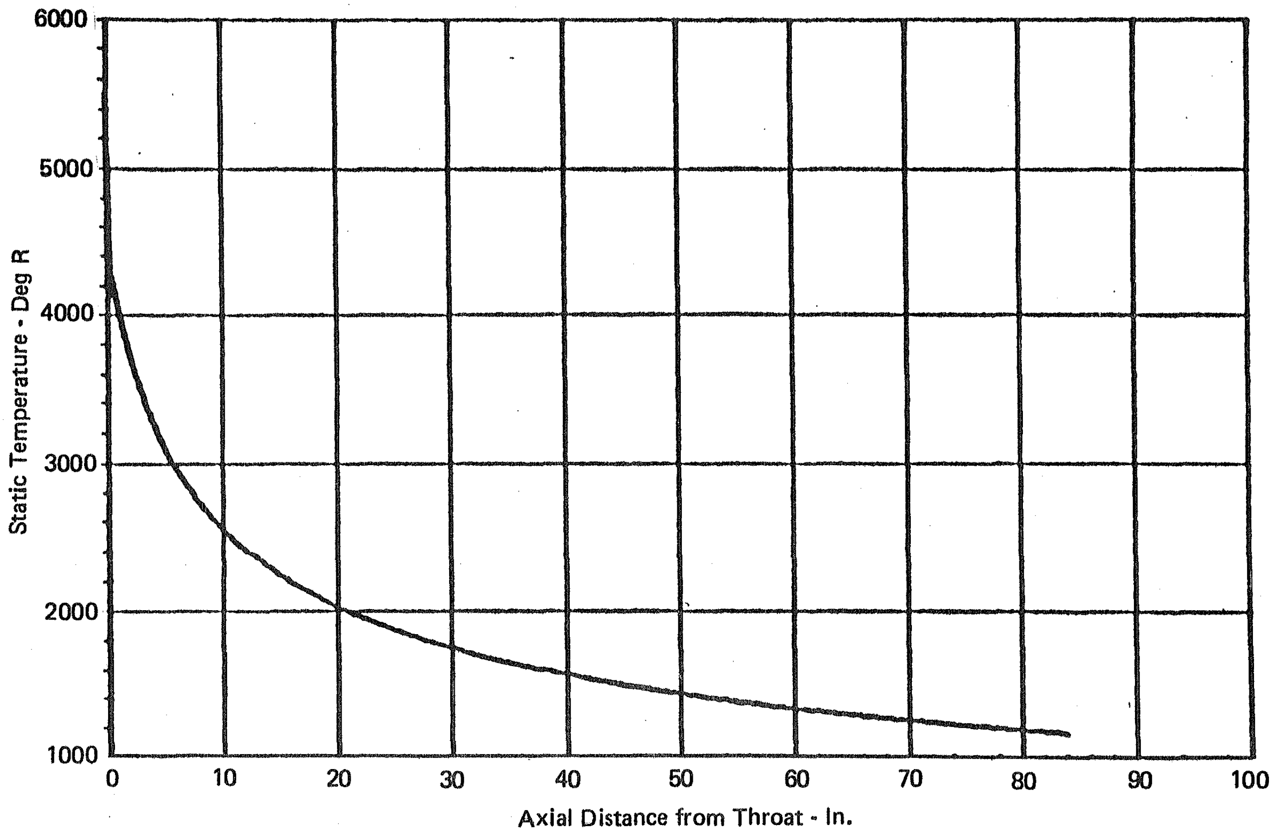


Figure 4-1. RL10-IIB Engine Nozzle Temperature Characteristics
O/F 5.0 T (Total) = 5922 Deg R

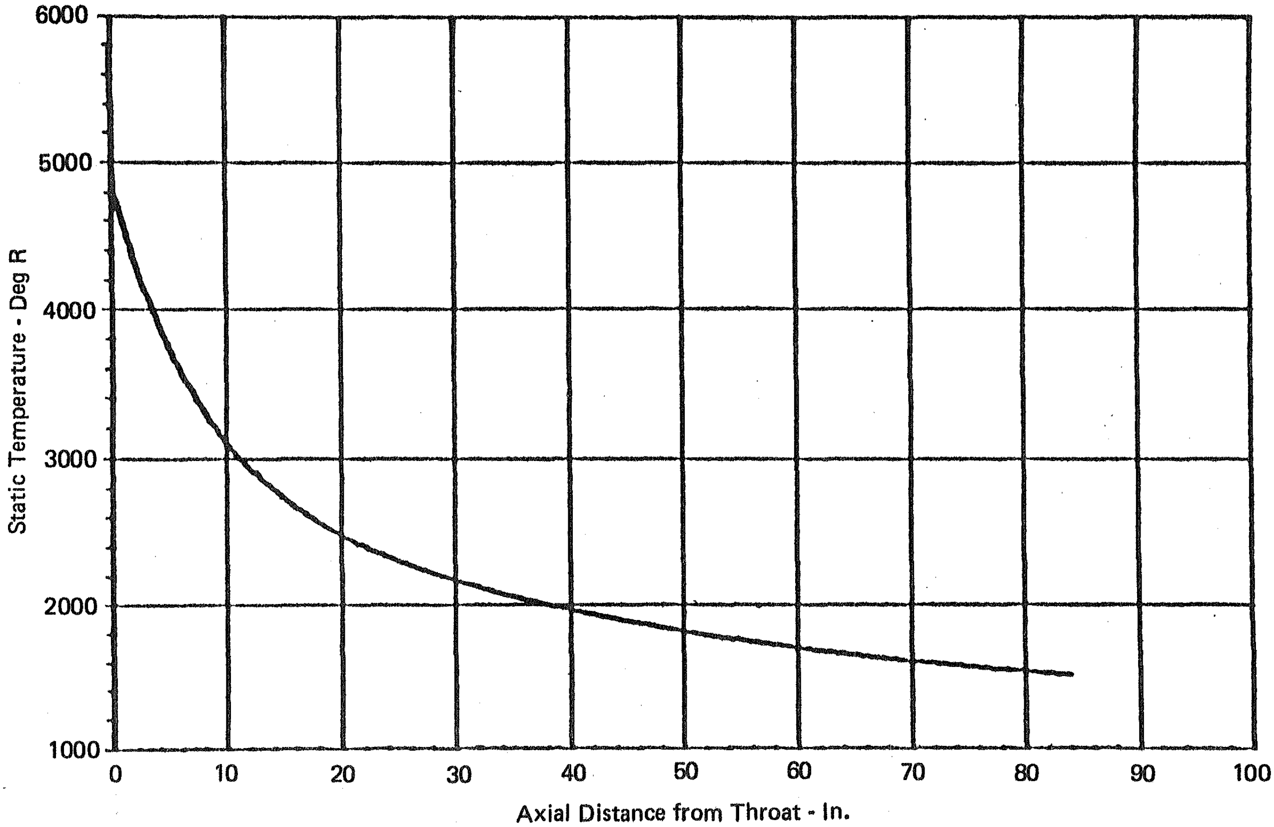


Figure 4-2. RL10-IIB Engine Nozzle Temperature Characteristics
O/F 6.0 T (Total) = 6185 Deg R

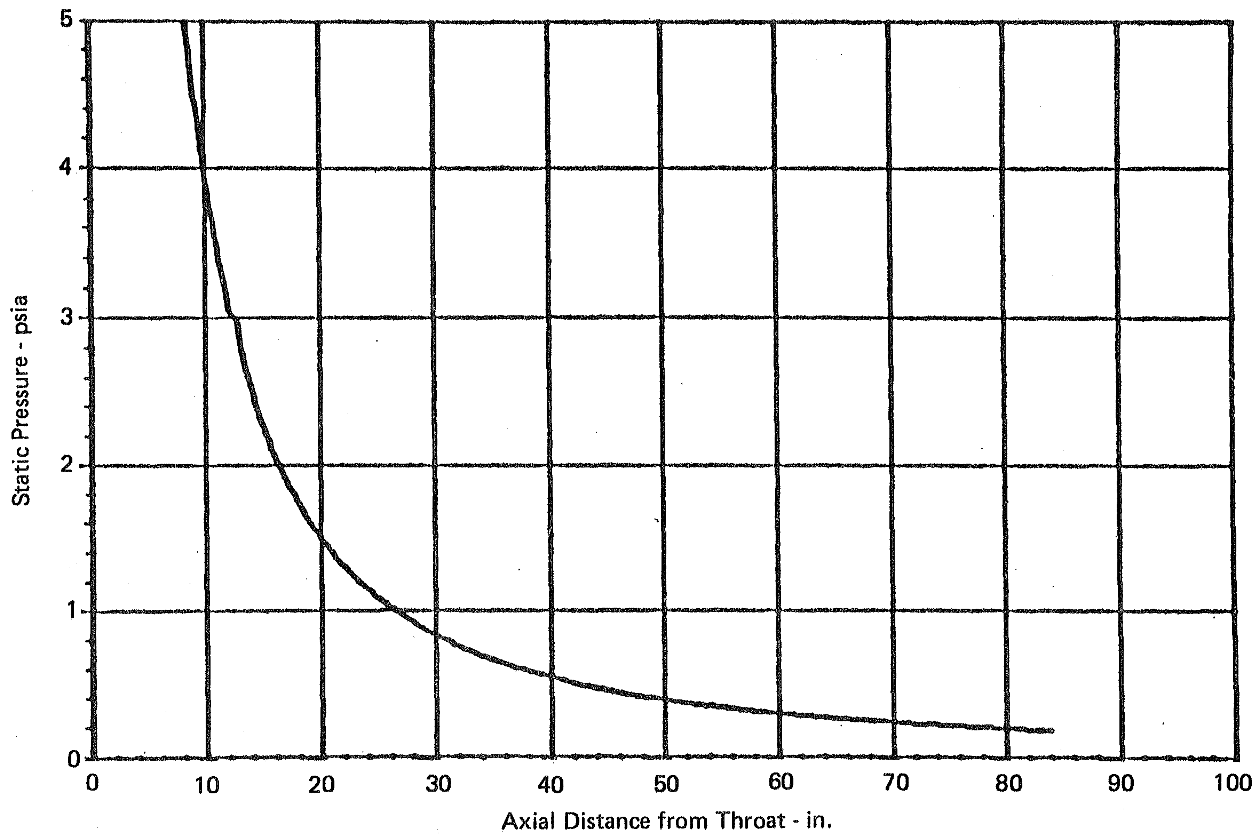


Figure 4-3. RL10-IIB Engine Nozzle Pressure Characteristics
O/F 5.0 P (Total) = 400 psia

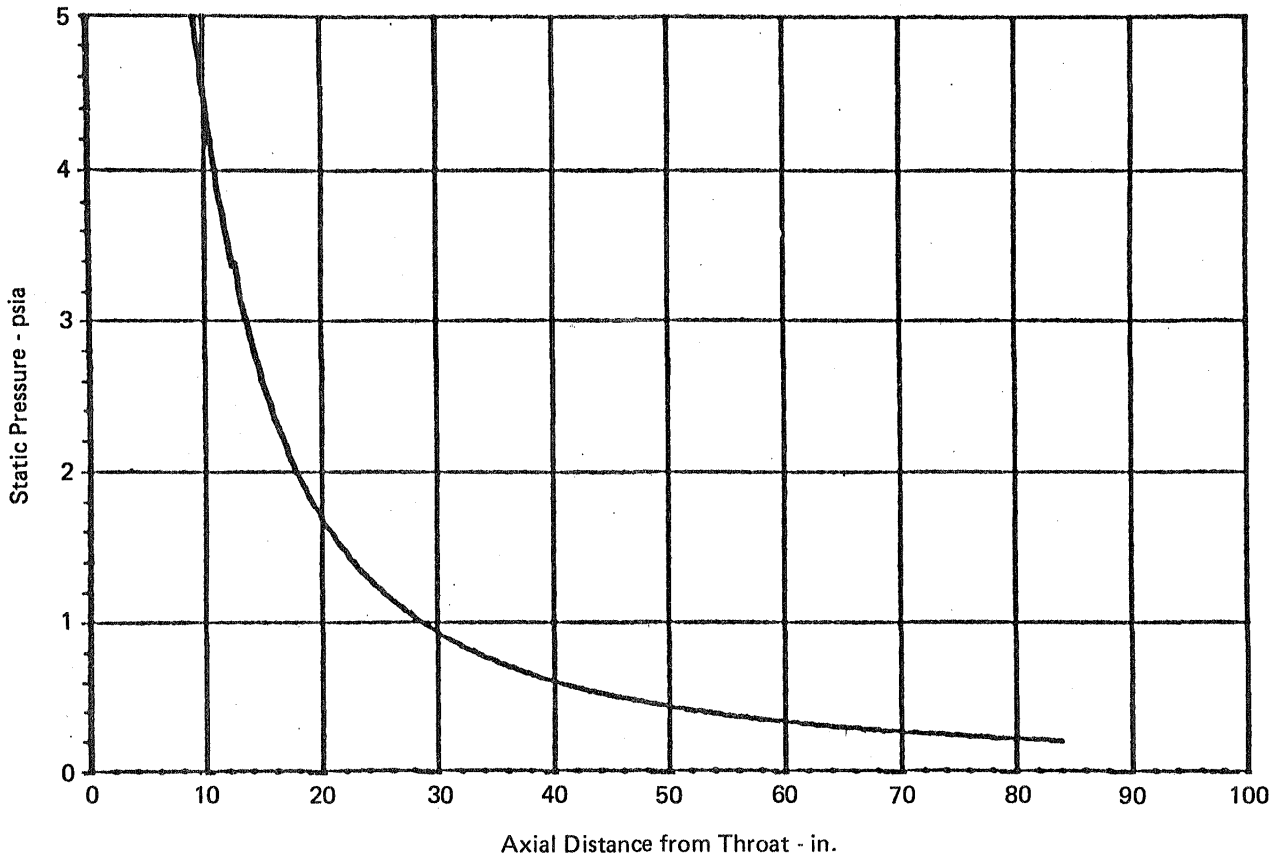


Figure 4-4. RL10-IIB Engine Nozzle Pressure Characteristics
O/F 6 P (Total) = 400 psia

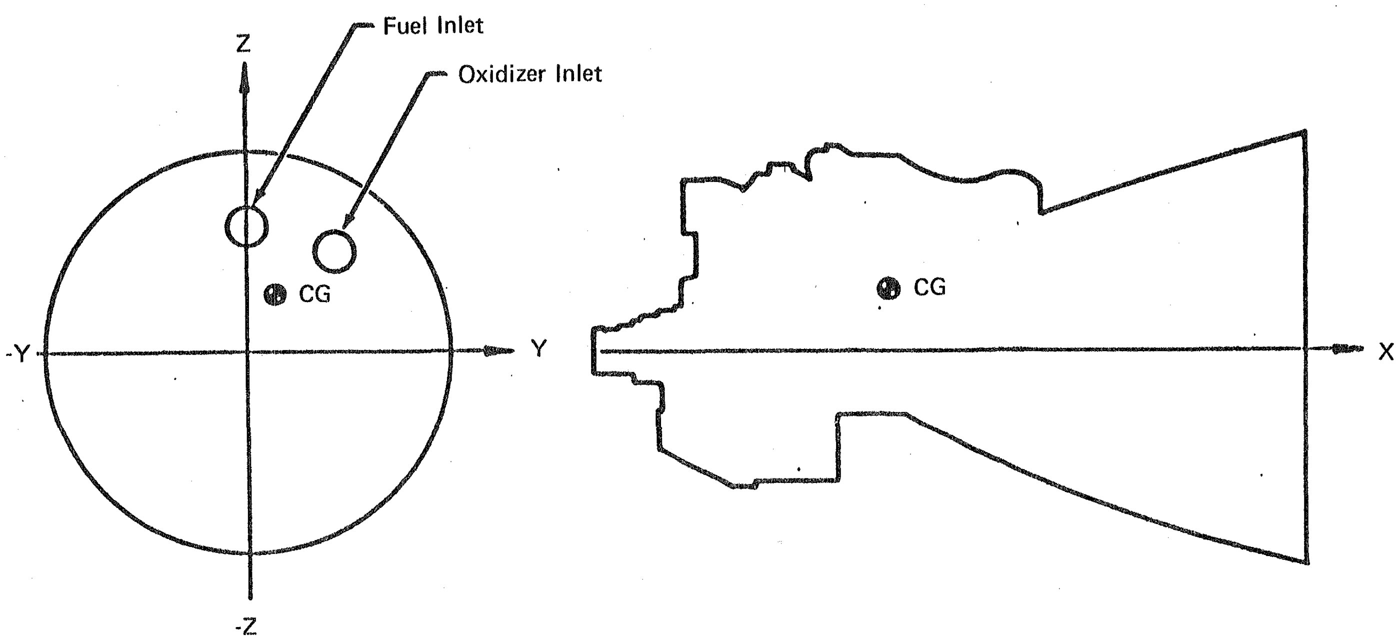


Figure 4-5. Location of Engine Center of Gravity

5.0 CONVOLUTED NOZZLE EXTENSION DESIGNS

Convoluted Nozzle system design and analysis begins with the design of the Convoluted Nozzle Extension. The approach to this study therefore consisted of (1) design of the deployed Convoluted Nozzle(s) for the operating loads and requirements, (2) study of stowed (Convoluted) configuration(s) and roll control and (3) optimization of the deployment system - in that order to minimize the number of calculations, analyses and design iterations.

5.1 INTERFACE DEFINITION AND MOUNT JOINT DESIGN

The first order of business was the definition of the interface between the CN and the RL10-IIB Engine. A CN design with a light weight mount joint was, therefore, prepared to support interface discussions with Pratt & Whitney Aircraft.

Bell visited P&WA on 23 August 83 in West Plam Beach, Florida, to participate in a kick-off meeting for the CN Design Study Project. The drawing of deployed CN Configuration No. 1 shown in Figure 5-1 was reviewed for the purpose of reaching agreement on the optimum features of the interface between the mounted CN and the RL10 Engine. This drawing incorporates the light weight mount flange system shown in Figure 5-2, which requires CN installation before the engine is mated to the Centaur vehicle. P&WA approved the transfer of CN thrust directly to the RL10 primary nozzle (e.g., rather than engine hard points), but felt that aft end installation of the CN on the engine in the vehicle is so clearly desirable for engine servicing access that it should be a study ground rule. Bell agreed and no further work was conducted on CN Configuration No. 1.

P&WA agreed that Bell could transfer CN loads into the RL10 primary nozzle through a 347 stainless steel flange that will be silver-brazed in place. Detailed engine and nozzle dimensional data was provided by P&WA and a tour of the silver-brazed st stl tube wall thrust chamber fabrication operation was given to Bell to insure sufficient information for good CN design for mounting on the RL10 primary nozzle.

To avoid controversy over CN design data, Bell requested and received the P&WA calculation of CN thrust and thermal analysis for use in the structural analysis of the baseline CN providing a nozzle expansion ratio of 205/1 (i.e., $\varepsilon = 205$). These data were needed because the water condensed in the primary nozzle boundary layer (by the $75^{O}R$ LH_2 cooled wall) will film cool the CN at the attachment end (to lower temperatures than Bell calculated) and the 1300 lb thrust developed in the CN is a function of total nozzle contour (best determined by P&WA). P&WA also supplied the total nozzle contour of expansion ratios greater than 205 for use in study of the maximum expansion ratio (ε) CN.

5.2 BASELINE CONVOLUTED NOZZLE, $\varepsilon = 205$

The baseline 205ε was then designed in Deployed Configuration No. 2, as shown in Figure 5-3, for aft end installation on the RL10 engine in the Centaur vehicle. The mount flange system detail is shown in Figure 5-4. The CN is advanced over the primary nozzle until the CN thrust ring flange (incorporating a 10 mil thick Grafoil adhesive gasket seal) engages the mount flange on the primary nozzle. Two aligning pins in the

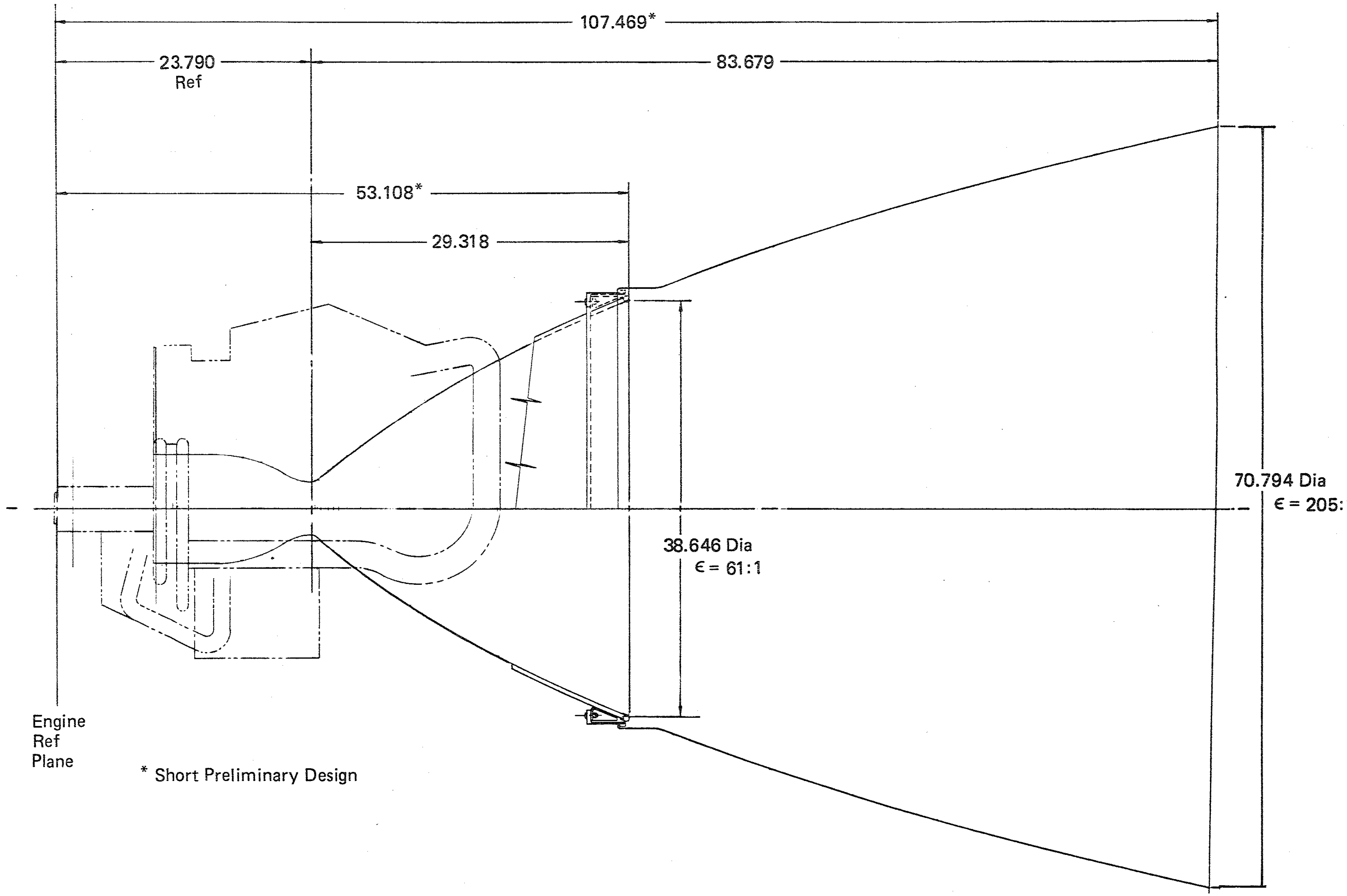


Figure 5-1. Deployed Convoluted Nozzle Configuration No. 1

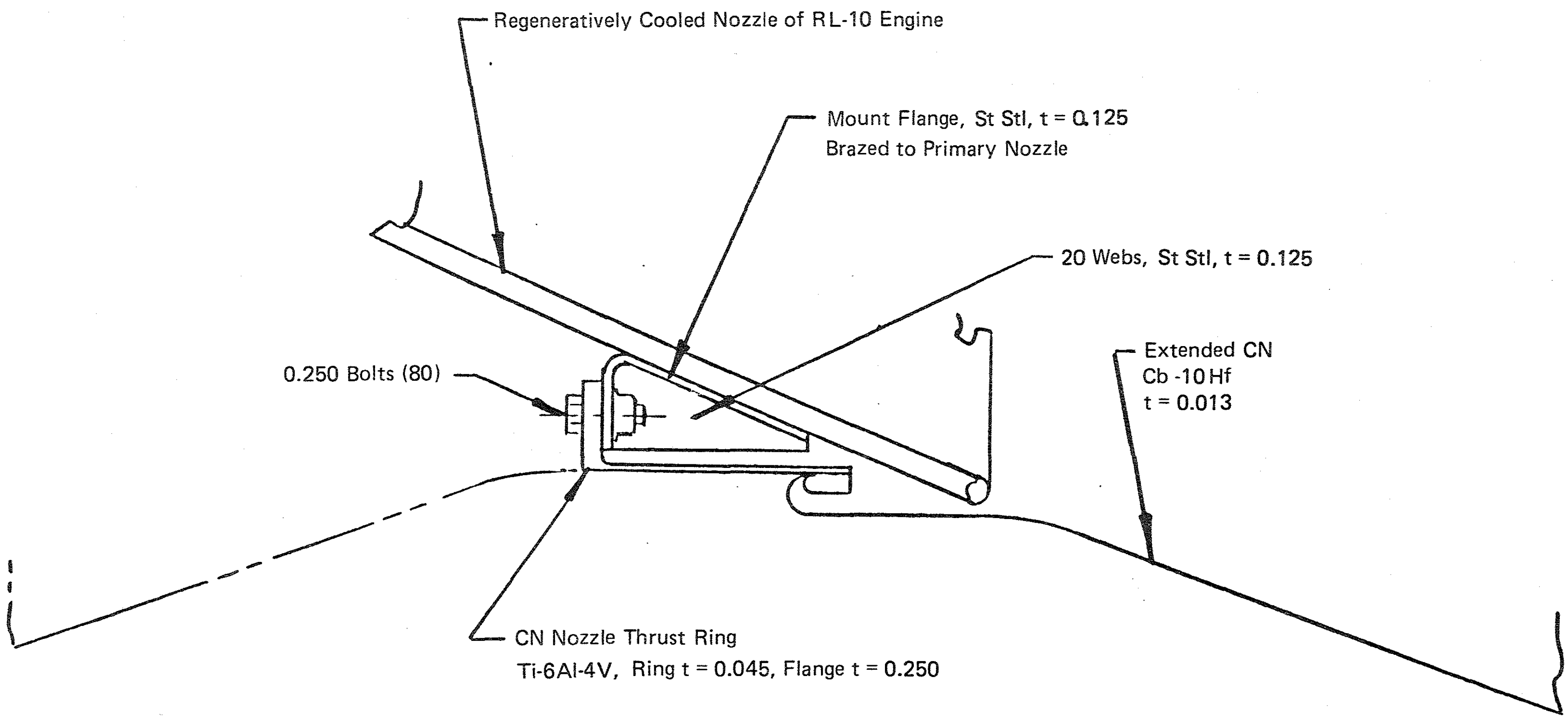


Figure 5-2. Convoluted Nozzle (CN) Mount Joint Config. No. 1A

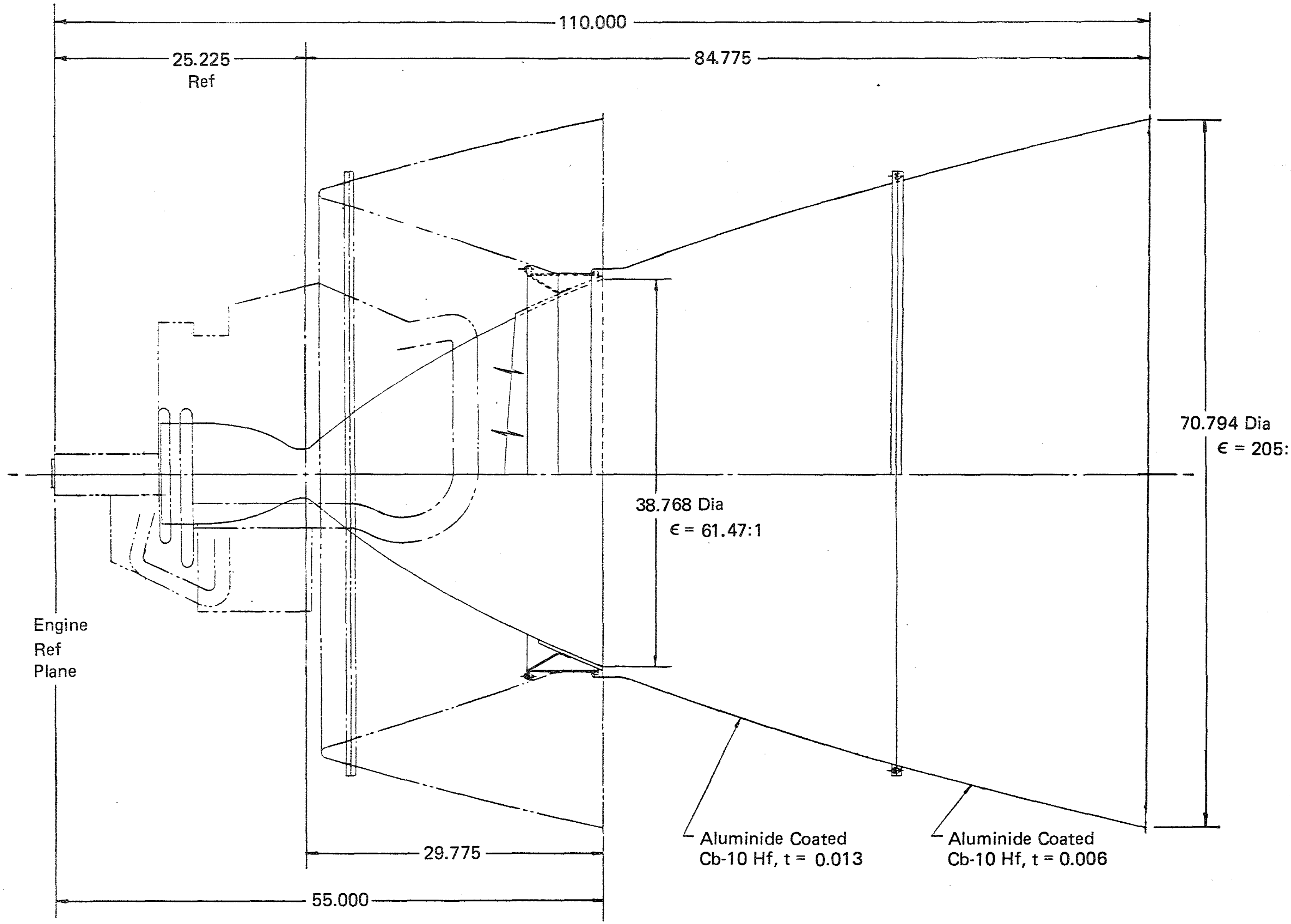


Figure 5-3. Deployed Convoluted Nozzle Configuration No. 2

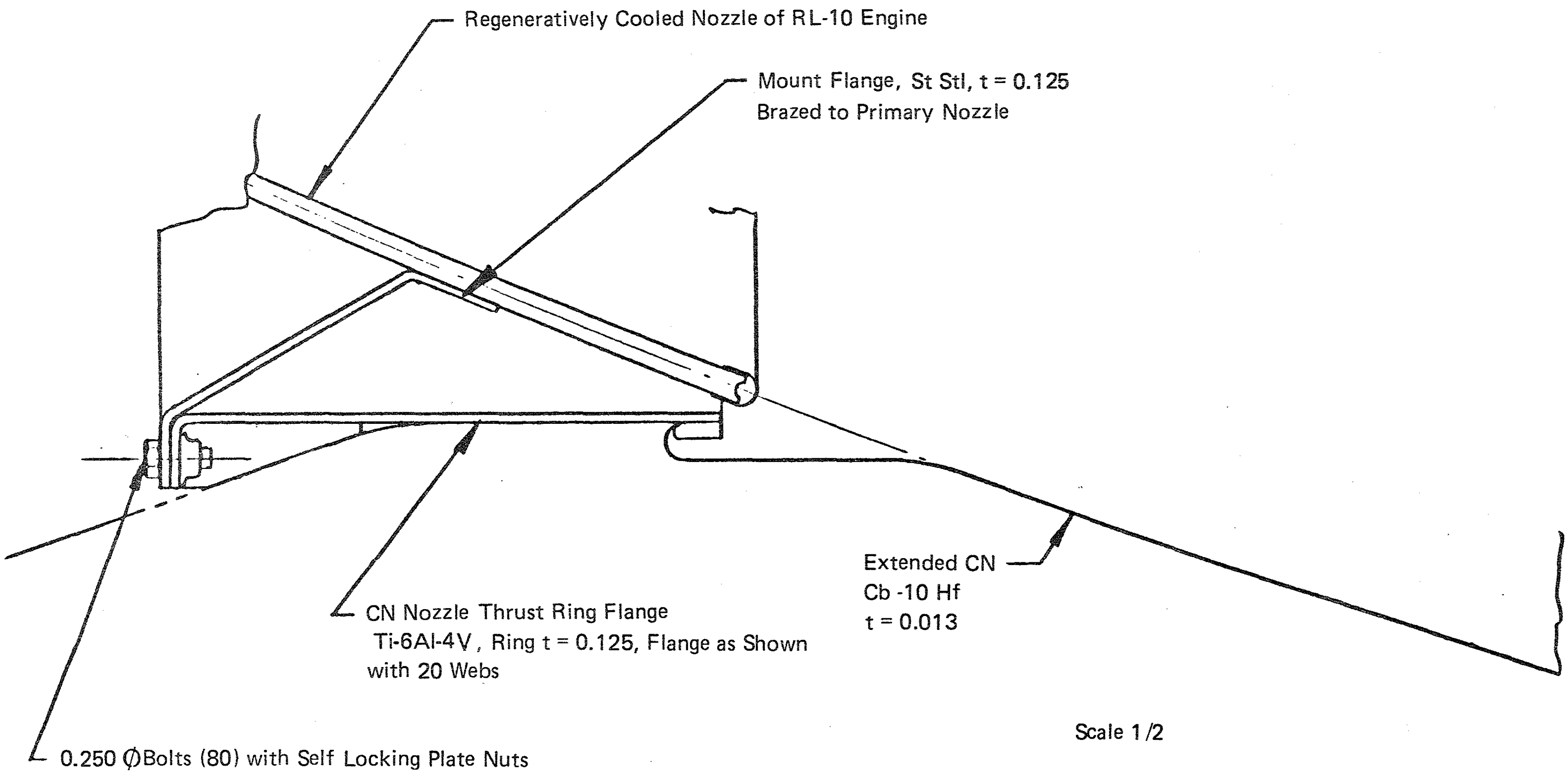


Figure 5-4. Convoluted Nozzle (CN) Mount Joint Config. No. 2

mount flange (not shown) provide rotational alignment for mount bolt insertion. The bolts will be inserted and locked from the primary nozzle side of the mount flange. This will require access from the area of the thrust chamber throat (see Figure 5-3). Access for CN mount bolt insertion may be increased by tilting the engine selectively on its gimbal joint.

5.3 MAXIMUM PERFORMANCE CONVOLUTED NOZZLE DESIGN, $\varepsilon = 303$

The maximum expansion ratio CN was designed to the high ε contour data supplied by P&WA. Layout studies showed that this contour would limit the expansion ratio to 303/1 within the 150 in. length limit for the engine with CN extended (as specified in the Guidelines and Ground Rules, Section 4.1). The 303 ε CN was also designed for aft end installation on the RL10 engine in the Centaur vehicle as shown in Figure 5-5 of Deployed CN Configuration No. 3. The drawing shows that, in the stowed position, this larger CN completely covers the RL10 engine so that the mount bolts must be inserted and locked from the CN side (downstream facing surface) of the mount flange as shown in detail in Figure 5-6. To satisfy the geometric demands of this requirement, the aft 4 inches of the primary nozzle is replaced with the removable refractory metal fairing shown in Figure 5-6. CN installation is accomplished by advancing the CN over the RL10 engine until the CN thrust ring flange (with Grafoil Seal) meets and aligns with the mount flange on the primary nozzle. The CN is then secured to the primary nozzle by threading 80 bolts into the nut plates on the mount flange as shown in Figure 5-6. The fairing is then installed and secured by threading 20 flush head screws into the nut plates in the webs on the thrust ring.

The purpose of the fairing is to hold the boundary layer in place and smooth the gas flow across the large joint discontinuity required to provide for CN installation entirely from the aft end of the RL10-IIB engine - after the engine has been installed (and serviced) on the Centaur vehicle.

5.4 DEPLOYED CN STUDY FINDINGS

Preliminary design analysis of the foregoing three CN configurations was conducted to establish preliminary material thicknesses for use in weight comparison and detailed structural/thermal analysis. The identity and characteristics of these designs are briefly summarized as follows:

Deployed CN Config. No.	1	2	3
Figure No.	5-1	5-3	5-5
CN Exit ε	205	205	303
Weight (deployed) - lb	69	89	114
Installation:			
Engine Level	x		
Vehicle Level		x	x

These layout studies of the deployed CN therefore identified a weight penalty associated with installation of the CN at the vehicle level (Config. No. 2 versus No. 1) and defined two CN designs for further study. This included the baseline design, configuration No. 2 and the maximum performance design, configuration No. 3.

However, thermal analysis subsequently showed that the mount joint design required on the maximum performance CN, for simple aft end installation at the vehicle level, could also be used on the baseline design (config. No. 2) to provide significant weight reduction.

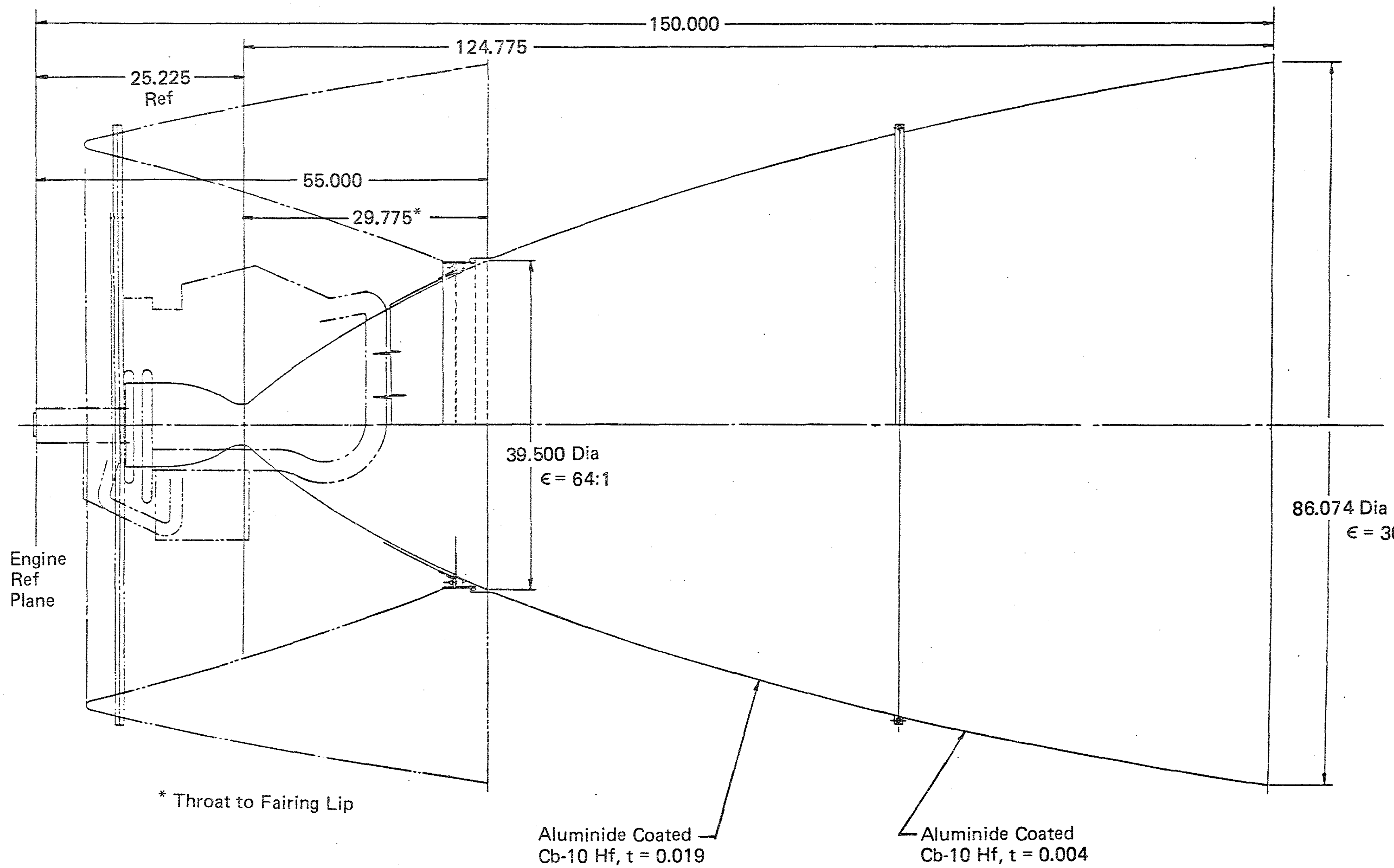


Figure 5-5. Deployed Convoluted Nozzle Configuration No. 3

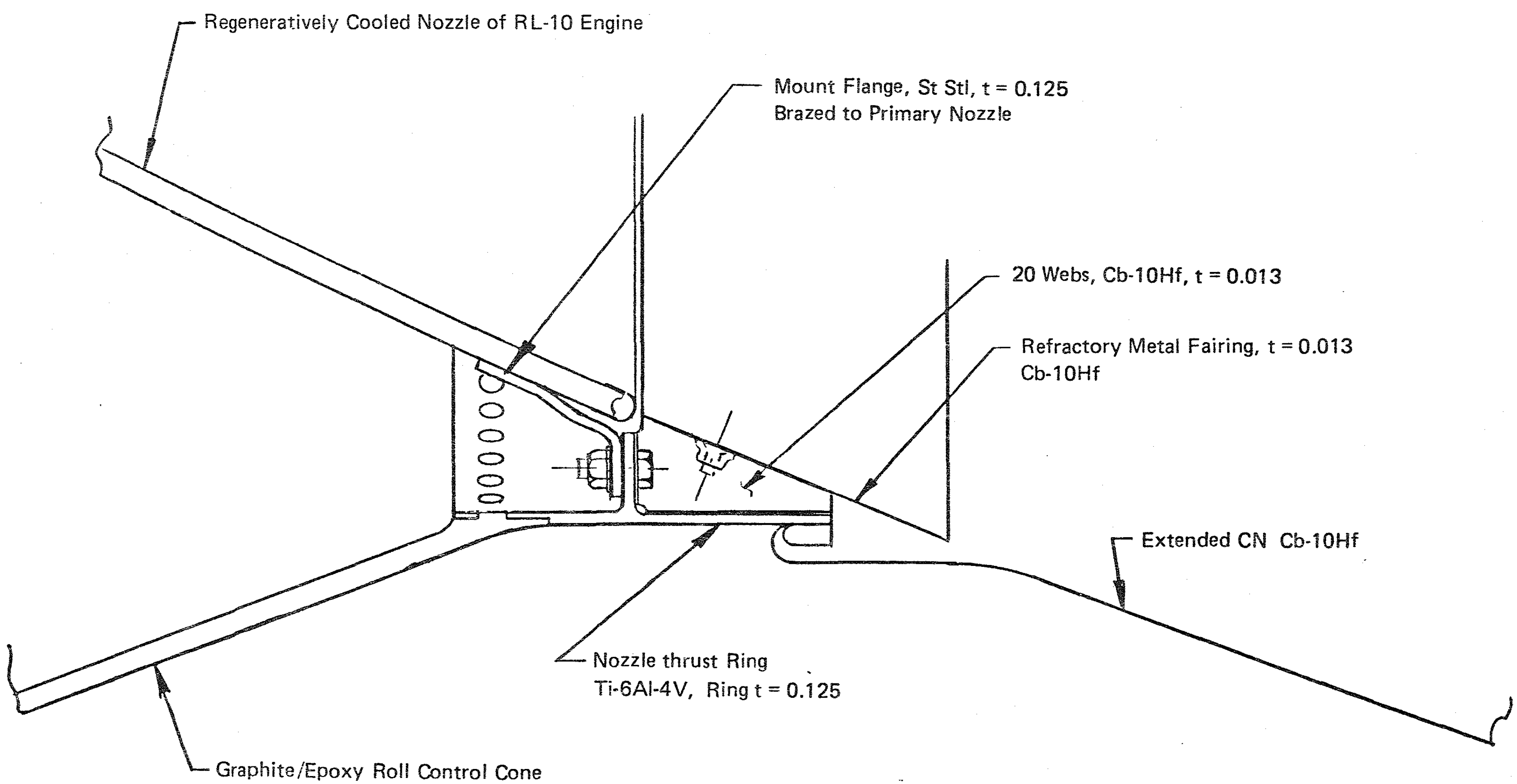


Figure 5-6. Convoluted Nozzle (CN) Mount Joint Config. No. 3
AFT 4 In of Primary Nozzle Replaced by Fairing

6.0 THERMAL ANALYSIS

Thermal analyses of the baseline 205ε CN and the maximum performance 303ε CN were conducted to define the operating temperature profiles of each CN for the purpose of establishing Cb-10Hf material properties to be used in structural analyses of these Convoluted Nozzle designs.

6.1 BASELINE 205ε CN

To incorporate the effects of water film cooling of the attachment end of the CN (by H_2O condensed in the primary nozzle boundary layer by the 75^oR LH_2 cooled wall), the P&WA thermal analysis results were employed without modification in the case of the 205 ε CN with mount joint configuration No. 2. This combination film and radiation cooling analysis (Refs 5 and 6) of a 0.010 in. thick columbium extendible nozzle produced the nozzle extension operating temperature profiles shown in Figure 6-1 as a function of emissivity. The predicted operating temperatures of the baseline 205ε CN are given in Figure 6-1 for the predicted minimum emissivity of 0.75 with the aluminide coating system.

This analysis showed that the maximum operating temperature of the baseline CN is 2410^oR or 1950^oF and that this maximum temperature is developed at a point 8.5 in. aft of the CN mount joint as shown in more detail in Figure 6-2. The predicted CN operating temperature profiles shown in Figure 6-1 and 6-2 were then increased by 150^oF (margin) for the structural analysis of the baseline CN reported in Section 7.0.

6.2 MAXIMUM PERFORMANCE 303 ε CN

In the case of the 303 ε CN with mount joint configuration No. 3, gas side recovery temperature and film coefficient data was extracted from the P&WA thermal analysis for use in a Bell thermal analysis computer program with a finite element model of mount joint configuration No. 3. The finite element model and computer program was necessary to treat the increased geometric complexity introduced by the presence of the faired joint. However, the purpose of the fairing is to maintain the boundary layer, prevent shocks and smooth the flow so it was not necessary to treat local variations in gas side film coefficients due to wall discontinuities.

The gas side recovery temperature and the heat transfer coefficients used for predicting the temperatures of the 303 expansion ratio convoluted nozzle were obtained based on data from References 5 and 6. Reference 5 presents data for the effect of water condensation on the cooled nozzle on the local recovery temperature downstream of the cooled nozzle. The RL10-IIB Engine with a mixture ratio of 6 is similar to the engine that would be used with the 303 nozzle, except that the cooled nozzle would be shortened four inches to allow for the attachment of the convoluted nozzle. Shortening the cooled nozzle will, of course, reduce the area on which condensation will occur and, hence, the total amount of water condensed. Shortening the nozzle by four inches reduces the total area of the divergent nozzle by about 24 percent. Since part of the divergent nozzle near the throat is too hot for condensation to occur, the area over which condensation occurs would be reduced even greater than 24 percent. For the present analysis, it was assumed that the amount of condensation would be about 0.077 lb/sec or 70 percent of that given for the RL10-IIB Engine. The lower flow rate of water

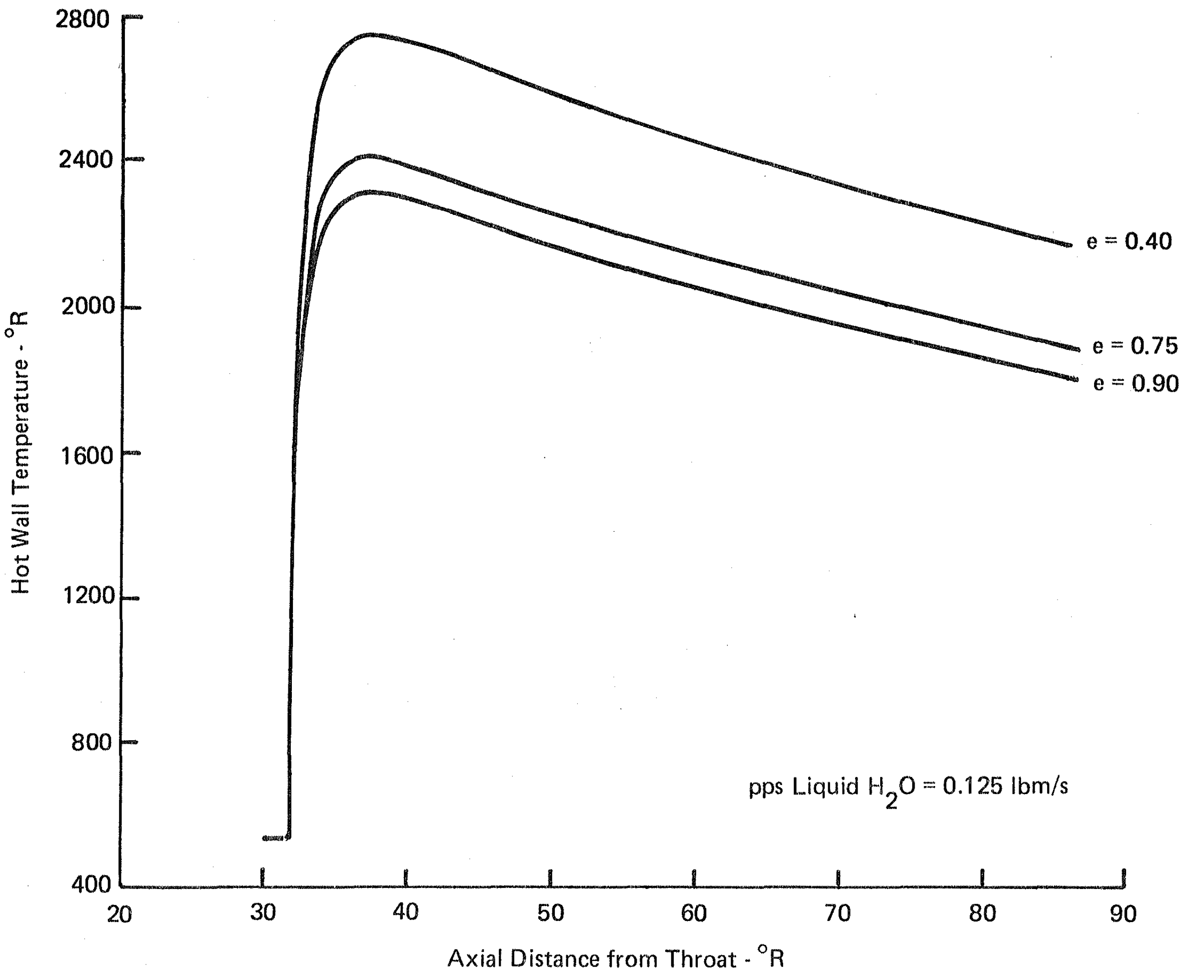


Figure 6-1. RL10-IIB Columbium Extendable Nozzle Hot Wall Temperature at an O/F = 6.0, 10 Mil Wall, ϵ = 205:1

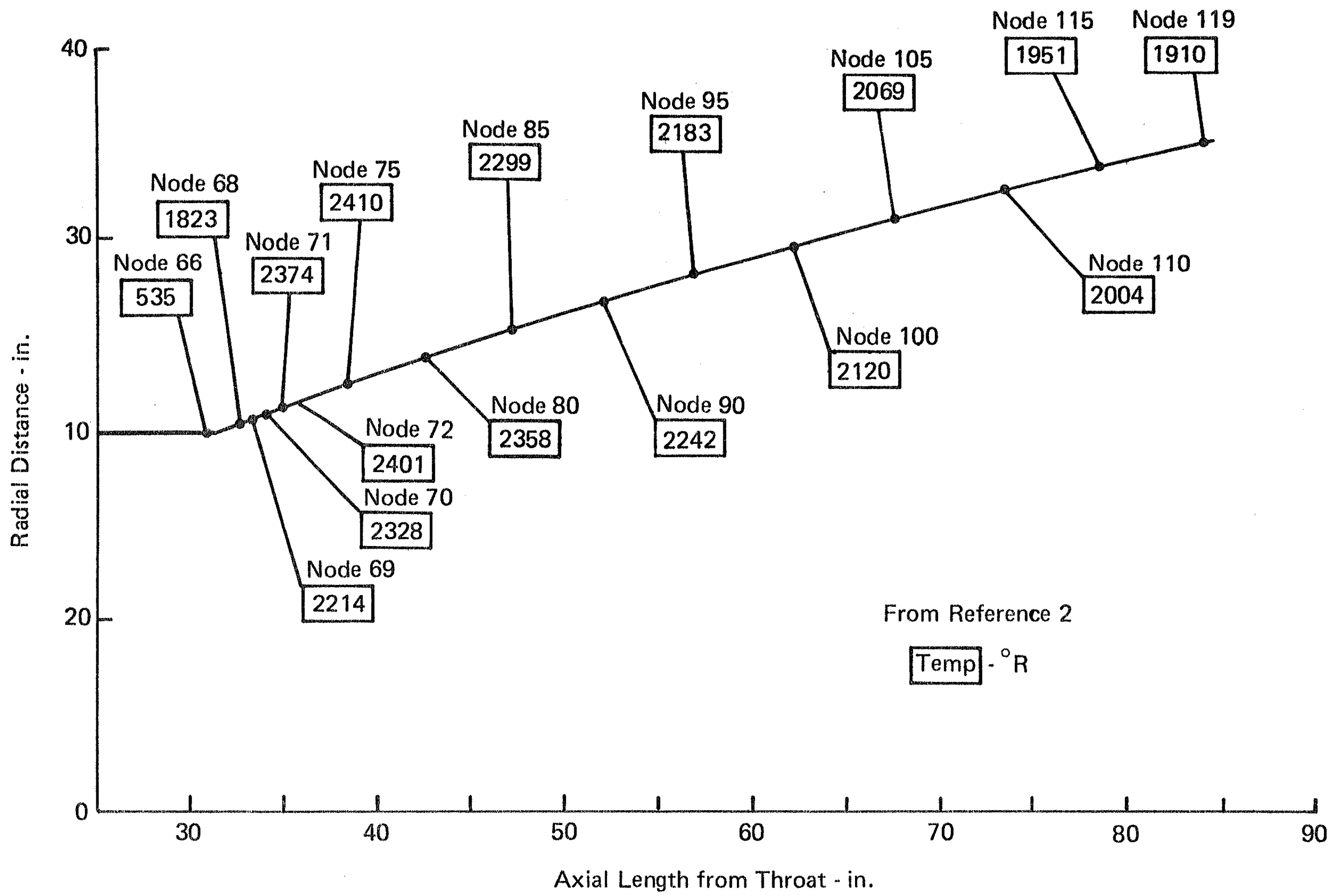


Figure 6-2. RL10-IIB Columbium Extendable Nozzle Full Thrust, O/F = 6.0 Emissivity = 0.75, 10 Mil Wall, ϵ = 205:1

and the higher heating rates at the smaller area ratio would reduce the length required to evaporate the liquid from 2.7 inches to about 1.5 inch. The temperature of the water vapor in contact with the nozzle will increase more rapidly with distance from the turnaround manifold than is shown in Reference 5, due to the lower water flowrate and smaller area ratio. The rate of temperature rise will be about 1.67 times faster. Figure 6-3 shows the predicted recovery (scrubbing gas) temperature for the 303ε CN.

Reference 6 presents temperatures predicted for a nozzle, using the boundary temperatures shown in Reference 5 for three surface emissivities, 0.4, 0.75, and 0.9. The local heat transfer coefficient can be found from the equation:

$$h = \frac{\sigma e T_w^4}{(T_r - T_w)} \quad (1)$$

where:

h = Heat transfer coefficient - Btu/ft^{2}hr^{o}R

T_r = Boundary recovery temperature - °R

T_w = Wall temperature - °R

σ = Stefan-Boltzmann constant - 1.73 x 10^{-9} Btu/ft^{2}hr°R^4

e = Emissivity

This was done at 10 locations from area ratio of 85 to 205 on the divergent nozzle for all three emissivities. It was found that the heat transfer coefficients obtained could be approximated by the following equation which neglects the effect of small differences in receovery temperature on the valueof the heat transfer coefficient.

$$h = 7086.2\ \varepsilon^{1.3656} \quad (2)$$

where: ε = area ratio

A thermal model of the attachment region of the 303 area ratio nozzle was established to predict the temperatures. Figure 6-4 shows the location of the nodes. Nodes 1 through 9 are on the fairing (Cb-10Hf), nodes 10 to 15 are on the nozzle thrust ring (Ti-6Al-4V), nodes 16 to 19 are on the mount flange (st.stl.), node 20 is the roll stop ring, and nodes 21 to 34 are on the Convoluted Nozzle. The model represents a slice of the nozzle between the webs; hence, there was no conduction included between the fairing and the nozzle thrust ring. Gray body radiation factor was computed between appropriate nodes and to the environment as well as conduction connection between the nodes.

Using Equation (2) for the heat transfer coefficients and Figure 6-3 for the local recovery temperature,the temperatures at the various nodes were determined using an existing (SDSTA2) steady state thermal analyzer program. The hydrogen-cooled primary nozzle was assumed to be at -360^{o}F (100^{o}R). Figure 6-5 shows the predicted temperature assuming the nozzle is radiating to a space, -460^{o}F (0^{o}R) environment. It is seen that the highest temperature is at the end of the fairing, node 9, and is 2561^{o}F. The maximum temperature on the convoluted nozzle is at node 26 and is 2173^{o}F. The model was also run, assuming the nozzle to be radiating to an ambient, 70^{o}F, environment as

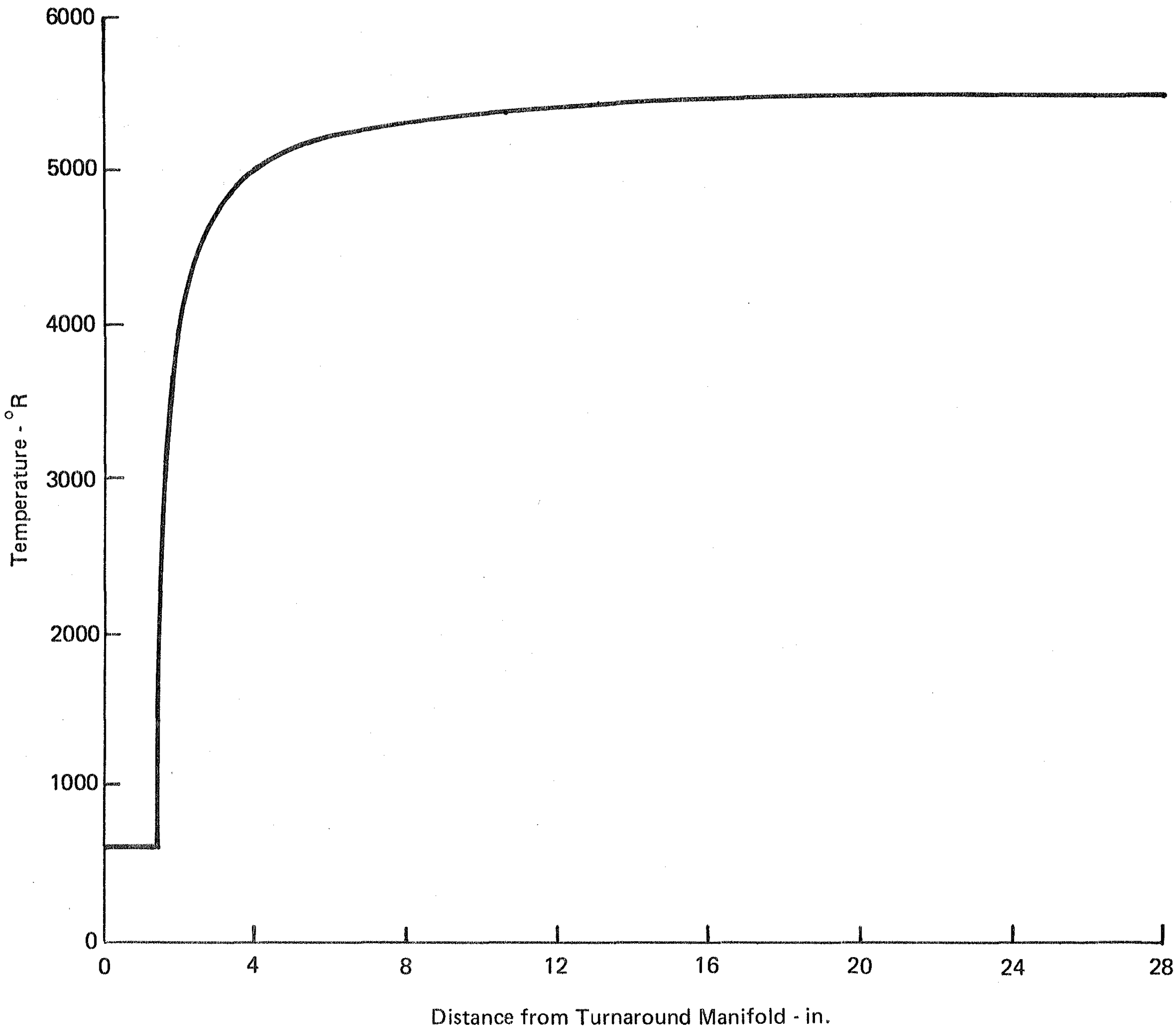


Figure 6-3. Recovery* Temperature

*Temperature of Water Vapor and Scrubbing Gas in Contact with the CN

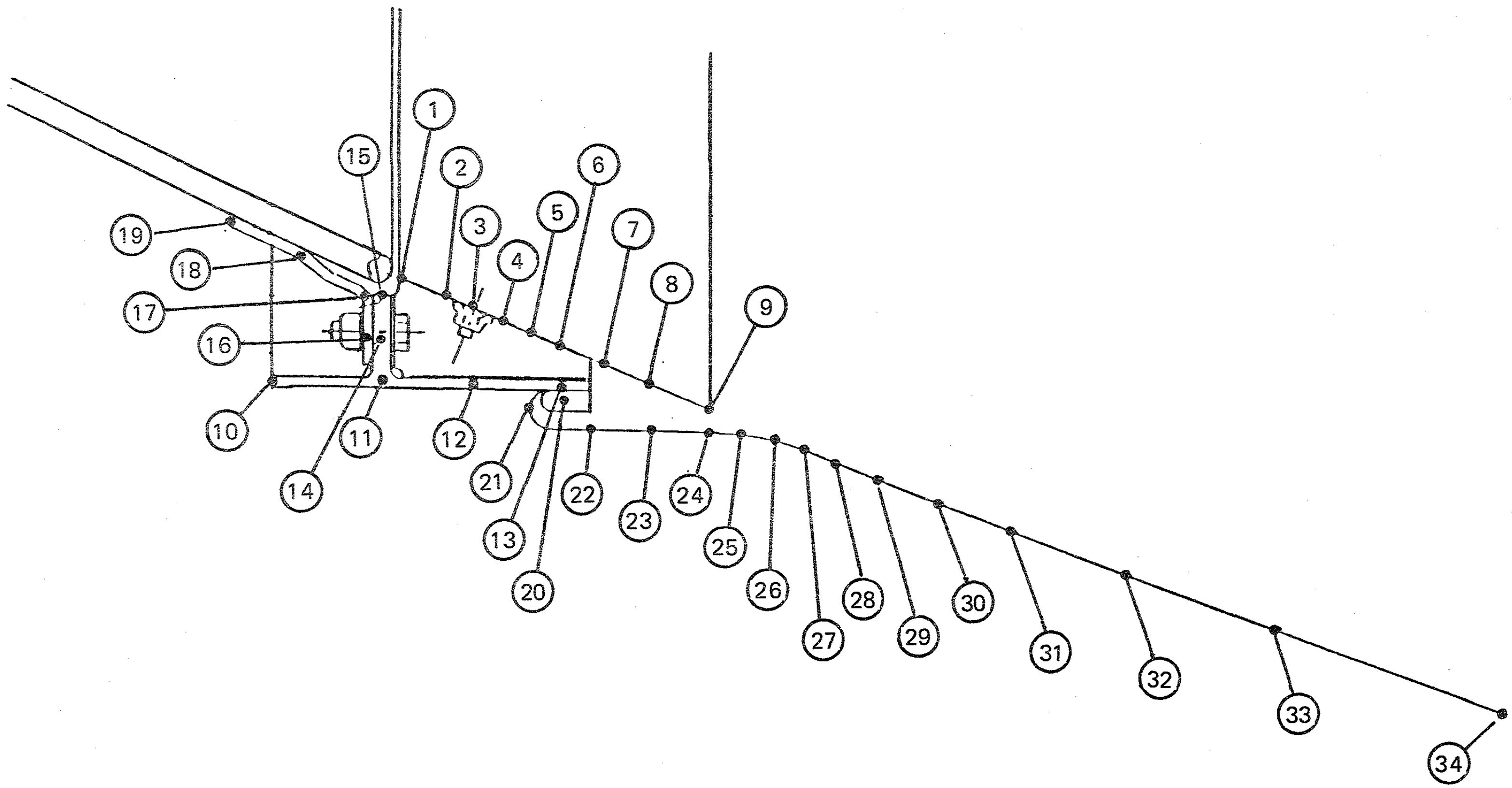


Figure 6-4. Thermal Model - Node Locations for 303ε CN Assembly

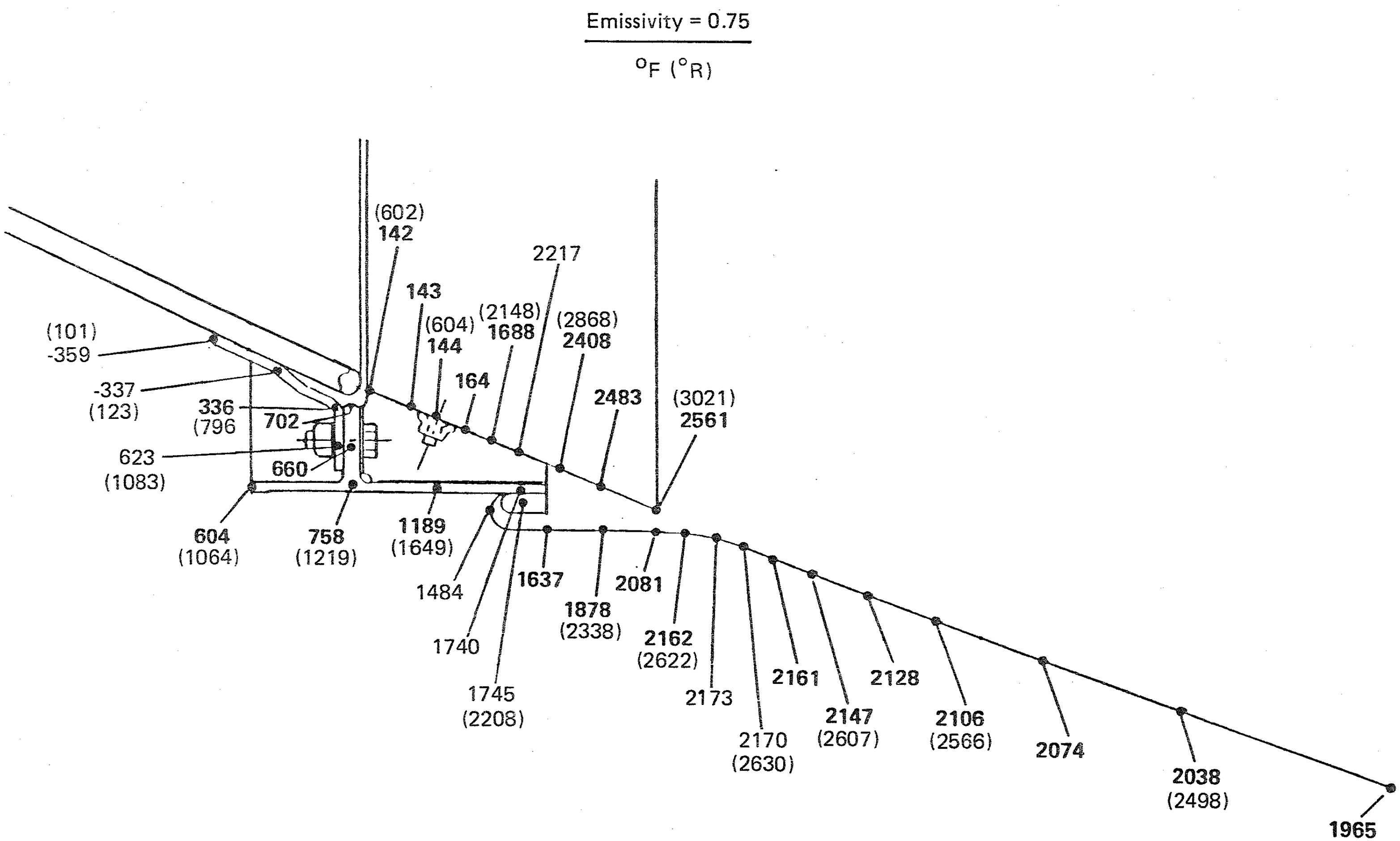


Figure 6-5. CN Temperature Distribution without H_2 Film Cooling

would be encountered in testing. The results showed that the fairing temperatures were increased by less than 1°F while the convoluted nozzle was 1 to 2°F hotter. The largest change was at node 10 where the temperature was 8° hotter. Figure 6-6 shows the nozzle steady state temperature at area ratios beyond the CN mount joint area. It is seen that the temperature decreases from about 2000°F at an area ratio of 90 to about 1260°F at area ratio of 303.

The maximum temperature of 2561°F at the tip of the lightly loaded fairing (See Figure 6-5) does not drive this design because the fairing is thermally overdesigned without significant penalty in CN system weight. The maximum operating temperature of the 303 ε CN is 2173°F, developed at a point 0.8 in. aft of the fairing as shown in Figure 6-5.

6.3 THERMAL ANALYSIS FINDINGS

The 2173°F maximum operating temperature of the 303ε CN is directly comparable with the maximum of 1950°F calculated for the 205ε CN and the difference is entirely attributable to the different mount joint designs (No. 2 versus No. 3). Thermal analysis therefore showed that mount joint configuration No. 3 (Figure 5-6) produced CN operating temperatures that are competitive with temperatures in configuration No. 2 (Figure 5-4). In these circumstances the physically smaller mount joint configuration No. 3 will have a net weight advantage over configuration No. 2. Furthermore, the aft end installation advantages of mount joint configuration No. 3 are also desirable for the baseline 205 ε CN. On the basis of these combined advantages, the faired mount joint configuration No. 3 shown in Figure 5-6 was therefore selected for both the 303ε maximum performance CN and the 205ε baseline CN

Preliminary structural analyses of the 205ε CN and the 303ε CN were carried out for the maximum operating temperature cases of 2100°F and 2200°F respectively. The results showed required factors of safety at CN minimum thicknesses of 0.013 in. and 0.019 in. respectively. Although the CN mount joint fairing operates at a maximum temperature of 2561°F (see Figure 6-5), the fairing loads are small compared to the material thickness and properties at this tempeature and therefore preliminary structural analysis of the fairing was not conducted.

The detailed structural analysis of the 205ε baseline CN was carried out for the maximum operating temperature case of 2100°F and a thermal profile obtained by adding a 150°F temperature margin to the data shown in Figure 6-2 for the P&WA thermal analysis results.

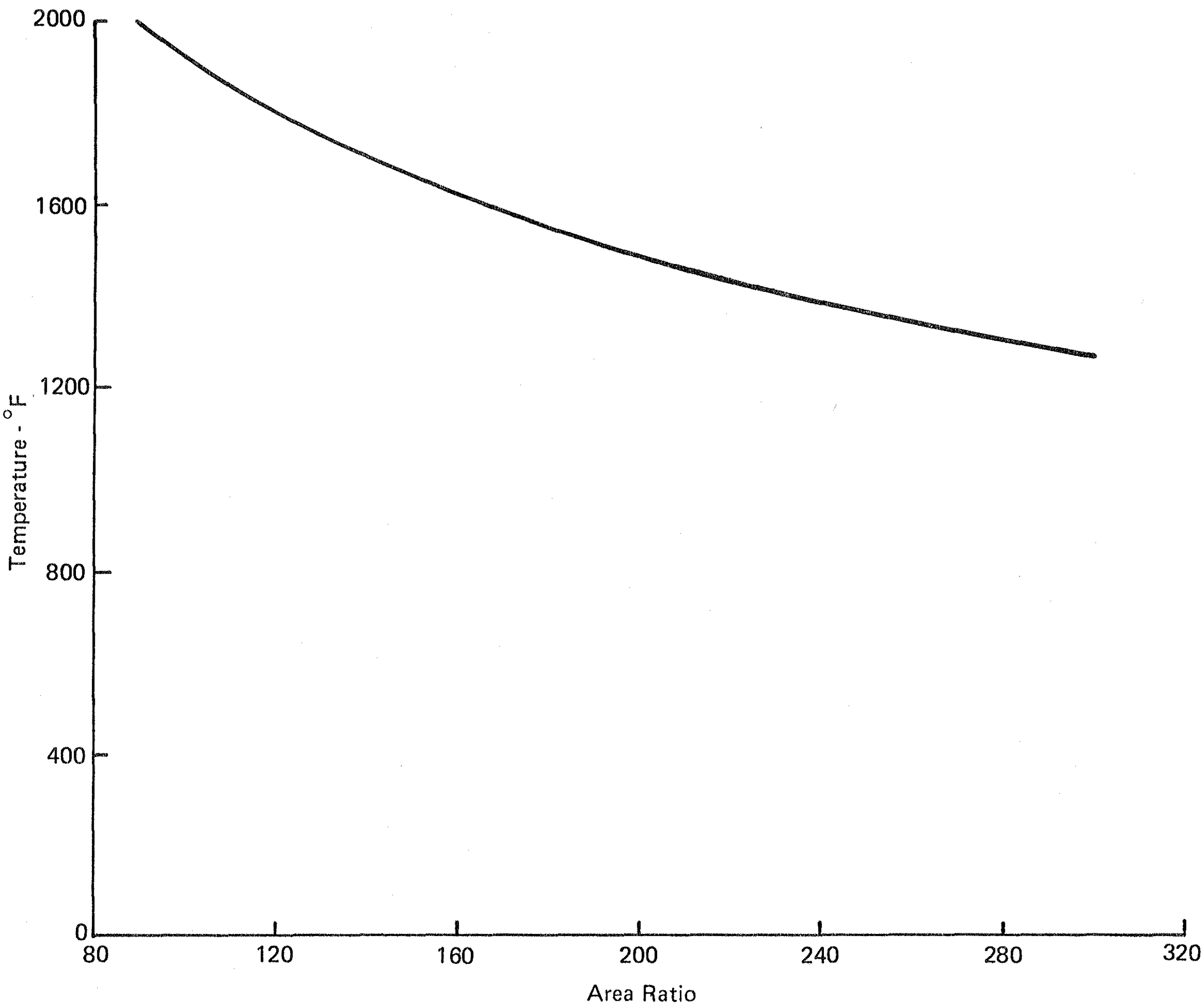


Figure 6-6. Nozzle Temperature versus Area Ratio

7.0 CN STRUCTURAL ANALYSIS, $\varepsilon = 205$

The structural analysis of the deployed CN was conducted to verify the shell thickness selected by preliminary analysis and to evaluate other design features such as attachment and joint geometry. The CN structure must react the loads, at the temperatures determined by the thermal analysis, with the strength of the C103 columbium material shown in Figures 7-1 and 7-2 as a function of operating temperature (Ref 3).

7.1 THRUST LOAD ANALYSIS

The thrust produced in the CN is a function of total nozzle contour and, as such, was calculated by P&WA and supplied to Bell. The CN will develop 1300 lb of thrust with an internal pressure gradient ranging from 0.95 psia at the CN mount joint to 0.21 psia at the CN exit as shown in Figure 4-4.

Since the nozzle shell is a surface of revolution, analysis for thrust buckling and stresses under the specified loading environment utilized the BOSOR4 computer program. BOSOR4 is a widely used program, developed by D. Bushnell of Lockheed, for nonlinear stress, stability, and vibration analysis of segmented, ring-stiffened, branched shells of revolution. It must be noted at the outset that the buckling loading determined by BOSOR4 does not account for manufacturing imperfections, being based on a perfectly uniform shell of revolution. Consequently, a "knockdown factor" of 3.0 was applied throughout this study to BOSOR4 buckling results to account for the small random imperfections that exist despite high quality manufacture. This safety factor is derived from Bell tests and empirical data in the literature.

The baseline design of the 205 ε Convoluted Nozzle in its deployed configuration was modeled for BOSOR4 using CADAM to insure a smooth meridian curve with commonality of tangents at segment junctures. The pressure distribution supplied by P&WA (See Figure 4-4) was modified slightly after the first BOSOR4 run to produce a thrust of exactly 1300 lb at the nozzle attachment.

BOSOR4 results for the initial design showed that the buckling factor (Eigenvalue) was less than the desired safety factor of 3.0. It was found that a thickness increase from 0.013 to 0.020 was required for this configuration to achieve the desired factor of 3.0. Before accepting the weight increase a study was made of the effect of mounting configuration.

The buckling mode showed that buckling inception occurred in the region of transition from the cylindrical mounting section to the specified nozzle contour coordinates. It was discovered that buckling in this region is sensitive to the blending radius and that by proper radius selection the buckling safety factor greater than 3.0 could be achieved with a minimum thickness of 0.013 in this region.

The model was subsequently modified using a thickness tapered (See Section 8.1) to reflect construction by shear spinning. A splice was also introduced along with a ring to support the deployment cover at the 58.84 in. diameter station 59.38 in. from the throat. The shell thickness aft of the splice was reduced to 0.006, constant to the exit. Subsequent BOSOR4 runs were made determining several eigenvalues for each

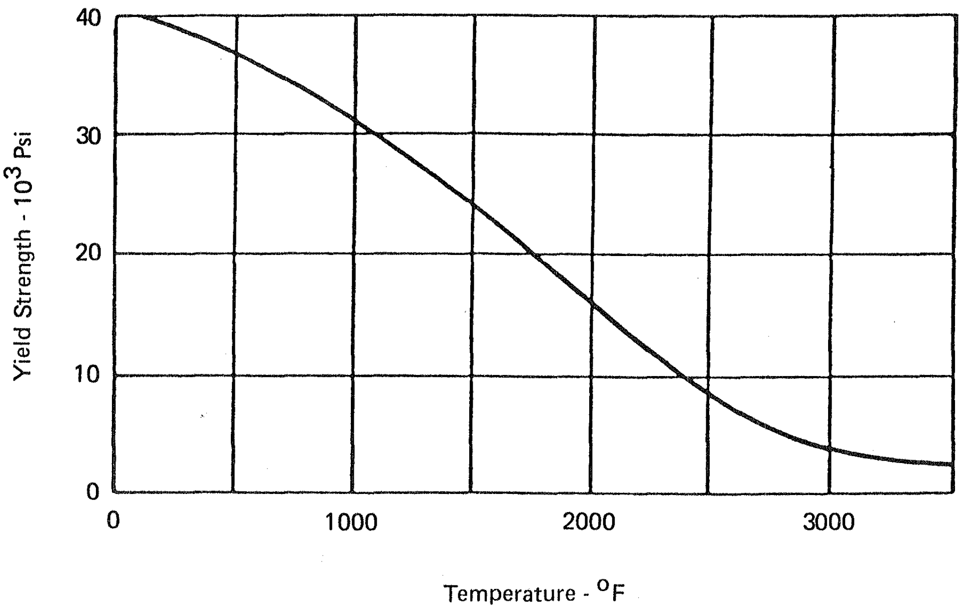


Figure 7-1. Yield Strenght of Cb -10Hf Alloy

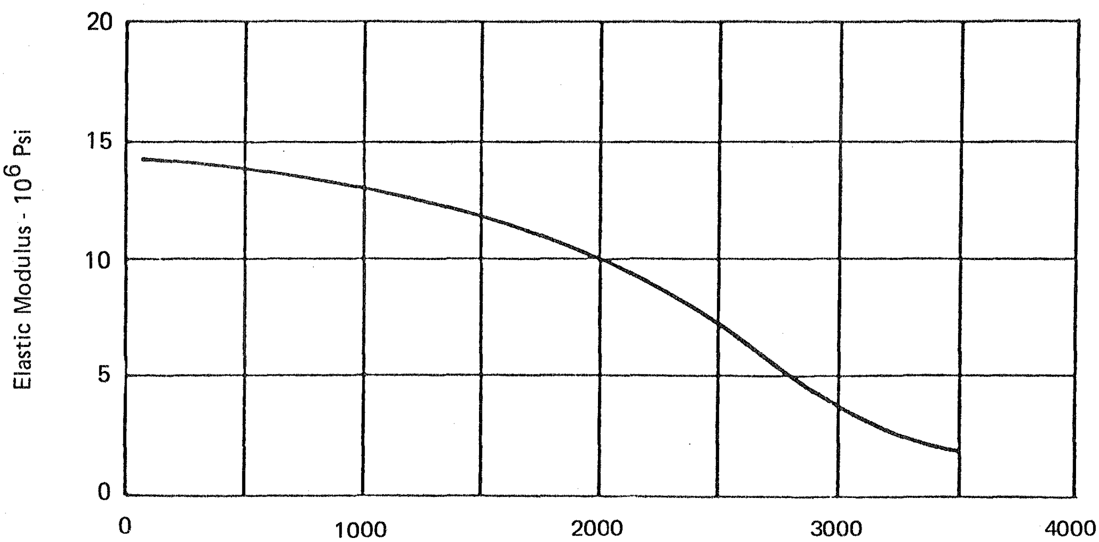


Figure 7-2. Elastic Modulus of Cb -10Hf Alloy

circumferential wave form to obtain minimum buckling factors in the shell on both sides of the splice.

The buckling analysis involves searching several values of "N", the number of circumferential waves, to find the lowest Eigenvalue versus N. A plot showing minimum buckling factor versus N is given in Figure 7-3. Note that a larger safety margin above the minimum design factor of 3.0 exists in the thinner aft section. This is due in large part to the influence of hoop tension produced by internal pressure in the aft section. The buckle in the tapered wall appears in the transition section which, because of the shape discontinuity effect under internal pressure, produces both hoop and meridional (direction) compression. The buckle point is also enough forward of the point of maximum temperature so that temperature effect due to reduced modulus is insignificant. In fact, when for comparison the design temperatures were increased by 350°F with the cylindrical section remaining cooled to 75°F, the minimum buckling pressure actually increased. This strange phenomenon appears to be caused by a range of temperatures where thermal stresses are beneficial in the transition section to a greater degree than attendant reduction of modulus. The buckling mode shape and location at "N" = 32 and 3.058 Eigenvalue is shown in Figure 7-4. The mode shape is defined relative to a normal deflection of unity assigned at the point of maximum normal deflection though that actual value is not computed. It was concluded that the thrust buckling analysis was valid and conservative.

7.2 COMBINED STRESSES

At the point of maximum temperature the combined stress on the inside surface at the 1300 lb thrust condition is 2017 psi. The maximum combined stress under the same applied loads in the region where buckling would first occur is 3605 psi but the design temperature is only 1270°F. Neither of these stress values is significant either from a yield or creep consideration.

The effect on the deployed CN of the 1 rad/sec^2 angular acceleration is also insignificant as this produces only about 1/4 g at the exit plane normal to the thrust axis.

7.3 STRUCTURAL ANALYSIS CONCLUSIONS

Structural analysis of the deployed baseline CN confirmed the design and material thickness selections with a minimum thrust buckling factor of safety of 3.058 and combined stresses below 15% of the C103 columbium alloy yield strength at the operating temperatures on all points of the CN. This verified the 0.013 in. to 0.009 in. tapered rolling section and the 0.006 in. fixed thickness exit section for the operating loads and temperatures of the CN.

The equivalent uniform pressure of the 1300 lb thrust load is 1.03 psi acting across the projected area of the cylindrical section of the CN. The minimum pressure required to roll back the CN is 1.33 psi and thus this free standing CN has a rollback factor of safety of 1.29. It was therefore concluded that backroll latches are not required for this CN design and cannot be used to reduce CN thickness (because the resulting CN would not have an adequate factor of safety in thrust buckling).

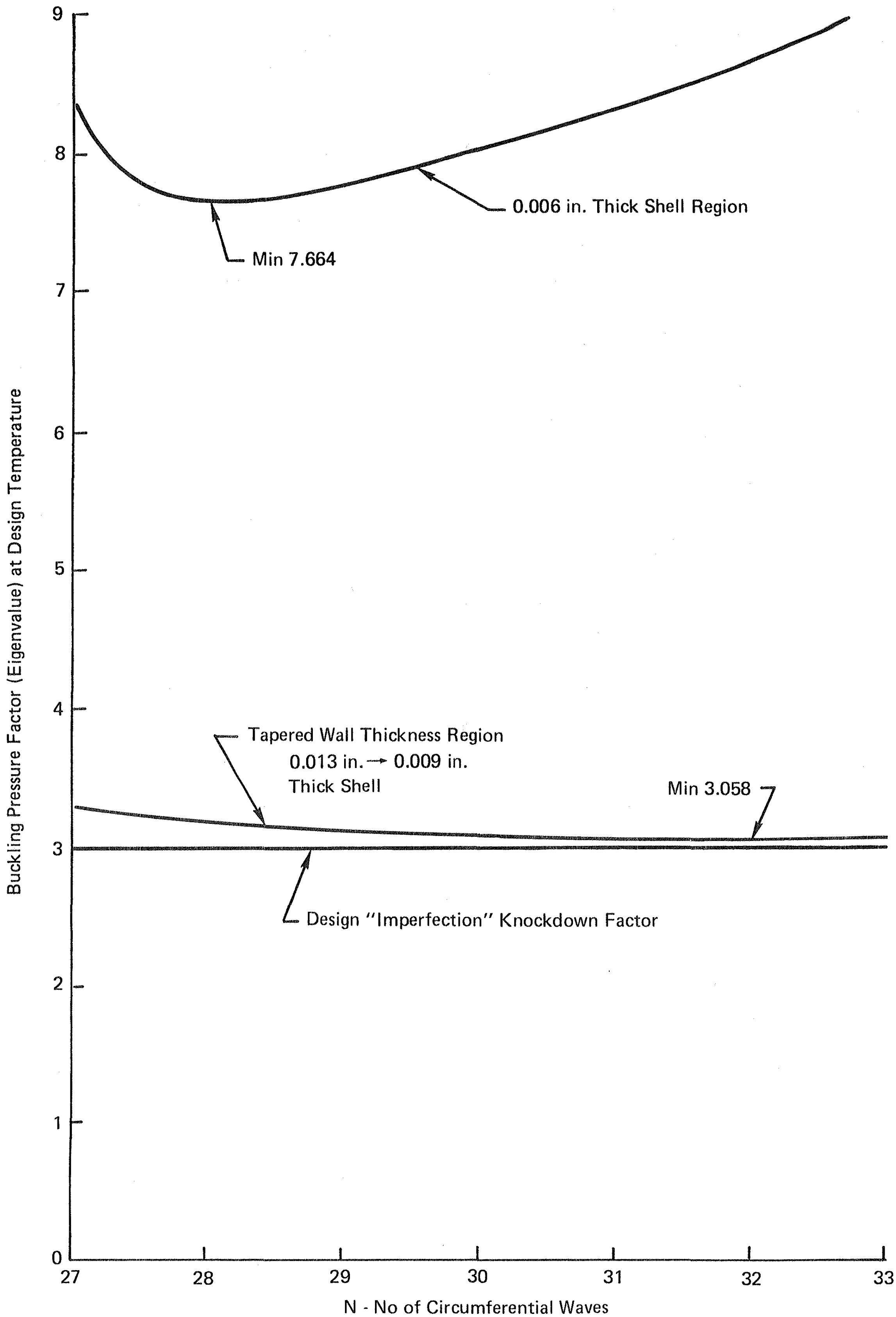


Figure 7-3. Computed Perfect Shell Buckling Baseline 205/1 Nozzle Design

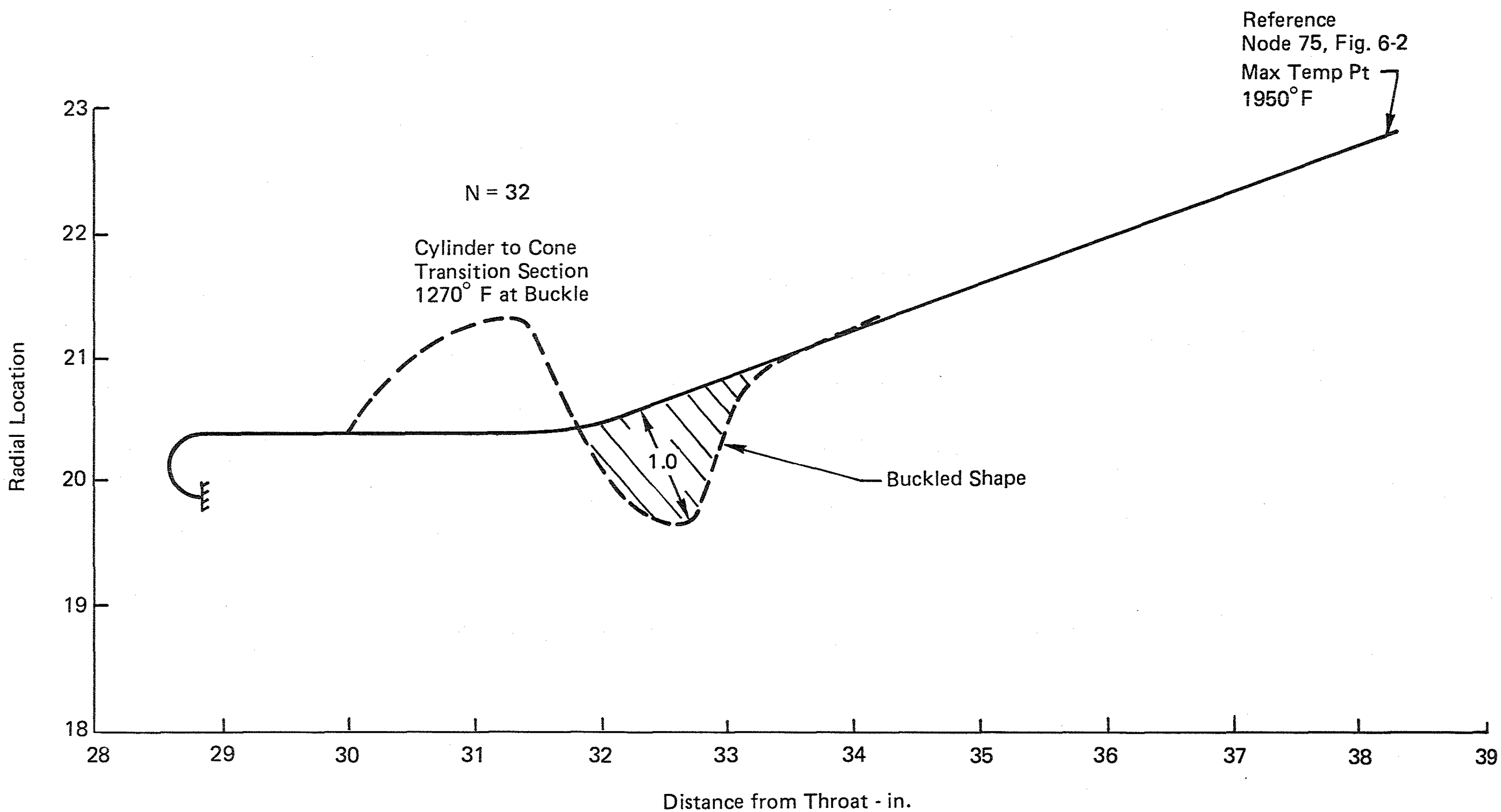


Figure 7-4. Thrust Buckling Mode Shape for 205ϵ CN

In this manner the thermal/structural analyses of the deployed convoluted nozzle confirmed the design and defined the thickness of the nozzle that will be deployed by rolling inside out from a convoluted configuration to a rigid extension of the primary nozzle.

8.0 CN DEPLOYMENT ANALYSIS, ε 205

The remaining optimization effort of the study was concentrated on a self actuated deployment system for the baseline 205 ε Convoluted Nozzle.

8.1 ROLL CONTROL ANALYSIS

A series of rolling and buckling calculations were conducted to determine the effects of nozzle contour, thickness taper and roll control cones on the relationship between the rolling and radial buckling pressures of the baseline 205 ε Convoluted Nozzle. The rolling pressures were calculated with a Bell computer program for conic section rolling and the radial buckling pressures were calculated with the BOSOR 4 general purpose computer program.

The pressure required to roll the CN is a proportional function of the local half angle of the nozzle and is inversely proportional to the local ratio of the nozzle diameter to thickness. With a minimum CN thickness of 0.013 in. at the attachment end, established by analysis of the deployed CN operating loads and requirements, the rolling pressures were calculated for a constant thickness CN (fabricated by seam welding formed sections) and for a tapered CN (fabricated by shear spinning a seamless unit). The results, given in Table 8-1 and Figure 8-1, show significantly lower rolling pressures for the tapered CN during the first half of the deployment where the pressure required to buckle the CN is also low. This advantage of lower rolling pressure (relative to buckling pressure), combined with lower CN weight (due also to the taper) and higher reliability with a seamless unit was sufficient to select the shear spinning method of fabrication for the baseline CN.

However, the radial buckling pressure calculations showed that while the low rolling pressures shown in Figure 8-1 will minimize the size and weight of the roll control structure, they are not low enough (even with further reduction by prerolling) to eliminate the need for a roll control structure to prevent radial buckling deformation. The base line design was examined for buckling in its fully stowed state (i.e., at the start of deployment) as well as a partially deployed state near the end of deployment (where the rolling radius is adjacent to the nozzle mounting bolts). In both of these cases, the BOSOR4 computed buckling pressure was well below the required rolling pressure. Consequently, the stowed nozzle will require a back-up support to prevent the inward motion that triggers buckling on the unsupported shell.

The lightest weight back-up support structure is achieved using a graphite epoxy faced sandwich. The graphite epoxy has a very high ratio of elastic modulus to density, being about 5 times that of aluminum. Trial calculations showed that, with a sandwich core depth of 0.25 in. and 0.15 in. thick faces, the back-up structure can support three times the rolling pressure. By forming the composite structure in place on the CN, the back-up sandwich contour will fit very closely to the rollable part of the stowed nozzle to preclude buckling during deployment. The back-up structure can be attached to the titanium thrust ring. With a sandwich core density of 6 lb/ft^3 the roll control structure weight can be as low as 9.5 lb.

The roll control analysis therefore defined the optimum CN thickness profile (tapered by shear spinning) and the roll control structure design approach for minimum weight.

TABLE 8-1. ROLL ANALYSIS

Tapered CN 205ε

Roll Action	Start					End
Roll Position - in.	0	5.826	11.329	17.340	22.138	26.900
Contour Sta X - in.	52.9848	47.1593	41.6556	35.6445	30.8467	N/A
Contour Rad Y - in.	27.5983	25.7958	23.9681	21.8106	19.9466	19.9466
Half Angle θ (deg)	16.63	17.77	18.99	20.53	21.96	0
Min t - in. (t_b = 0.035)	0.0100	0.0107	0.0114	0.0123	0.0131	0.0130
D/t Ratio	5520	4822	4205	3546	3045	3069
r/t Ratio	44	38	34	28	24	19
Roll Press. - psi	0.6	0.8	1.0	1.30	1.63	1.90

Const t CN 205ε
(Min t = 0.013 in.)

D/t Ratio	4246	3969	3687	3355	3045	3069
r/t	34	31	29	27	24	19
Roll Press. - psi	1.0	1.1	1.2	1.41	1.63	1.90

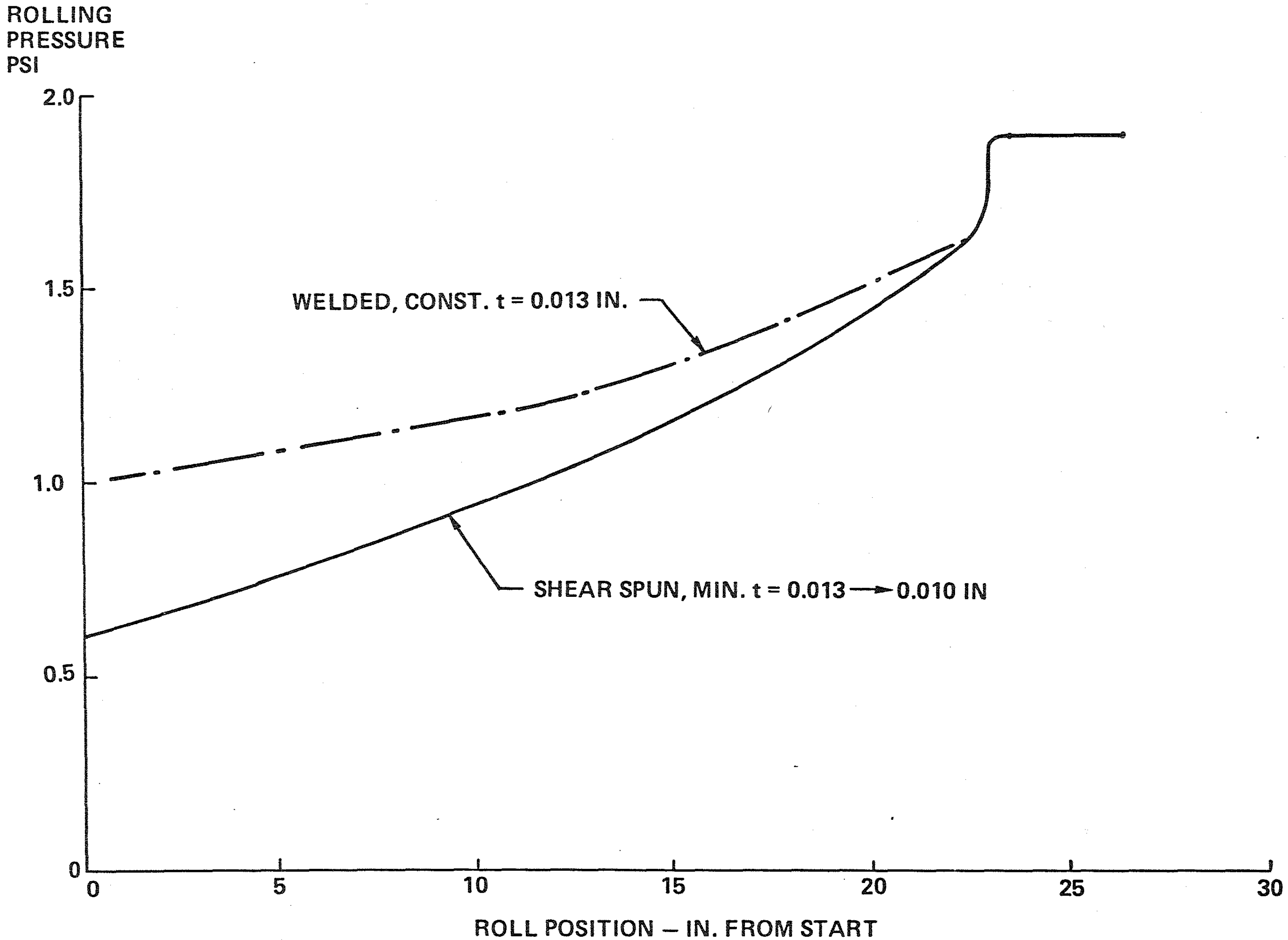


Figure 8-1. Rolling Pressure – 205 ϵ CN

8.2 DEPLOYMENT BY WARM GAS GENERATOR

The basic design of the self deployed CN system consists of 1) a CN that is bolt ring mounted to the primary nozzle with a static seal, 2) a conic shaped, rubber impregnated nylon cloth cover (with a styrofoam ring stabilizer) that is adhesively positioned on the CN as shown in Figure 2-2 and is secured to the CN by riveted mating rings and 3) a low pressure gas source.

8.2.1 Nylon Cloth Deployment Cover

The nozzle is deployed by the pressure force retained by the flexible cover, which pulls on the flange between the fixed nozzle extension and the rolling part of the nozzle. The required pressure increases as the deployment proceeds, as previously shown in Table 8-1 and Figure 8-1.

The installed shape of the cover is a frustum of a cone with the top (small diameter) nesting across the end of the engine nozzle. A light foam disc, which is bonded to the middle of the cover, forms the top of the cone and serves to locate it into the engine nozzle.

The cover must incorporate a vent port to keep the pressure differential across the cover down to 0.3 lb/in. during the climb into shuttle orbit to prevent CN movement or the start of deployment. The rate of change of shuttle bay pressure has a maximum of 0.5 psi/sec early in the climb, after which it is near-constant at 0.2 psi/sec until the pressure is down to about 1 psia, when the rate gradually drops to zero. The critical time for venting is the 1 psi point: at this time a vent 1 in. diameter minimum is required.

When under pressure, during deployment, the cover will stretch from its conical shape to something more rounded. The stretch of the nylon fabric will cause it to lie along the nozzle for a short distance, so that a hoop stress from the deployment pressure will appear in the nozzle extension. The thickness of the extension is normally fixed by the criterion of buckling under the thrust load of engine operation. Therefore, if the deployment is to cause no weight penalty, the maximum deployment pressure must be limited to the capability of that same nozzle thickness. In this design, the 0.006 in. thick nozzle extension has an excess of strength (7 psi capability) to withstand the actual deployment pressures and its limiting effect appears only as a limit on deployment rate, in the following way.

In order to ensure full deployment under all conditions, the deployment charge will have excess propellant. At the end of the deployment stroke, the gas flow which was increasing the pressure and volume now serves to raise the pressure until the flow rate from the open vent matches gas generator flow or the gas generator reaches burnout, whichever is sooner. The maximum permissible pressure, therefore, limits the flow rate and hence the deployment time.

The limitation imposed by the nozzle extension hoop strength could be avoided by building stiffer material into a band around the conical part of the deployment cover near the flange and modifying its shape to prevent it lying against the nozzle. The advantage to be gained would be quicker deployment and less charge weight, because there is then less time with gas escaping through the apex vent and less heat loss. The penalty is cover weight, so there would be a trade-off to be made.

In practice, the volume involved is very large compared with the gas generator flow, therefore, it will be possible to build-in an adequate margin of gas generator burn time without reaching the maximum pressure. (That is, the steady state where apex vent flow equals gas generator flow.) However, for this design, the conservative approach has been taken: the nozzle and deployment cover will withstand steady state pressure.

8.2.2 Gas Generator

The gas generator is mounted as shown in Figure 2-2 on the inside of the CN roll control cone so that it can inject gas through the nozzle mount flange into the space behind the fairing. The fairing is easily able to withstand impingement of the hot gas and serves to diffuse and distribute the gas as it flows into the nozzle space.

The design incorporates a solid propellant gas generator for nozzle deployment. A low temperature type of propellant is envisaged producing a gas at 2200°F, for example, an ammonium nitrate based propellant.

This temperature is well within the tolerance of the metallic parts of the nozzle and engine. Also, provided the gas does not impinge directly on the cover, it will be acceptable to a rubber coated nylon material. The temperature of the gas leaving the gas generator will drop rapidly in the actuation space because a) the turbulence velocities created by the high injection velocity will produce high heat transfer, b) the heat transfer area represented by the nozzle is very large, c) the heat capacity of the metal parts of the nozzle is an order of magnitude greater than that of the gas. Preliminary design calculations shows that for turbulance velocities of about 100 ft/sec, the deployment gas temperature could drop as low as 600°F. Accepting this figure leads to a conservative deployment charge weight of 0.62 lb and a deployment time of 6.7 secs as shown in Figure 8-2. This weight includes a 33% margin of propellant; that is, the gas generator is sized to run 10 seconds. Figure 8-2 also shows that this 3.3 seconds excess running time will not be sufficient to raise the pressure from 1.9 psi at the end of deployment to the permissible 7 psi. Therefore, there is some scope for reducing deployment time, but the effect on weight will be small. It is a refinement which will be investigated at a later stage of design when more precise estimates of gas temperature have been made.

This propellant has no metallic ingredient so the combustion gas has no solid particles to contaminate the engine injector. The composition of the gas is as below:

Component	% by Weight
Nitrogen	29
Carbon Monoxide	26
Water	25
Carbon Dioxide	16
Hydrogen	3

A large number of gas generator propellants are available, tailored to specific requirements of temperature, burning rate, storage life, etc. The one above was chosen as an example and is not necessarily the optimum. The charge design will be optimized when heat transfer to the nozzle and temperature tolerance of the cover has been studied in more detail.

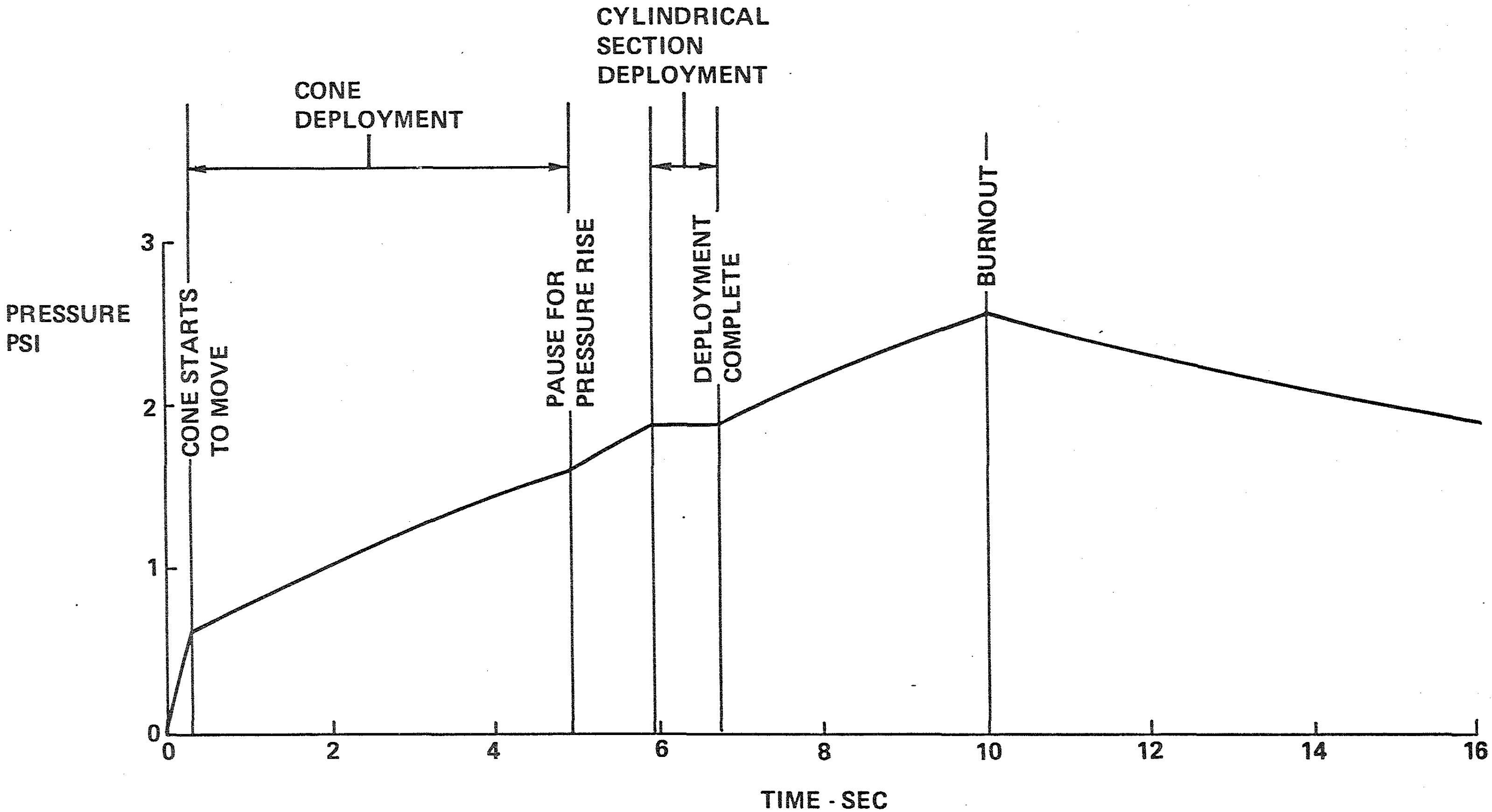


Figure 8-2. Deployment Time Profile for Constant Rate Gas Flow

Another potential source of contamination is the igniter. The usual rocket motor igniter produces metallic particles and slag, but this is a result of the requirements for rapid ignition and flame spread. Our application does not have this requirement and therefore can use a non-contaminating igniter of the heated wire type.

8.2.3 Deployment Cover Separation

Thrust buckling and rollback calculations for the CN at the end of deployment, shows that the exit cover cannot be released until the deployment pressure decays to 1.0 psia or lower. This will provide a factor of safety of 1.33 on the minimum pressure of 1.33 psi required to roll back the CN. Separation of the cover at higher pressures than 1.33 psi will produce a cover ejection thrust pulse that will rollback or buckle the CN. The deployment gas pressure will decay below 1.0 psia approximately 15 seconds after the gas generator burnout shown in Figure 8-2. The CN exit cover separation must therefore be initiated at any time subsequent to 25 sec after the deployment gas generator is initiated.

The lightest possible method of retention and then separation of the deployment cover was found by separating the retention and separation functions. The deployment cover is retained for deployment by fastening tabs secured in the riveted joint between the convoluted section and the fixed section of the CN (see Figure 2-2). The nylon cloth cover is separated after deployment by a rapid burning fuse sewn into the cloth around the periphery near the retaining joint tabs as shown in Figure 2-1. The purpose of the fuse is to burn and melt the base of the nylon fastening tabs while the cover is still loaded by residual deployment pressure (at any level below 1.0 psia) so that it will be blown off of the CN. The residual stubs of the cloth tabs will then be burned flush with the CN wall by exhaust gases during the first operation of the engine.

8.3 DEPLOYMENT LOADS ANALYSIS

The extendible convoluted nozzle is divided into two parts. The forward (rolling) portion attaches directly to the RL10 primary nozzle through a 347 stainless steel mount flange. This portion of the columbium extendible nozzle tapers from a 0.013 in. minimum thickness at its mount location, to a thickness of 0.009 in. at its aft end. The aft portion of the CN has a constant thickness of 0.006 in. The nozzle sections are clamped together by a circumferential ring structure located on the extendible nozzle so as to provide for a 55 inch nozzle extension when full deployment is achieved.

Nozzle deployment occurs when a nylon cloth (rubber impregnated) exit cover is pressurized. The exit cover is clamped to the nozzle at the ring structure which connects the two portions of the nozzle. The pressure is provided by warm gas actuation and the force is reacted through the convoluted nozzle into the RL10 nozzle. The CN rolls under this pressure from its stowed position to full deployment. A pressure of 0.6 psi begins the rollng process and builds to a value of1.9 psi at the completion of deployment.

Depending on the flexibility of the pressurized cover material, the cover under maximum pressure may act at a variety of angles with the convoluted nozzle at their clamped interface. For stiff material, it might be assumed the cover angle with the convoluted nozzle would hold at its initial relationship, which exists in the stowed position. A very flexible material would fold itself against the inside of the CN, effectively reducing the angle between nozzle and bag to zero. The transfer of the exit cover pressure force to the CN at the ring structure will impart a "kick" load to the ring. The greater the angle the exit cover makes with the CN, the greater the "kick" load on the ring.

A conservative assumption was made with respect to the exit cover material flexibility. Under maximum pressure (1.9 psi), the angle the exit cover makes with the convoluted nozzle in the stowed position was assumed to be halved at full extension and this angle becomes $\sim 10°$. A summation of static forces at the juncture point of the exit cover and convoluted nozzle, leads to a "kick" load on the ring of 12.71 lb/inch of circumference.

The ring section consists of back to back angles with the flanges at the outer edge. A ring depth of 1 inch was chosen to provide a satisfactory gripping width for the nozzle and contained exit cover material and to assure sufficient edge distance would be provided for the connectors used (1/4 in. ϕrivets).

An analysis of the ring under uniform compression indicates the section requirements of the ring dictate a minimum uniform thickness of 0.060 inch for the angles. The flanges on the angles are 1/2 inch wide. The material is titanium (6 Al - 4V). The critical load is the uniformly applied external pressure provided by the "kick" load referred to above. The portion of the web which extends radially inward from the rivet circumference was also checked for bending. This portion of the web acts like a cantilever beam under end loading provided by the pull of the exit cover during deployment.

The stress in the nylon cloth (rubber impregnated) exit cover was determined under maximum deployment pressure. In house test data on the same material was used to determine the margin of safety for this component.

A factor of safety of 1.5 was applied to all loads used in analysis.

At the completion of nozzle deployment an integral confined burning fuse is ignited which burns away the exit cover at its attachment to the CN. The cover is ejected from the nozzle by residual gas pressure from the warm gas generator burnout. If tests show that cover separation is not consistantly clean (e.g., no whipping) then ignition of the confined burning fuse can be delayed until the residual pressure decays to zero. The separated cover will then be ejected by motor ignition. That portion of the cover clamped between the titanium ring angles (i.e., the tabs) will remain after cover ejection. The elements clamped together at the ring structure are; a 0.010 inch flange on the forward part of the nozzle, a 0.006 inch flange on the aft part of the nozzle and, between these two flanges, a 0.020 inch thickness of cover material.

The details of these calculations are given in Appendix I. On the basis of this analysis of the deployment loads, the cover retaining joint flange thicknesses were established and it was concluded that this self-deployed CN system is structurally sound.

9.0 BASELINE CN DESIGN, $\varepsilon = 205$

By a process of design refinement and optimization during the course of thermal analysis, structural analysis and deployment analysis (as described in the preceding sections), the conceptual design of the baseline 205 ε Convoluted Nozzle developed into the preliminary design shown in Figure 9-1.

9.1 DESIGN FEATURES

The baseline 205 ε CN design consists of a modular assembly of Convoluted Nozzle, thrust/mount ring, roll control cone, warm gas generator, cover separation fuse and deployment cover of rubber impregnated nylon cloth as shown in the upper half of Figure 9-1. The RL10 engine is omitted from this figure to enhance clarity. Details of the thrust/mount ring interface with the RL10 engine are given in Figure 9-2 for the deployed CN configuration shown in the lower half of Figure 9-1. The baseline 205 ε CN assembly on the RL10 engine is shown in Figure 9-3 and component details are shown in Figure 9-4. The mount joint configuration incorporates a fairing to provide simple aft end installation at low CN system weight. The mount joint consists of a stainless steel mount flange that is brazed to the RL10 primary nozzle, a titanium alloy thrust ring that is welded to the CN and a 4 in. long columbium alloy fairing as shown in Figure 9-2.

CN installation is accomplished by advancing the CN over the RL10 engine (Figure 9-3) until the thrust ring flange (with Grafoil static seal) meets and aligns with the mount flange on the primary nozzle. The CN is then sealed and secured to the primary nozzle by threading 80 bolts into nut plates on the mount flange shown in Figure 9-2. The fairing is then installed and secured by threading 20 flush head screws into the nut plates in the webs on the thrust ring.

The purpose of the fairing is to hold the RL10-IIB engine exhaust gas boundary layer in place and smooth the gas flow across the large CN mount joint discontinuity required to provide for CN installation entirely from the aft end of the engine - after the engine has been installed and serviced on the Centaur vehicle.

After the fairing is installed, the CN assembly is completed by securing the apex of the 2 piece deployment cover with a nylon hinge cable as shown in Figure 9-4 (the base of the deployment cover is fastened during fabrication in the riveted flange joint between the rolling and fixed sections of the CN as shown in detail A of Figure 9-4.

9.2 OPERATING CHARACTERISTICS

The Convoluted Nozzle may be deployed as soon as the Centaur OTV has been separated from the Space Shuttle. Deployment is initiated by 28 Vdc supplied to the igniter of the warm gas generator by a single command discrete. The warm gas ($T_c \sim 2000°F$) pressurizes the CN and flows out through the small apex vent of the cloth exit cover (sized to vent the CN during shuttle ascent to LEO). The CN starts rolling at an internal pressure of approximately 0.6 psia, continues rolling as the pressure rises above this value (e.g., phantom line position in Figure 9-5), and completes rollout at a pressure of approximately 2 psi in a burn rate/grain design controlled interval of approximately 7 sec. The gas generator burns out in 10 sec. (after consuming the design margin excess propellant) with the CN pressurized to approximately 2.6 psi. The pressure will then begin to decay by continued gas loss through the apex vent, dropping below 1.0 psi at 25

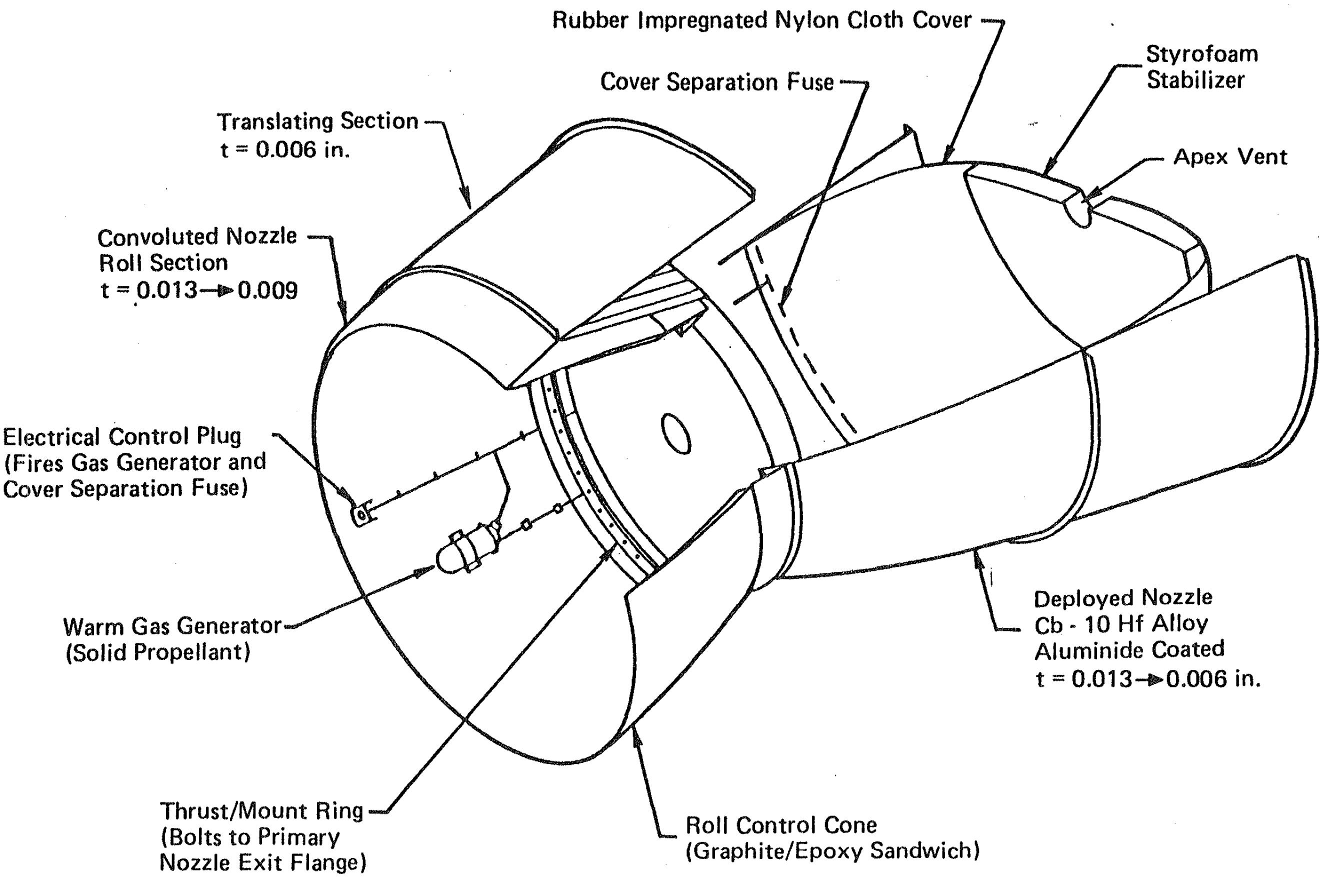


Figure 9-1. Baseline 205 ϵ CN Self Deployed System

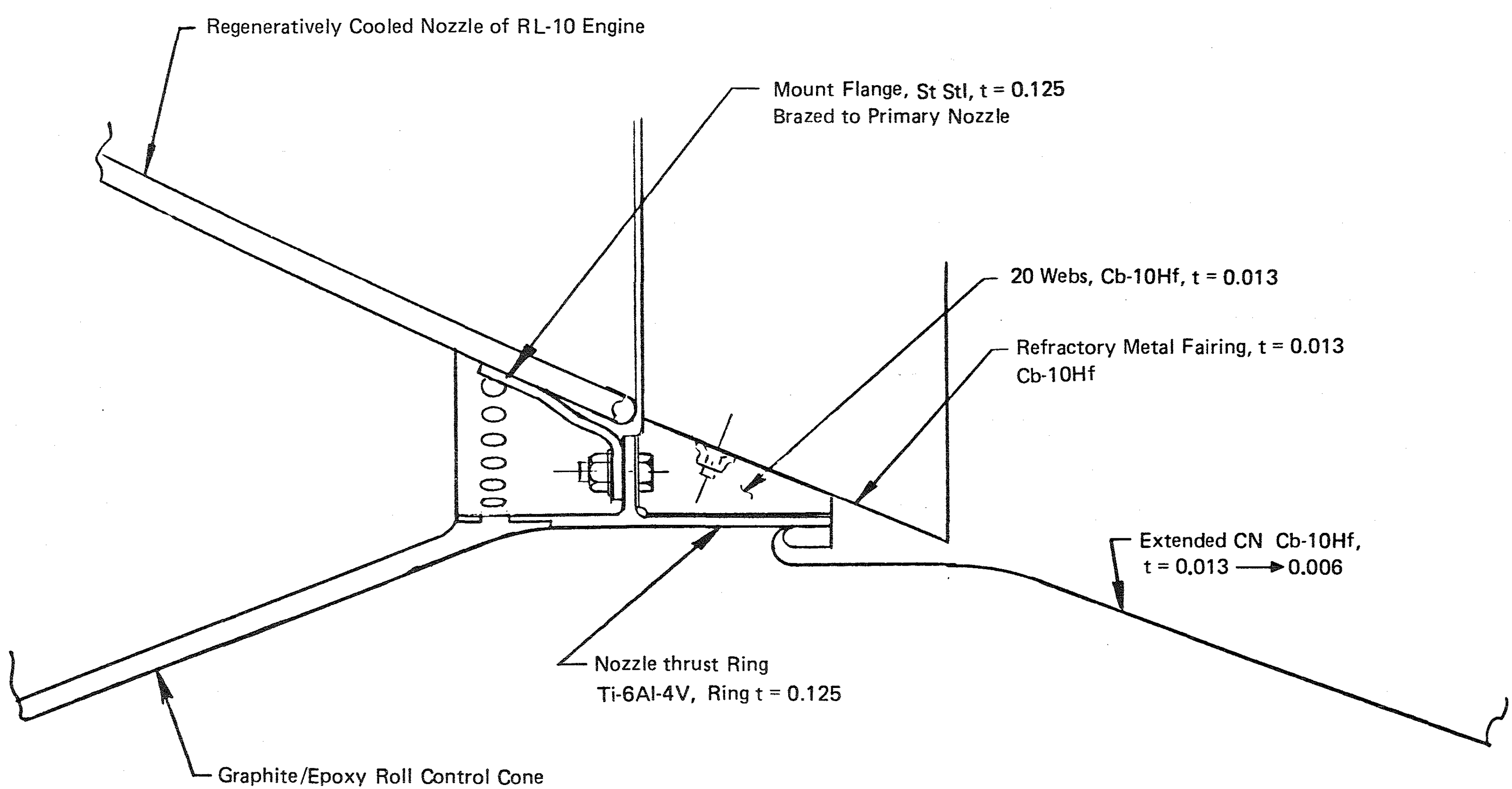


Figure 9-2. Convoluted Nozzle (CN) Mount Joint Config. No. 3
Selected Baseline Design

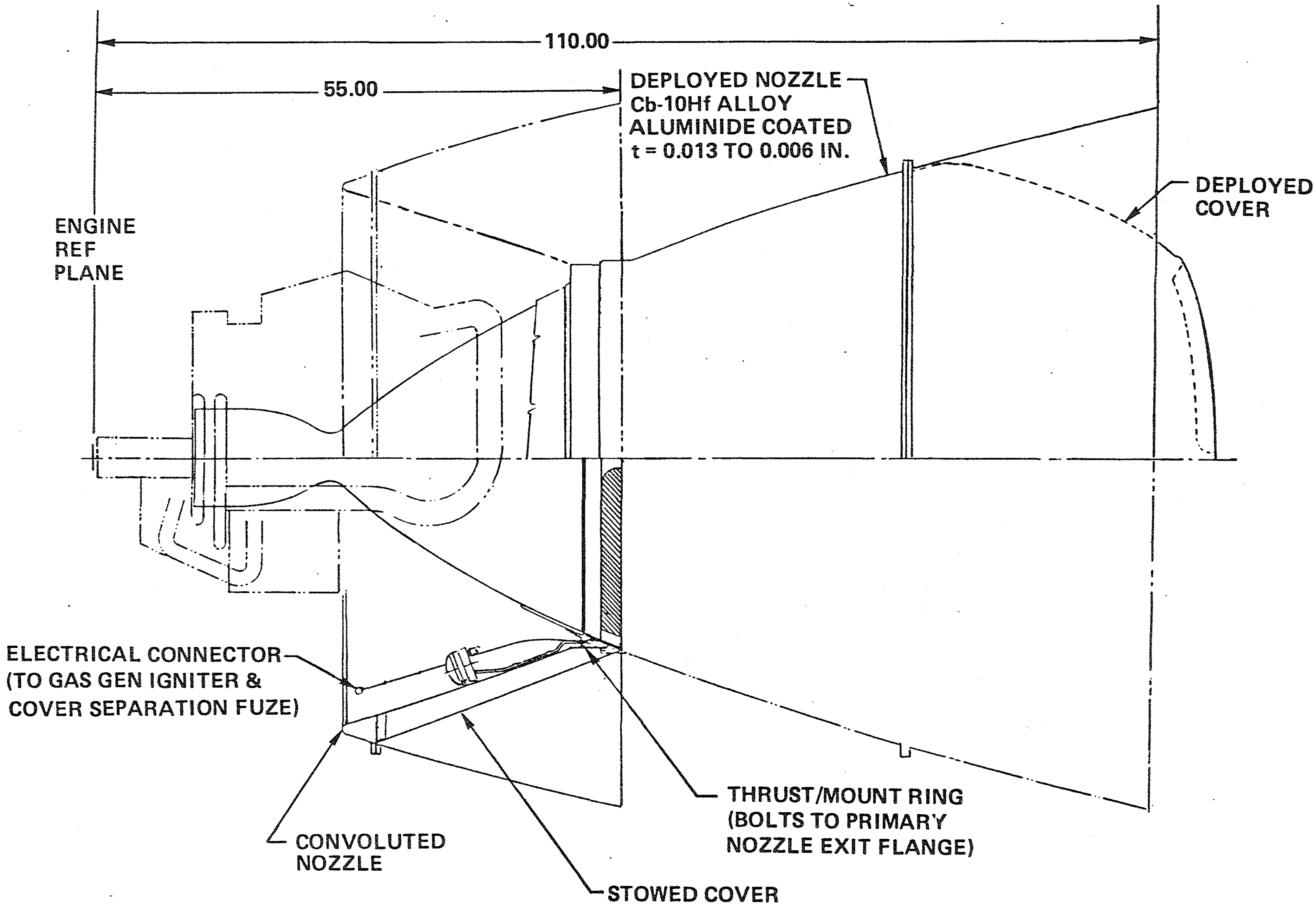


Figure 9-3. Baseline CN Design Self Deployed Assembly, $\epsilon = 205$

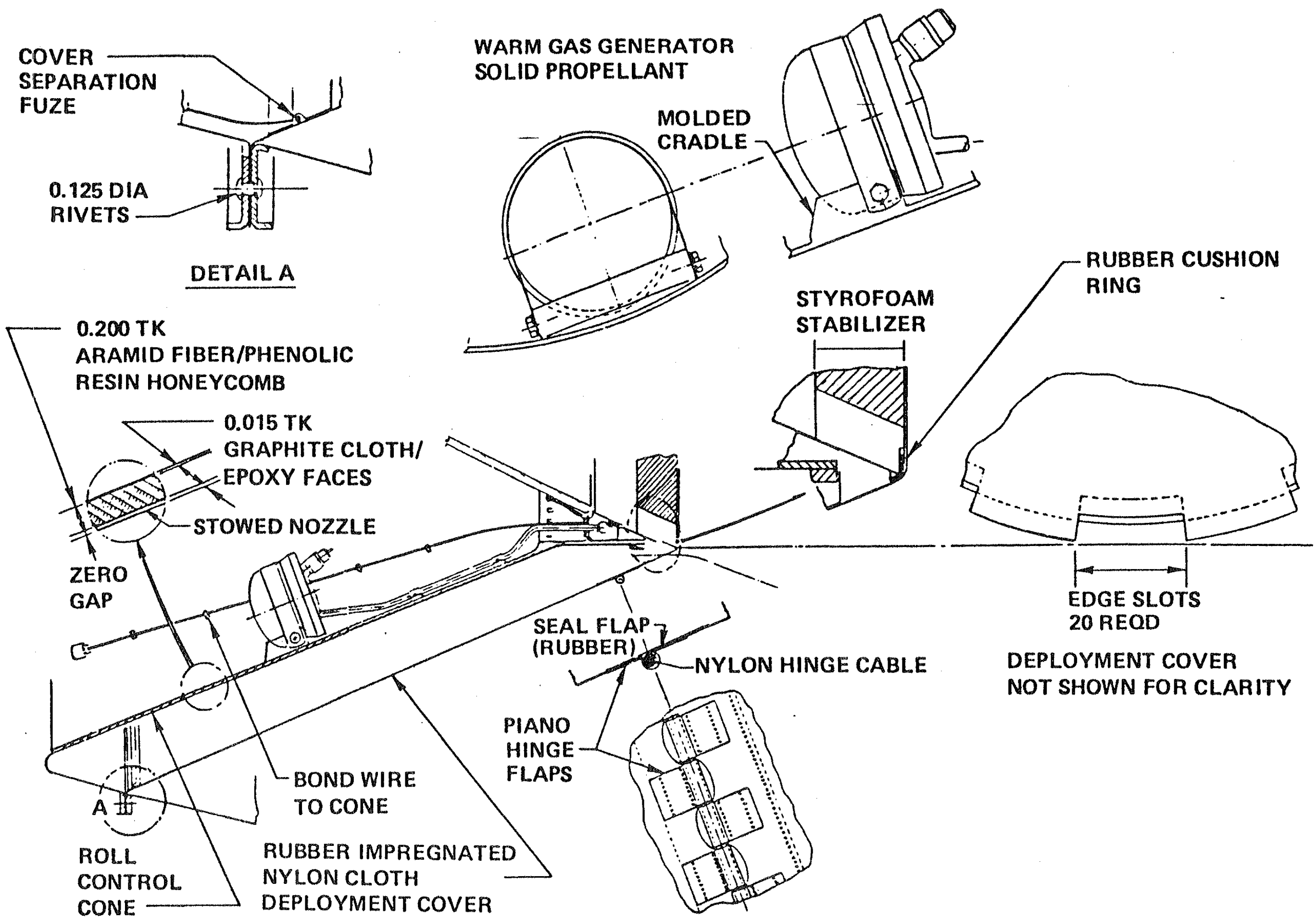


Figure 9-4. Baseline CN Design Self Deployed Details, $\epsilon = 205$

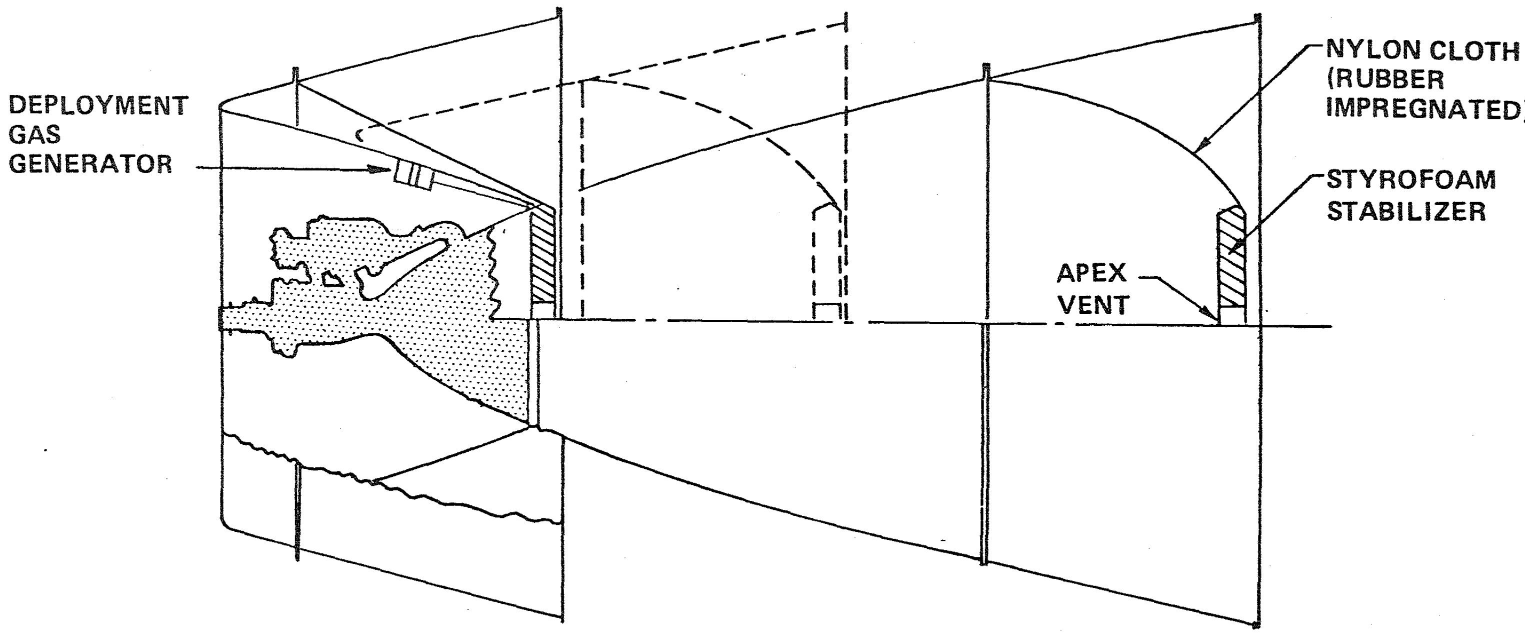


Figure 9-5. CN Self Deployment

sec into the deployment sequence. At this pressure the deployment cover ejection thrust pulse loads are acceptable and cover separation can therefore be initiated at any subsequent time. The integral confined burning fuse is then ignited by 28 Vdc to burn away the nylon cloth cover attachment to the CN. The 8.5 lb nylon cloth cover is then ejected by residual gas pressure in the CN to leave a simple, rigid refractory metal nozzle extension in place on the RL10-IIB rocket engine. This self deployment sequence is summarized in Table 9-1.

TABLE 9-1. CN SELF DEPLOYMENT SEQUENCE

- 28 Vdc supplied to igniter of warm gas generator.
- Warm gas pressurizes CN and flows out through small apex vent of cloth exit cover (sized to vent CN during ascent to LEO).
- CN starts rolling at an internal pressure of approx 0.6 psia and completes rollout at a pressure of approx. 2 psia in a controlled time interval of approx. 7 sec.
- Gas generator burns out at 10 sec (with CN pressurized to approx. 2.6 psia)
- 28 Vdc supplied to cover separation fuse at 25 sec or later (to permit CN pressure to decay below 1 psi).
- The fuse then burns away the nylon cloth exit cover attachment to the CN and the cover is ejected from the CN by residual gas pressure (from the warm gas generator burnout)
- The remaining CN is a simple rigid refractory metal nozzle extension that is ready for engine firing.

The operating weight of this baseline 205 ε CN is 77.6 lb after deployment (and ejection of the 8.5 lb cloth cover) and the specific impulse gain is 16 sec (compared to the standard RL10 engine operating at a mixture ratio of 5.0 with a fixed nozzle ε = 57). This CN is designed for a single deployment to be followed by extensive use and reuse in space based OTV service of the RL10-IIB engine. The service life goal of 36,000 sec of operation in 180 firings is believed to be achievable with the columbium alloy and aluminide coating system selected for the Convoluted Nozzle (on the basis of successful application of this same alloy and coating system on the nozzle extensions of the Apollo Service Module Engine and the LEM Descent Engine).

10.0 MAXIMUM PERFORMANCE CN DESIGN, $\varepsilon = 303$

The maximum performance increase obtainable with the Convoluted Nozzle (or any other nozzle extension) was determined by the deployed nozzle contour supplied by P&WA and the length limitation specified in the Guidelines and Ground Rules (Section 4.1). Layout studies (See Figure 5-5) showed that this contour would limit the expansion ratio (ε) to 303/1 within the 150 in. length limit for the engine with CN extended. In other respects this CN design is a scale up of the self deployed 205 ε CN as shown by comparison in Figure 10-1.

The design features and operating characteristics of the maximum performance 303 ε CN are identical to the 205 ε CN except for numerical details of dimensions, thicknesses and deployment pressures. After deployment and ejection of a 12.6 lb cloth cover, the operating weight of the maximum performance 303 ε CN is 130.4 lb and the specific impulse gain is 22 sec. The 303 ε CN therefore provides 6 more sec of specific impulse than the 205 ε CN for a weight increase of only 53 lb. It was concluded that this 303 ε design is the maximum performance Convoluted Nozzle that can meet the design requirements of Section 4.0.

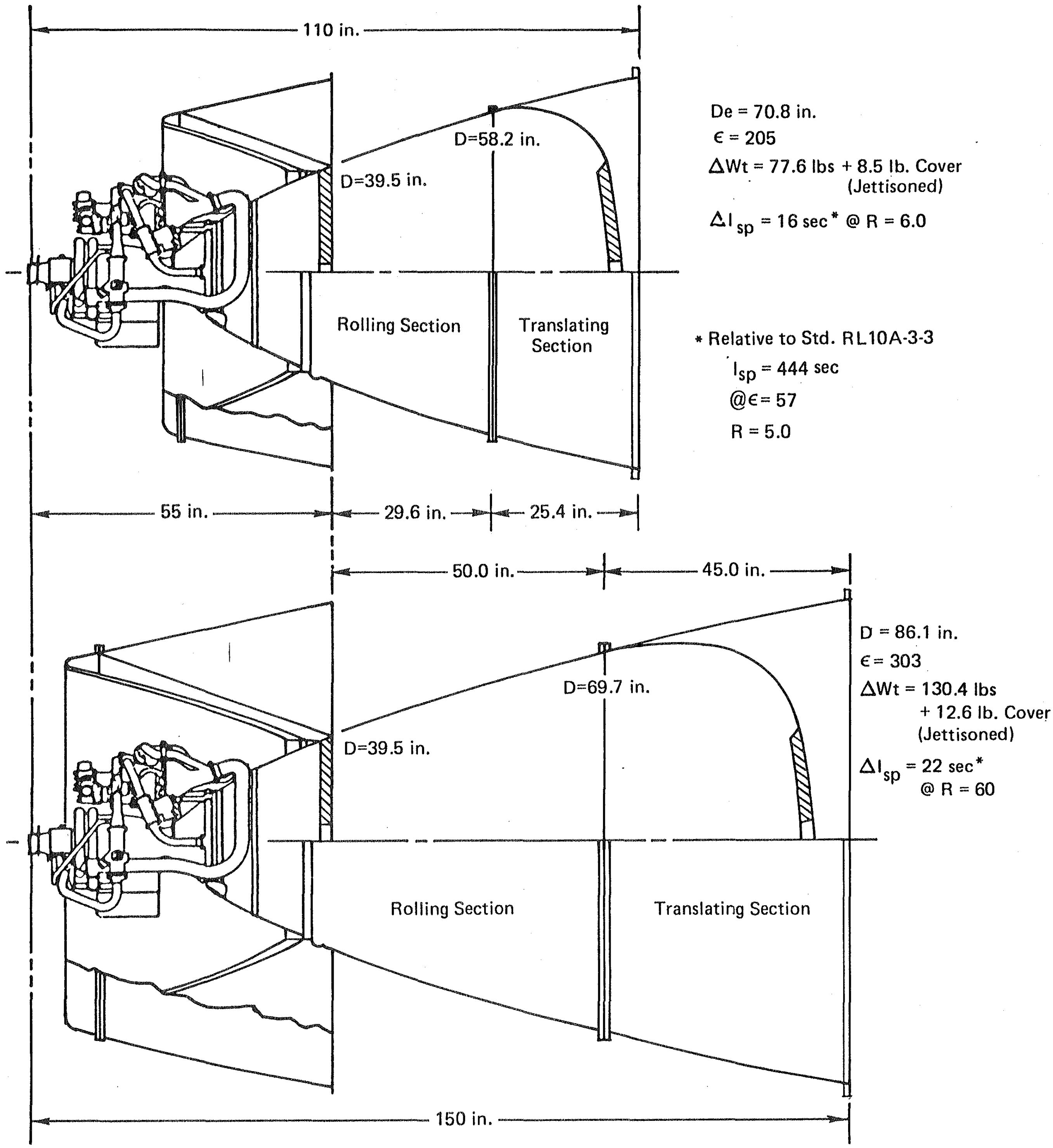


Figure 10-1. Max. Performance 303 ε Convoluted Nozzle Self Deployed System

11.0 EXTENDIBLE/RETRACTABLE CN DESIGN, ε = 205

The extendible and retractable CN is a kit modification of the baseline 205 ε Convoluted Nozzle design to add nozzle retraction capability when required by the mission. The deployment cover and gas generator is replaced by a gas actuator kit as shown in Figure 11-1 for missions consisting of a single deployment followed by extensive firing use and then retraction (for OTV stowage in the Space Shuttle) in ground based OTV service of the RL10-IIB engine.

11.1 DESIGN FEATURES

This extendible/retractable modification kit design was derived from the actuator deployment analysis of the CN. It consists of three double-acting gas actuators, deployment rings to distribute actuator forces on the CN shell, actuator brackets for trunnion mounting and an actuator support ring that forms a torsion box with the actuator support and roll control cone as shown in Figure 11-1. The CN shell, thrust/mount ring and mechanical interface with the RL10-IIB engine is identical to the baseline CN.

11.1.1 Nozzle and Support Structure

The nozzle contour and shell thickness is identical with that of the self-deployed version, but additional structure is needed to distribute the actuator force around the circumference. This is done with a pair of stiff rings, like external bulkheads, around the nozzle near its exit end: the moving end of the actuators apply their forces, both extend and retract, against this deployment ring. The fixed end of the actuators are reacted against another ring at the forward end of the roll control cone which transmits the forces directly to the mount ring and thus no extension or retraction forces are transmitted to the engine.

The convoluted nozzle, nozzle extension, actuators, control cone and mount ring form a compact subassembly for attachment to the engine by bolts through the mount ring at any convenient time during the vehicle preparation sequence.

11.1.2 Actuation System

The power source chosen for actuator design is engine gas (hydrogen) tapped off the turbine inlet manifold at approximately 500 psia. This means that nozzle actuation can be performed only when the engine is running. The engine gas deployed (EGD) system was chosen, rather than an independent stored gas system, principally because of lower weights. The EGD nozzle also has the reliability advantages of eliminated gas storage and control components and the stabilizing effect of internal nozzle pressure during both the rollout and rollback of the EEC.

The proposed actuator concept shown in Figure 11-2 is a unique design in which the order of staging is automatically controlled in both extension and retraction to synchronize the force of 3 actuators on the deployment ring. This is accomplished by a keeper ring during extension and stage porting during retraction (i.e., stages act as valves). The design also incorporates an expansion piston to follow the thermal expansion of the deployed nozzle.

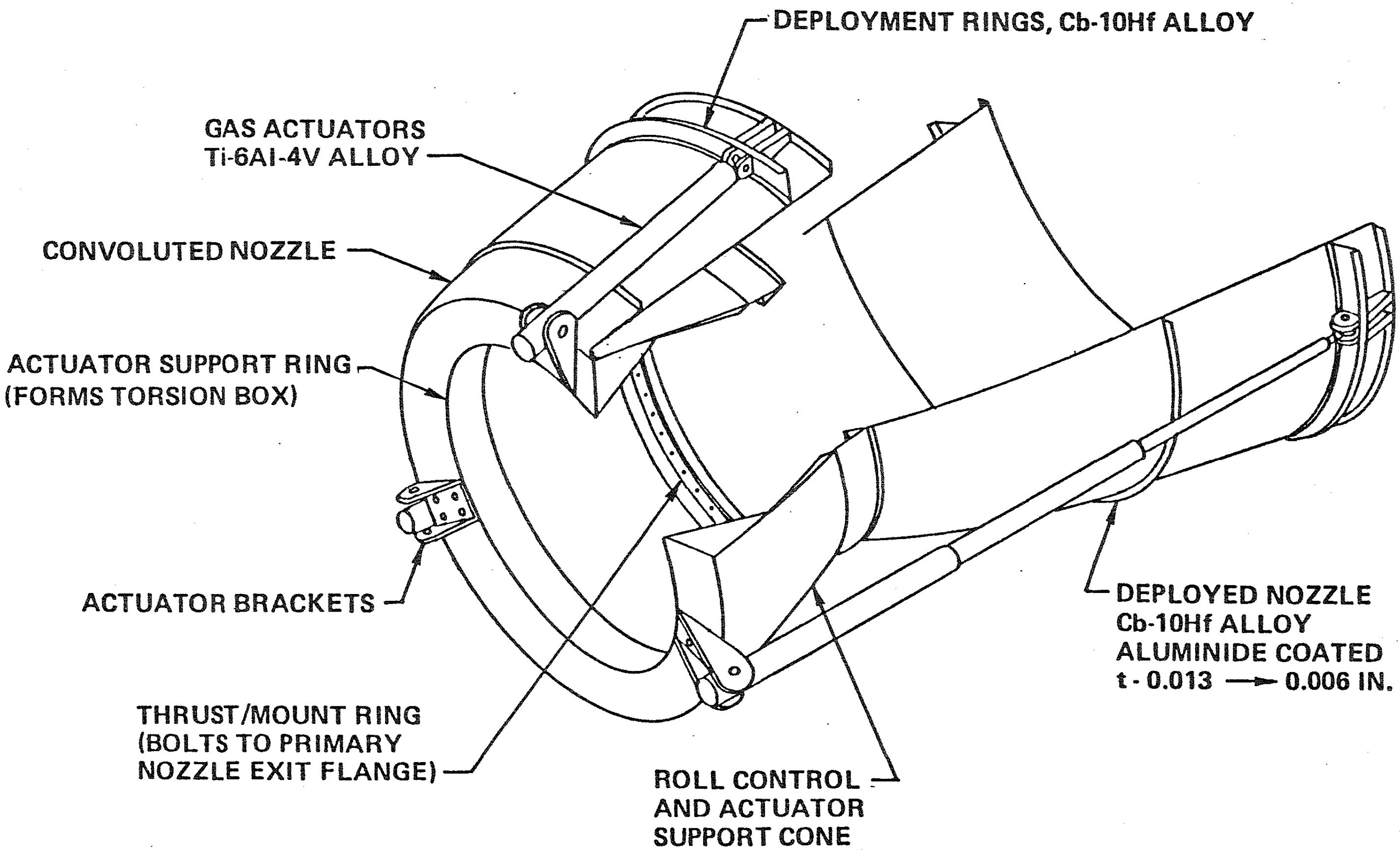
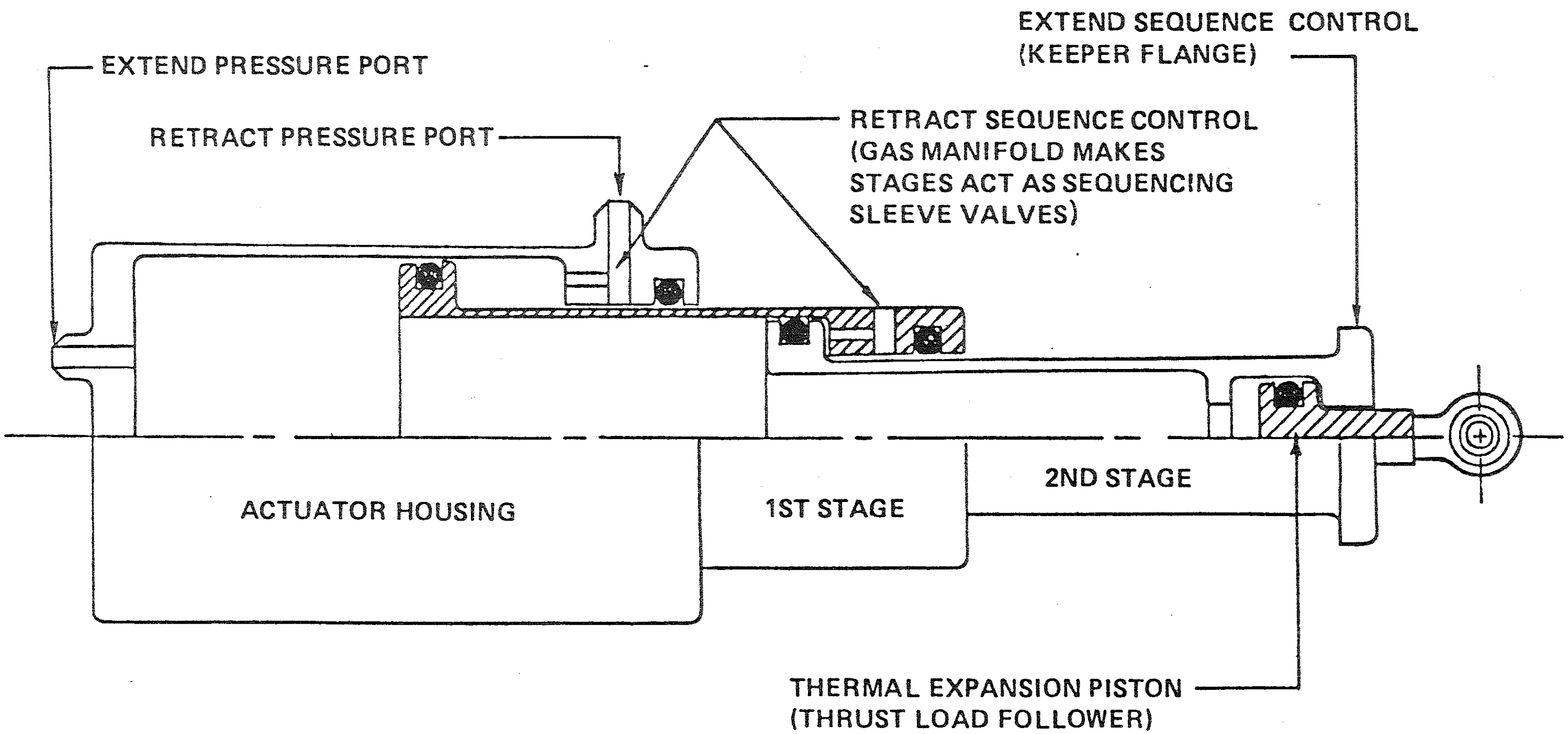


Figure 11-1. Alternate 205 ϵ Convoluted Nozzle – Extendiable/Retractable System



NOTE: O-RING SEALS – 5 PLACES

Figure 11-2. Extendible – Retractable Nozzle Actuator

The actuator design is a double acting three-stage telescoping device with a total stroke of 54 in. The installed length of the actuator is 25 in. from the end cap to the center of the rod and bearing. The following presents the basic design features:

- Tube Material
  - Housing and Stage 1 = 7075-T6 Aluminum
  - Stage 2 and 3 = 6Al-4V Titanium
- Maximum Working Pressure
  - Extend, Retract = 400 psia
- Actuator Force Output
  - Deployment = 1200 lb/actuator
  - Retraction = 650 lb/actuator
- Thermal Expansion Piston
  - Stroke = 0.8 in. max.
  - Maximum Following Force = 430 lb/actuator
- Weight
  - Weight = 13.0 lb/actuator
- Actuator Volume
  - Extend = 276 in^3/actuator
  - Retract = 91 in^3/actuator

The double acting actuator is extended by supplying pressure to the end cap pressure port. To reverse the motion, the extend pressure is vented and pressure is applied to the retract port at the end of the housing tube. A pressure of 70 psia increasing to 400 is required to provide the force necessary to extend the nozzle and a nominal working pressure of 400 psia is required for nozzle retraction.

Large bearing lengths (total length of four inches) at each actuator stage interface provide high column stability of the actuator in the extended position. A thermal expansion piston is included in the actuator. This design feature serves two purposes. First, it allows the actuator to follow the axial expansion of the nozzle due to thermal growth during heatup. Secondly, the diameter of the thermal expansion piston is sized to counteract the thrust load on the nozzle, thereby making the nozzle actuator-supported during engine operation.

The dynamic seals in the actuator consist of Vitron "O" rings with teflon slipper seals. The slipper seals are included to minimize sliding friction. The Vitron "O" ring/teflon slipper seal combination was selected due to proven long life and re-use capabilty.

Another consideration in the design of the actuator is ease of manufacture. The actuator stages are fabricated from extruded aluminum and titanium tubes. A machined cap is welded to each end of the tube. These caps contain the grooves required to accommodate ther actuator seals. 7075-T6 aluminum and 6Al-4V titanium were chosen as the materials for actuator fabrication. These metals have high strength/weight ratios and are widely used aerospace materials.

11.2 OPERATING CHARACTERISTICS

Figure 11-3 is a plot of the actuator pressure and stroke required to provide the CN roll force ± thrust for extension and retraction of the CN. During extension, the actuator will first move all stages together until the first stage (outer cylinder) reaches its stop. It will then continue with the two inner stages for the middle third of its stroke and then finish the movement with the third stage (center rod) only. Thus, the effective area decreases in steps during the stroke. The rolling force required for deployment increases as the deployment proceeds; therefore both effects combine to require an increase of actuator pressure as shown in Figure 11-3. At each of the staging steps, there will be a pause in the movement to allow pressure to build up. Towards the end of the stroke, when the nozzle efflux flow attaches, an extra increment of force will be needed from the actuators to balance the thrust. This will amount to an extra 145 psia of actuator pressure (not shown in Figure 11-3). Contrarily, at the start of retraction the thrust will assist the roll-back. Figure 11-3 is conservative insofar as it ignores residual stresses from deployment, which would assist retraction. In effect, it assumes that the nozzle has become fully annealed in its extended shape.

The working gas for deployment and retraction is hydrogen at turbine inlet pressure. The working gas is controlled by a 4-way solenoid valve (not shown in Figure 11-1) and 1/4 in. titanium gas lines to the extend and retract ports of the double-acting actuators. Gas flows in these lines only during a deployment or retraction cycle. The CN is deployed during the first few seconds of the first firing and then retracted during the last few seconds of the last firing of the mission. The deployed CN is free standing and does not require detents or actuator pressure to react the additional thrust developed in the CN. The feasibility of CN deployment and retraction during engine operation has been demonstrated by the Minuteman Third Stage Convoluted Nozzle (Reference 2).

The specific impulse gain of the extendible/retractable CN is the same as the baseline 205 ε CN but the installed and operating weight of this CN is 145.8 lbs. This amounts to a weight increase of 68 lbs to obtain the retraction capability. For this reason the actuator deployed version of the CN is recommended as a modification kit to be used only on those missions that require CN retraction.

However, missions requiring CN retraction are ground based and the CN can therefore be refurbished and reused. In the context of the CN life requirements (of Section 4.0), the only part of the extendible/retractable CN with limited life is the rolling section of the CN shell. Tests of small scale (5 in. dia.) Convoluted Nozzles have demonstrated up to 3 mission cycles of deployment and retraction but the reusability of the rolling section must be determined empirically for each CN design. It is conservatively estimated that the rolling section of the RL10-IIB CN shell will have to be replaced on every second or third refurbishment of the extendible/retractable Convoluted Nozzle.

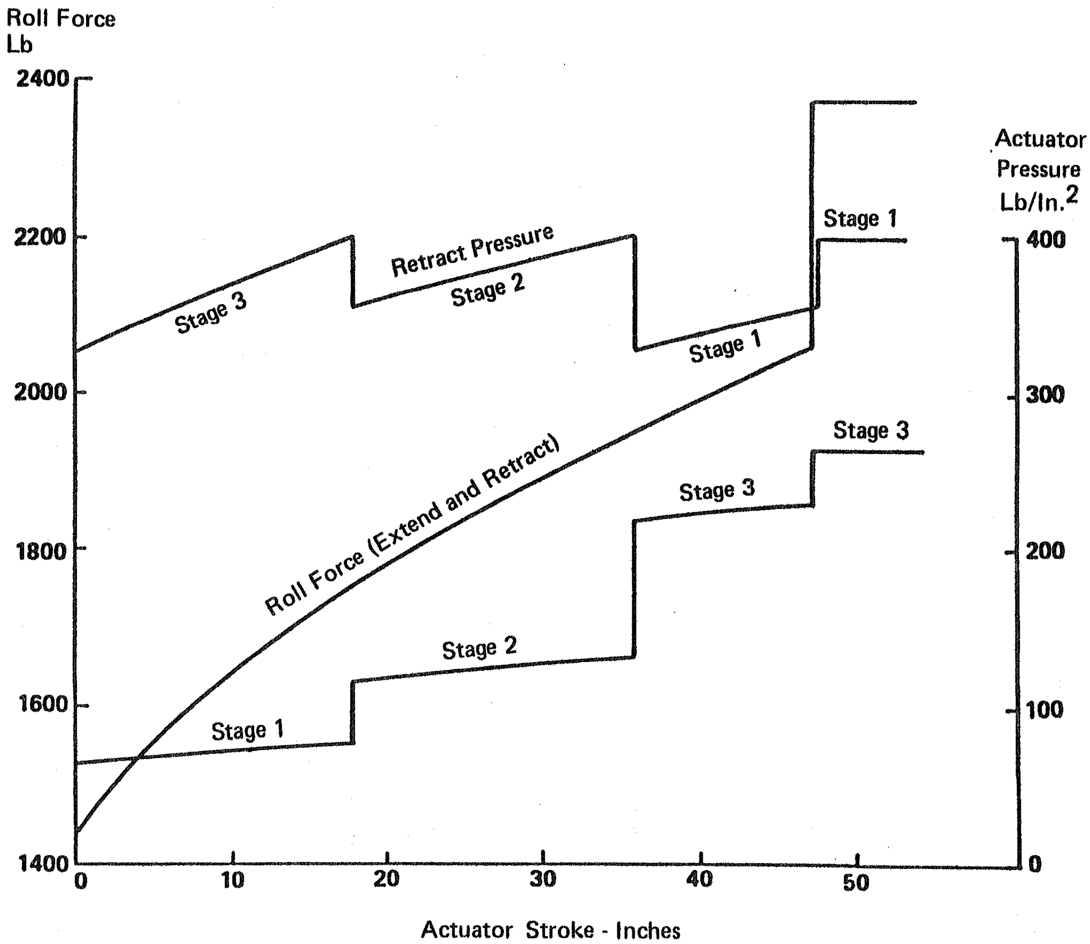


Figure 11-3. Rolling Forces – 205 ϵ Extendible/Retractable CN

12.0 ENABLING TECHNOLOGY

Enabling technology is the additional technical data base that is needed to enable high confidence/low risk entry into subsequent engineering development and operational use of the Convoluted Nozzle. It consists of those additional CN analyses and tests that are required to resolve technical issues and demonstrate the feasibility of the CN in the RL10-IIB engine application.

This section of the report deals with CN subjects that involve enabling technology program recommendations. This includes the rolling capability of the Cb-10Hf alloy and coatings at temperatures down to -300°F, the effect of exhaust gas atmospheres on the hot Cb-10Hf and coatings, the need to experimentally demonstrate the self deployment system and the need to evaluate the prospects of meeting the service life goals by test.

12.1 CN COATING SYSTEM

The baseline coating system selected for the CN was the Vac Hyd-2 Aluminide coating. This coating is applied as a 90% Al-10% Ta slurry and diffused into the Cb-10Hf substrate by firing in a vacuum furnace for one hour at 1850°F. This produces a secure diffusion zone approximately 0.001 in. thick (i.e., into the substrate) and 0.001 to 0.002 in. thickness of excess coating bonded to the surface-which acts as a material source for further diffusion during nozzle operation to heal any cracks or flaws that may develop in the diffused zone which protects the Cb-10Hf substrate. This VH-2 coating provides oxidation protection and a minimum surface emissivity of 0.75 at operating temperatures up to 2800°F.

Cb-10Hf Convoluted Nozzles with the VH-2 aluminide coating were satisfactorily roll deployed and fire tested for 60 sec on Minuteman III Third Stage motors. The same columbium alloy and aluminide coating was also used in the nozzle extensions of the Apollo Service Module and LEM Descent Engines where an extensive life test data base was developed, including 2880 sec of operation in 86 firings on one single service module nozzle extension. In terms of potential for oxidation or embrittlement by oxygen or hydrogen, the nozzle operating temperatures and the nozzle exhaust gas atmosphere of these engines are very similar to the RL10-IIB engine as shown in Table 12-1. This indicates that the RL10-IIB engine single mission requirement of 1500 seconds operation in 7 firings is achievable with the Vac. Hyd-2 aluminide coated Cb-10Hf alloy.

However, CN development for the RL10-IIB engine qualification test of 9000 sec operation in 20 firings will require a comprehensive program of rigorous analysis and test evaluation.

Although the CN operating temperatures are too low for failure by internal surface oxidation,an uncoated Cb-10Hf nozzle would fail by oxygen embrittlement in a few hundred seconds of operation. A coating system is therefore required to protect the Cb-10Hf from the oxygen in the exhaust species. A coating system is also required to protect the Cb-10Hf from hydrogen embrittlement.

Hydrogen embrittlement of Columbium alloys is caused by contamination of the metal with interstitial H_2. The level of H_2 contamination at any given time (e.g., in the life of the CN) is controlled by the cumulative H_2 absorption and the H_2 solubility. At high Cb-10Hf temperatures (i.e., above 900°F), H_2 embrittlement is no problem because, although the absorption of H_2 into columbium increases with

TABLE 12-1. ALUMINIDE COATED Cb-10Hf NOZZLES

Nozzle Extension		Apollo SM	LEM-D	RL10-IIB
Nozzle Temp:	Max.	1900	2300	2100°F
	Min.	1600	1500	1600°F
Propellants		N_2O_4/Hydrazine Blend		O_2/H_2
Mixture Ratio		1.65		6.0
Exhaust Species: (Mol. Fraction)	H_2	24.3%		24.4%
	H_2O	27.2%		75.6%
	CO_2	12.2%		
	CO	5.0%		
	N_2	31.3%		

temperature, the solubility decreases exponentially with temperature. At low Cb-10Hf temperatures (i.e., below 800°F) the absorption is too low to produce embrittling levels of H_2 contamination. However if parts of a continuous structure are subjected to a large thermal gradient (e.g., the CN mount joint region) so that it experiences simultaneously, temperatures much above and much below 800°F. The H_2 will diffuse from the hot section where the absorption is high to the cool section where the solubility is high and cause embrittlement of the cool section (Reference 7).

However, a tin-aluminum coating (R505) applied by Hitemco to the Cb-5V-5Mo-1Zr alloy was found (Reference 7) to be a nearly complete barrier to H_2 absorption into CN parts operating at temperatures above 800°F. This coating would therefore prevent H_2 diffusion into CN parts (in mount region) operating at temperatures below 800°F. There should be little or no H_2 absorption in the low temperature joint region because of the H_2 barrier of the coating and the low rate of absorption at low temperatures. It was probably for these reasons that no H_2 embrittlement problems were reported on the Apollo SM and LEM-D engine development programs.

The alternate coating system selected for the CN was therefore the Hitemco R505 Aluminide coating. This coating is applied as a 75% Sn-25Al slurry and diffused into the Cb-10Hf substrate by firing in a vacuum furnace at 1900°F. This coating also provides oxidation protection and a minimum surface emissivity of 0.75 at operating temperatures up to 2800°F. Although the R505 aluminide coating does not have the extensive rolling and fire test data base of the VH-2, it has the data base on H_2 embrittlement protection and it may offer a ductility advantage for low temperature (-300°F) deployment of the Convoluted Nozzle.

At the CN maximum operating temperature of 2100°F Hitemco estimates that the life of the R505 coating will be 10 hours. Bell engineering judgment is that this is also true of the VH-2 coating and therefore prospects are good that the reusable life goal of 10 hours operation in 180 firings can be achieved.

A coating technology program is recommended to obtain early confidence and confirm or revise the baseline selection. It will consist of (1) a review of the Apollo SM and LEM-Descent Engine reports to acquire the details of development and operational experience with the VH-2 coating on Cb-10Hf nozzle extensions and (2) a series of coated Cb-10Hf strip tests (approx. 20) conducted in a materials laboratory to evaluate the rolling capabilities of the VH-2 and R505 aluminide coatings at temperatures ranging from 76°F to -300°F.

12.2 CN ROLLING AT LOW TEMPERATURES

In operational cases where the CN is insulated in the stowed position or deployed shortly after the RL10-IIB engined OTV is staged away from the Space Shuttle, the CN will roll at temperatures above 0°F and deployment characteristics will vary little from room temperature development data. However, in a case where the OTV is required to loiter in LEO with the stowed CN in a shaded position, the CN will lose heat by radiation to space and CN temperature could approach -300°F. In this case the CN rolling resistance will increase significantly and the deployment system (warm gas generator, etc.) will have to be designed for operation over a large temperature range. For this purpose a review of the rolling capability of the Cb-10Hf alloy was conducted at temperatures down to -300°F.

The shear spun rolling section of the CN has no welds and is in the fully recrystallized condition as a consequence of in-process annealling and vacuum furnace firing to diffuse the aluminide coating. A literature search yielded a limited body of data showing that fully recrystallized Cb-10Hf is still ductile at the convenient (liquid nitrogen cooled) test temperature of -320°F. (This was demonstrated by 2t bends of 90° at this temperature.) Ductile-brittle transition data on recrystallized Cb-10Hf is therefore of no interest to this investigation because it is beyond the lower temperature limit of -300°F. However, limited data from several sources (including Reference 8) indicates that the tensile yield and ultimate strengths increase and the elongation decreases as temperature decreases. This change in properties may produce a practical limit to CN rolling at some temperature above -300°F which should be determined by tests.

A material properties evaluation program is therefore recommended to obtain tensile modulus, yield strength, elongation and ultimate strength data on uncoated, VH-2 coated and R505 coated Cb-10Hf alloy throughout the 76°F to -300°F temperature range. Approximately 36 tests will be conducted in the Bell Materials Laboratory to evaluate 6 specimens each at temperatures of 76°F, 0°F, -75°F, -150°F, -225oF and -300°F.

The resulting property data will then be used with the Bell computer program for conic section rolling to theoretically define the lower rolling temperature limit (if -300°F or higher). The theoretical data will then be correlated with the results of the strip roll test program previously discussed (Section 12.1). If satisfactory rolling cannot be obtained for realistic minimum CN deployment temperature cases in RL10-IIB engine service on the OTV, then the deployment cover will be insulated and an electric wire heater will be incorporated in the Graphite/Epoxy roll control cone to maintain an acceptable minimum rolling section temperature until deployment has been completed.

12.3 SUBSCALE DEPLOYMENT TESTS

A one third scale CN deployment test program is recommended for low cost evaluation and feasibility demonstration of the self deployment system and the extendible/retractable system at room temperature and at the minimum operating temperature defined by the previously discussed low temperature rolling and material properties investigation.

The effort will also include the design definition phase development of the warm gas generator and cover separation fuse for the self deployment system. The Bell preliminary design of end burning gas generator and confined burning separation fuse is arbitrary and will be replaced by procurement specifications to obtain low cost development units from ordinance vendor competition.

Candidate propellant formulations will include composites containing coolants if required, and no condensibles in the products of combustion. A solid propellant contractor, such as Thiokol (Elkton Division), McCormick Selph or Talley Industries will supply the gas generator in accordance with a Bell design specification. The propellant formulation will be one that has been fully characterized ballistically with defined physical and mechanical properties. Known formulations such as ammonium nitrate and ammonium perchlorate containing oxidizers with fuel binders will be specified in accordance with the contractors demonstrated usage. The gas mass flow-time history as specified by Bell will permit the contractor to design a grain configuration with a web thickness that provides the optimum packaging for the candidate propellants and web burnout to match the nozzle deployment time.

The ignitability of the grain will be determined over the range of environmental temperatures with provision in the design to minimize pressure spikes and saddles. The igniter will contain a fully characterized initiator and charge formulation to assure a smooth ignition train of events and to provide the required propellant gas mass flow within a permissible delay time.

For a case-bonded grain, insulation, liner and adhesive will be compatible with the propellant and hardware over the Bell specified storage time. For a cartridge type grain, propellant supports will be designed to sustain the grain in its position so that the designed gas generation rate is maintained.

The gas generator and confined burning fuse design will be optimized after Bell has concluded the required pressure and mass flow calculations based on computer modeling of the complete deployment subsystem. The optimum solid grain configuration can conceivably be a single or multiple perforate or end burner or other geometrical shape. However, the design will contain a sufficient web thickness to ensure grain structural integrity compatible with environmental and rapid pressurization loads. The confined burning fuse may be a new development or an adaptation of existing equipment (e.g., confined detonating fuse).

The scope of this 1/3rd scale CN deployment test effort will include approximately 15 CN deployment tests to evaluate roll pressures, stability, self deployment, cover separation and extendible/retractable operation at room temperature and at low temperature.

12.4 SMALL SCALE LIFE TESTS

The prospects of achieving the 10 hour (36,000 sec) operating life goal or even the 2.5 hour (9,000 sec) qualification test requirement cannot be realistically assessed by extrapolation from test data consisting of a very small fraction of the requirement and fire testing at simulated altitude for a large amount of altitude cell time is very expensive, even at 1/3rd scale. Bell therefore recommends life tests of 3 small scale aluminide coated Cb-10Hf nozzle extensions on a small (5 to 25 lb thrust) O_2/H_2 rocket motor in a small altitude test cell at Bell or P&WA.

Bell has successfully fired two Silicide Coated Cb-10Hf radiation cooled N_2O_4/MMH rocket motors of small size (5 lb thrust) for total durations of 26 hours (93,600 sec in 400 firings) and 32 hours (115,200 sec in 800 firings) respectively. On the basis of this experience Bell believes that the CN service life goal of 36,000 sec in 180 firings can be credibly demonstrated at low cost on a similar O_2/H_2 rocket motor.

13.0 COST ANALYSIS, BASELINE CN

The cost of producing the full scale Convoluted Nozzle, including development, qualification, production and delivery was estimated for the baseline design (i.e., the self deployed 205 ε CN, configuration 2).

13.1 Simulated Altitude Tests

A major element of cost for the development and qualification of the RL10-IIB engine with a Convoluted Nozzle arises from the need for simulated high altitude tests to evaluate both the performance and service life of this large area ratio nozzle extension. Furthermore, engine acceptance test at simulated altitude for the sole purpose of including the CN will cost as much or more than the CN itself.

Similar circumstances were encountered by Bell in the development, qualification and production of the Agena engine with a refractory metal nozzle extension that also could not be tested at sea level. The solution selected was to conduct a portion of the development and qualification tests at simulated altitude to acquire a statistically significant nozzle performance data base and to demonstrate the operating life requirements. The tests were conducted at Arnold Engineering Development Center (AEDC). Since nozzle extension performance is dependent only on geometry, production acceptance was based on measurement of geometry. Production fire testing of the refractory metal nozzle extension was considered to be unnecessary and prohibitively costly. The cost effectiveness of this approach was proven by the subsequent successful space flight of 356 Agena engines with complete flight data confirmation of the nozzle extension performance data obtained in the qualification test program.

Bell recommends the same approach for the RL10-IIB engine and Convoluted Nozzle. The reliability of the CN is derived from the large thermal/structural design margins and the inherent reliability of simplicity (e.g., no moving seals or complex controls) and therefore, reliability can be evaluated by deployment tests at sea level. Performance and service life data however must be obtained at simulated altitude. The validity of this data is dependent on maintaining test altitudes low enough to insure full flow in the CN with no local flow separation. Bell therefore recommends RL10-IIB Engine/CN qualification testing in an altitude test cell, such as J-4 at ADEC or cell 401 at WSTF, with a minimum steady state altitude pressure of 0.2 psi to obtain full flow in the CN - without depending on stable over-expansion of the flow. No acceptance fire tests will be required on production Convoluted Nozzles.

13.2 CN Fabrication

Another major element of cost is the CN fabrication process. Manufacturing options were studied and the lowest cost CN fabrication process was identified. The process steps for each detail part in this assembly are discussed in this section. The process is shown as a flow diagram in Figure 13-1.

The central part of this assembly is the convoluted rolling section of the CN. This part is made from a 0.035 in. thick blank of columbium C103 material. The blank is cut to a 60 in. diameter circle and is then shear spun to a cone having a 27° half-included angle. In this operation the blank is placed on the end of a mandrel, centered, and clamped in place with a 34 in. diameter plate on the tail stock. The mandrel has a 37 in,

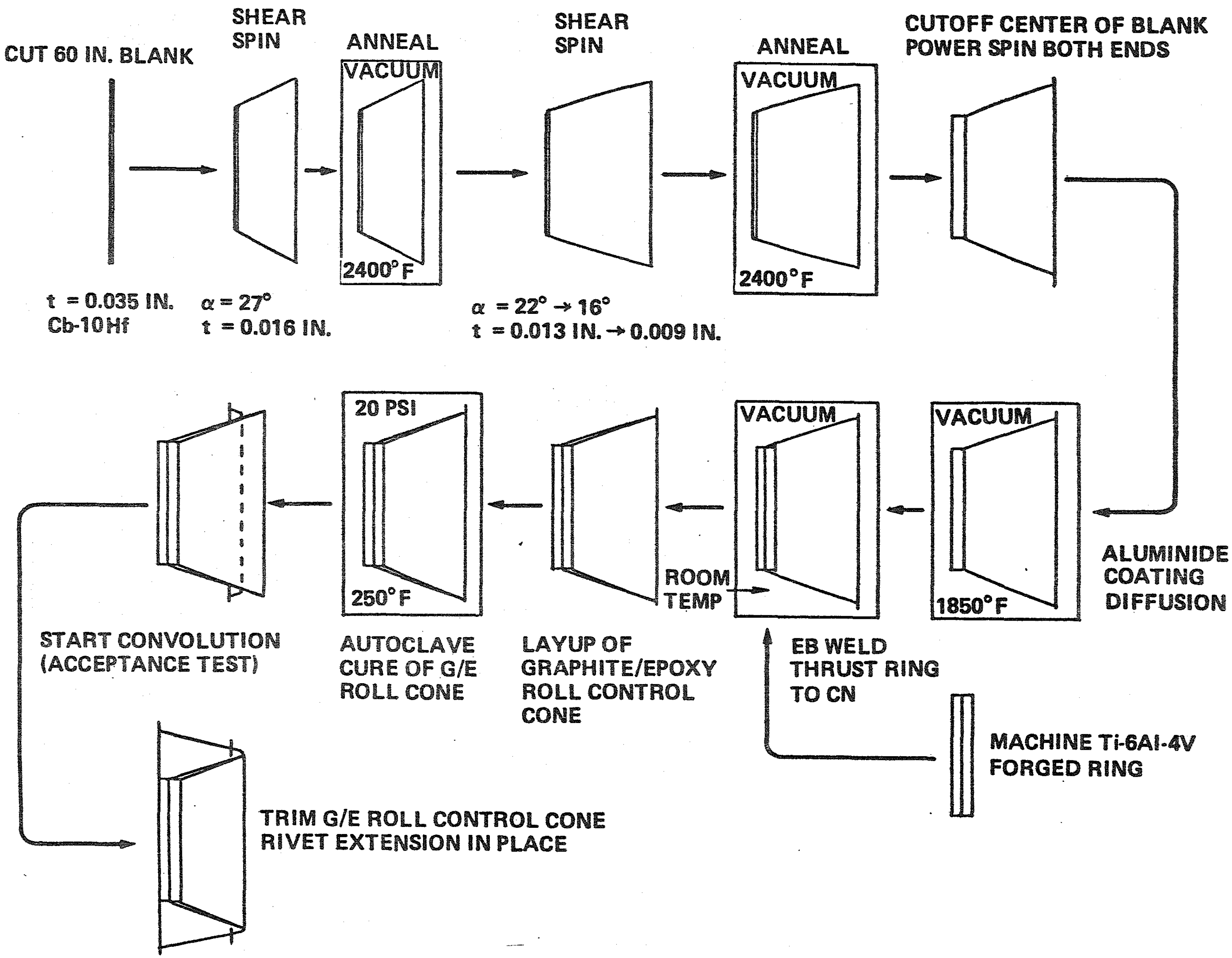


Figure 13-1. Convoluted Nozzle Fabrication

diameter on the small front end and a 60 in. diameter on the large end. The shear spin roller spins the blank to the shape of the mandrel in one forming pass at room temperature. The material is thinned in proportion to the sine of the included angle, from 0.035 in. to 0.016 in. This is a 57% cold work reduction. The blank is then vacuum annealed at 2400°F to remove the effect of cold working. The cone shaped blank is then placed on a second mandrel, centered, and clamped with the same 34 in. diameter tail stock plate. The second mandrel is contoured from a 22° included angle at the 37 in. diameter to a 16° included angle at the 60 in. diameter. The shear spin roller again spins the blank to the shape of the mandrel. The material in the contoured cone section will taper from 0.013 in. thickness at the 37 in. diameter to 0.009 in. at the 60 in. diameter.

After the part is again annealed, the dome section is machined away. The open small end is power spun outward against a forming ring to a 40 in. diameter cylindrical section on the small end of the cone. The aft end is also flanged outward in the same fixture. An aluminide diffusion coating is then applied to the cone.. This process requires vacuum heating to 1850°F, which reanneals the part at the same time. The small end of the cone is masked to prevent coating in the vicinity of the subsequent EB weld joint (to the thrust ring).

Thrust and roll stop rings are machined from a titanium 6Al-4V forged ring. The roll stop will be match machined to the diameter of the thrust ring with an allowance for the thickness of the columbium cone wall. The fit-up of the thrust ring, support cone and stop ring will have a maximum gap of 0.002 in., to achieve a successful EB weld of this interface.

To insure that the graphite epoxy roll control cone is in intimate contact with the rolling section, the graphite epoxy is layed up and cured inside the rolling section (after a parting agent is placed on the rolling surface). Developed segments of graphite cloth impregnated with epoxy are layed up on the inside of the rolling section. Developed segments of honeycomb and additional segments of graphite/epoxy are then positioned. The unit is then plastic vacuum bagged and cured in an autoclave.

The next operation is to convolute the end of the rolling section. This is done in a double action hydraulic press. The assembly is placed in the press with the large end down. Two rings are clamped to the flange on the large end and pins are placed in the press plenum chamber to contact the rings. A formica support cylinder (42 in. ID x 46 in. OD) is placed over the small end of the rolling section and the press ram is lowered to contact the cylinder. The double action plenum chamber is activated and the pins raise the rings clamping the flange, thus convoluting the cone.

The fixed extension is fabricated from five pieces of 0.006 in. thick columbium C103 sheet metal. Developed segments are cut for a truncated 15° cone, 60 in. diameter at the small end and 72 in. diameter at the large end. The segments are roll formed, trimmed and EB welded to form the cone. The cone is placed in a cavity tool and bulge formed by trapped rubber to a curvilinear contour. The fore and aft ends are then flanged for mounting and the part is aluminide coated and annealed.

The deployment cover is made in two parts from rubber impregnated nylon cloth. The cover center is made from a 46 in. diameter blank of nylon cloth. A styrofoam center is cut from a 2 in. thick block on a band saw to produce a tapered styrofoam disc. The styrofoam center is then bonded to the nylon cloth and a hinge joint is stitched to the outside edge of the cloth disc. The cover cone is made by cutting developed segments of rubber impregnated nylon cloth for a 22^{o} angle truncated cone 40 in. diameter at the small end and 64 in. diameter at the large end. The segments are sewn together to form a cone and a hinge joint is stitched to the small end.

The last assembly operation is to rivet the fixed extension, the deployment cover cone and two titanium rings to the large end of the rolling section.

13.3 Development Program

The other major elements of cost include design and analysis, tooling and manufacturing process development, development tests at Bell, qualification tests at P&WA and AEDC and/or other test centers and program management, technical direction and documentation. If Bell recommendations for the enabling technology programs of Section 12.0 are implemented, the full scale CN development program can be completed on the short schedule shown in Figure 13-2. This is a high confidence, success oriented program based on the assumption of prior resolution of all technical issues (i.e., technology programs).

The estimated cost of the CN development program shown in Figure 13-2 is approximately $3,500,000 with the inclusion of the tooling and manufacturing process development costs in the first ten units fabricated for development and qualification tests. Subsequent Convoluted Nozzles, in 10 unit buys for flight operations will cost approximately $97,000 each. All costs are given in 1984 dollars.

In the context of the engine performance improvement (16 sec ΔI_{sp}) to be gained, the CN development and qualification costs are relatively low and the OTV payload gain that can be provided (approx. 800 lb) with this specific impulse gain makes the CN a very cost effective improvement in the RL10-IIB engine capability.

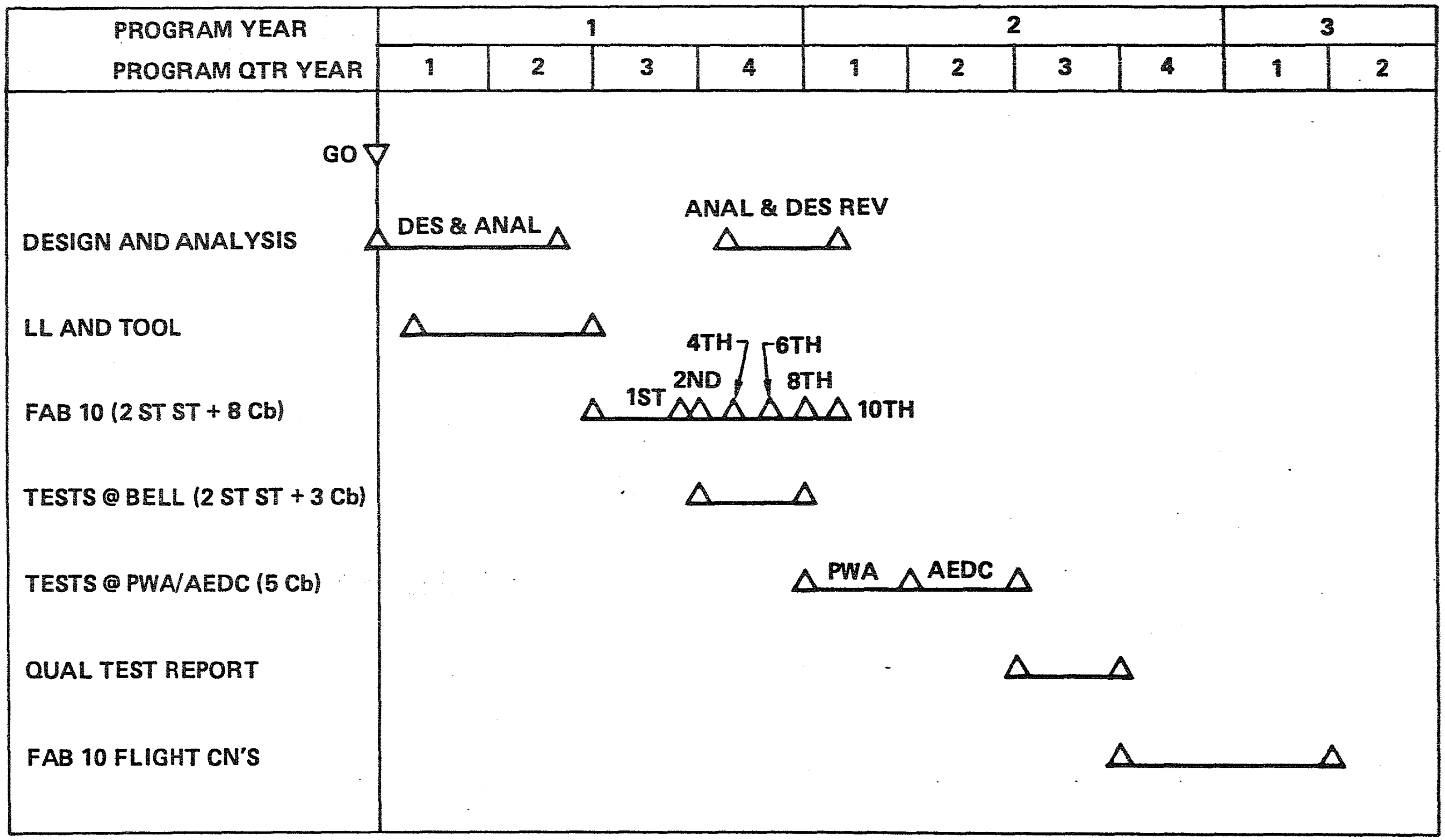


Figure 13-2. RL10-IIB Convoluted Nozzle Development Schedule

14.0 REFERENCES

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2. Kobalter, G.F., "Development of Expandible Rocket Nozzles", JANNAF Propulsion Meeting, Chemical Propulsion Information Agency Publication 242, Vol. II, Nov. 1973, pp 67-85.

3. Baker, W.H. and Evanoff, P.D., "Development of Extendible Exit Cones for the Trident I (C4) Second Stage Nozzle, Vol. II - Metallic Extendible Exit Cone", Hercules Inc./The Thiokol Corp. (A Joint Venture), Bacchus Works, Magna, Utah, 15 June 1974.

4. Carey, Lee and Ellis, Russell, "Extendible Exit Cone Development for the C4 Third-Stage Motor," Journal of Spacecraft and Rockets, Vol. II, No. 9, September 1974, pp 624-630.

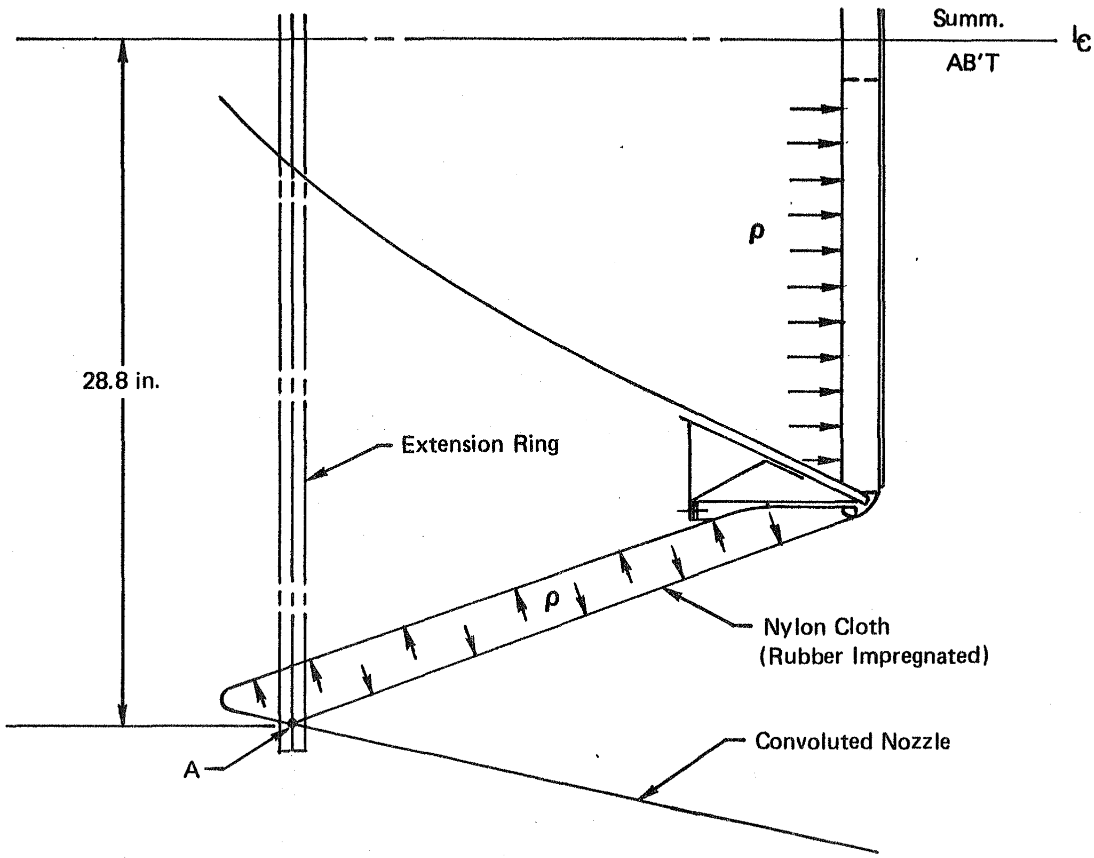
5. Black, J.R., Cooling Effects of Water Condensation in the RL10-2B Cooled Nozzle on the Carbon/Carbon Extension's Boundary Conditions, P&W Internal Correspondence, 18 April 1983.

6. Peckman, R.J., Hot Wall Temperatures for the RL10 Derivative IIB Columbium Extendible Nozzle Have Been Generated, P&W Internal Correspondence, 18 August 1983.

7. Walter, R.J., and Chandler, W.T., "Compatibility of Hydrogen with Tantalum and Columbium Alloys, " Rocketdyne Division of North American Aviation, Inc., AIAA 6th Structures of Materials Conference, April 5-7, 1965.

8. DMIC Report 148, "Review of Current Data on the Tensile Properties of Metals at Very Low Temperatures", Defense Metals Information Center, Battelle Memorial Institute, 14 February 1961.

APPENDIX I
DEPLOYMENT LOAD CALCULATIONS



STOWED CONFIGURATION
(At Initial Pressurization)

Pressure at start of deployment = 0.6 psi

P_{total} on extension ring = pA

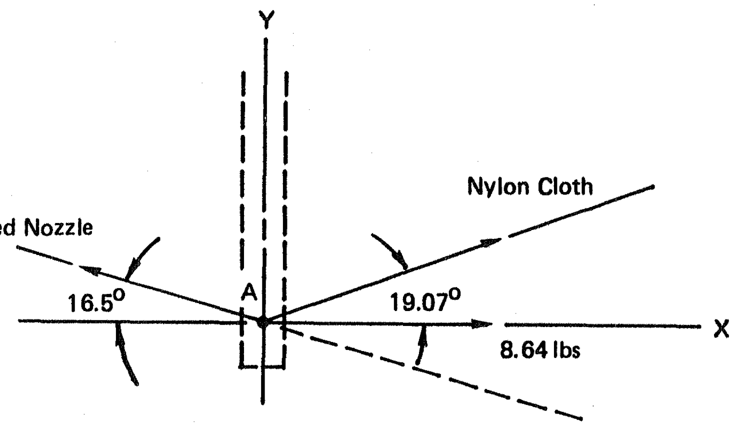
$= 0.6\ \pi\ (28.8)^2$

= 1563.5 lb

Load per inch = $1563.5/2\ \pi\ (28.8)$

= 8.64 lb/in.

JOINT A



Nylon cloth produces 8.64 lb/in. tension axially

Cloth Tension = 8.64/cos 19.07

= 9.142 lb/in.

$\underline{\Sigma F_X = 0}$

CN cos 16.5 + NC cos 19.07 = 0

$$CN = 9.142 \left(\frac{0.945}{0.959}\right)$$

$$= 9.01 \text{ lb/in.}$$

$\underline{\Sigma F_Y = 0}$

9.01 sin 16.5 + 9.142 sin 19.07 = Ring compression

Ring compression = 5.55 lb/in.

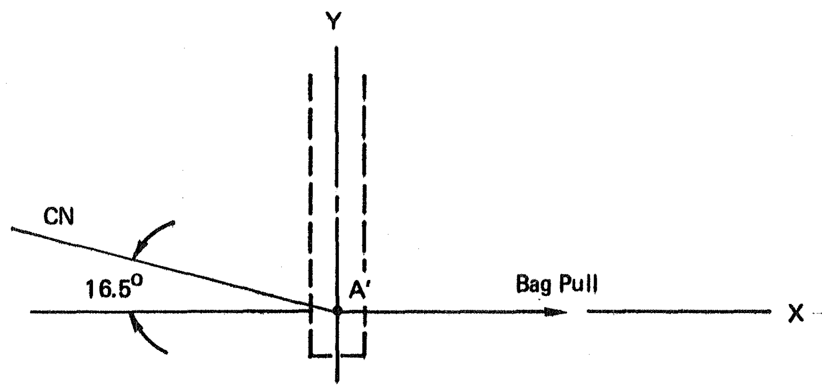
RING COMPRESSION WHEN FULLY DEPLOYED

Analyze for 3 degrees of nylon cloth stiffness:

1) Cloth stiff. Angle with ring same as in stowed condition (19.07°).

2) Cloth flexible enough so pull is parallel to ℄.

3) Cloth flexible enough so pull is at half of angle with ring in stowed position.



Max cover pressure = 1.90 psi

P_{TOTAL} on extension ring = pA

$= 1.9\,\pi\,(28.8)^2$

$= 4950.95$ lb

Load per inch = $4950.95/2\,\pi\,(28.8)$

$= 27.36$ lb/in. Bag Pull

$\Sigma F_X = 0$

CN cos 16.5° = 27.36

CN = 27.36/cos 16.5° = 28.54 lb/in.

$\Sigma F_Y = 0$

28.54 sin 16.5 = Ring compression

Ring compression = 8.11 lb/in.

1) Same figure as top of P.2 with cover pull = 27.36 lb/in.

Cloth tens. = 27.36/cos 19.07 = 28.95 lb/in.

$\Sigma F_X = 0$

CN cos 16.5° = 28.95 cos 19.07°

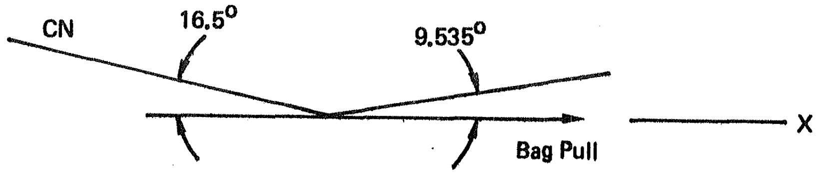
$$CN = 28.45 \; \frac{0.945}{0.959} = 28.54 \text{ lb/in.}$$

Note: CN tension per in. is constant for any cover angle with extension ring

$\Sigma F_Y = 0$

28.54 sin 16.5 + 28.95 sin 19.07 = Ring compression

Ring compression = 8.11 + 9.46 = 17.57 lb/in.



Cloth Tens. = 27.36/cos 9.535° = 27.74 lb/in.

$\Sigma F_X = 0$

CN cos 16.5° = 27.74 cos 9. 535°

$$CN = 27.74 \frac{0.986}{0.959} = 28.54 \text{ lb/in.}$$

$\Sigma F_Y = 0$

28.54 sin 16.5 + 27.74 sin 9.535 = Ring compression

Ring Compression = 8.11 + 4.60 = 12.71 lb/in.

Design ring for condition 3 until nylon cloth (rubber impregnated) properties adopted.

Assume ring consists of back to back angles with flanges at outer edge. Angles clamp convoluted nozzle elements, 0.10 in. forward and 0.006 in. aft, together with nylon cloth bag together. Assume angles 1 in. deep with 0.5 in. flanges and made of titanium.

EXTENSION RING

Material: Ti 6Al - 4V

$E_c = 16.4 \times 10^6$

For 1 in. deep angles

$r = 28.8 + 0.5 = 29.3$ in.

$pw = \frac{3\,EI}{r^3}$

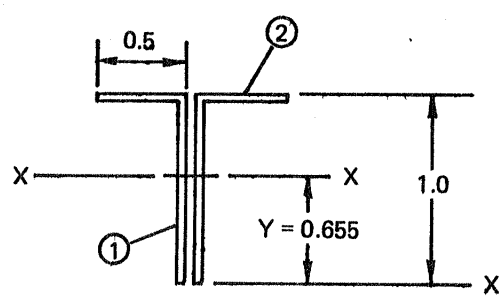
From Case 3, p.4, p = 12.71 lb/in. use factor of safety = 1.5

Then, p = 12.71 x 1.5 = 19.07 lb/in.

$I = \frac{pr^3}{3\,\epsilon} \qquad \frac{19.07\ (29.3)^3}{3 \times 16.4 \times 10^6}$

$I = 0.00975\ \text{in.}^4$

RING SECTION (1ST PASS)



Item	A	Y	A_y	A_y^2	I_o
①	0.0582	0.485	0.028227	0.01369	0.00456
②	0.0300	0.985	0.02955	0.02911	0.000002
Σ	0.0882	1.470	0.057777	0.04280	0.004562

$\overline{Y} = \frac{\Sigma A_Y}{\Sigma A} = \frac{0.057777}{0.0882} = 0.655\ \text{in.}$

$I_{x\text{-}x} = I_o + A_y{}^2 - \bar{y}^2\ (\Sigma A)$

$= 0.004562 + 0.0428 - (0.655)^2\ (0.0882)$

$= 0.00952\ \text{in.}^4$

$< 0.00975, \therefore$ NG

TRY t = 0.032 in.

Item	A	Y	A_y	$A_y{}^2$	I_o
①	0.06195	0.484	0.02998	0.01451	0.00484
②	0.032	0.984	0.03149	0.03098	0.000003
Σ	0.09395		0.06147	0.04549	0.004843

$$\bar{y} = \frac{\Sigma AY}{\Sigma A} \quad \frac{0.06147}{0.09395} = 0.654\ \text{in.}$$

$I_{x\text{-}x} = I_o + A_y{}^2 - \bar{y}^2\ (\Sigma A_Y)$

$= 0.004843 + 0.04549 - (0.654)^2\ (0.09395)$

$= 0.01015\ \text{in.}^4$

$> 0.00975, \therefore$ ok

Comparable plate t to produce I = 0.01015

$$\frac{bd^3}{12} = 0.01015 \text{ (where d = 1)}$$

$v = 12\ (0.01015) = 0.1218$

From Roark, Table XVI, Case 19

$$S^1 = k \frac{E}{1-\nu^2} \left(\frac{t}{a}\right)^2$$

where b/a = 28.8/29.8 = 0.966

= 0.155

$$S^1 = 0.155 \frac{16.4 \times 10^6}{0.91} \left(\frac{0.122}{29.8}\right)^2$$

= 46.82 psi

$$P_\omega = \sigma_A = 46.82\ (0.122)$$

= 5.71 lb/in. NG

Try t = 0.060 in.

Item	A	Y	A_y	A_y^2	I_o
①	0.1128	0.47	0.05302	0.02492	0.008306
②	0.0600	0.97	0.0582	0.05645	0.000018
Σ	0.1728		0.11122	0.08137	0.008324

$$\bar{y} = \frac{\Sigma A_Y}{\Sigma A} \quad \frac{0.11122}{0.1728} = 0.644 \text{ in.}$$

$$I_{x\text{-}x} = I_o + A_y^2 - \bar{y}^2\ (\Sigma A)$$

$= 0.008324 + 0.08137 - (0.644)^2\ (0.1728)$

$= 0.01803$ in.^{4}

Equiv. plate t to provide I = 0.0103 in.^{4}

$db^3/12 = 0.01803$ where d = 1

b = 12 (0.01803) = 0.216 in.

Again using Roark, Table XVI, Case 19

$$S^1 = \frac{E}{1-\nu^2}\left(\frac{t}{a}^2\right)$$

$$= 0.155 \frac{16.4 \times 10^6}{0.91} \left(\frac{0.216}{29.8}^2\right)$$

$$= 146.76 \text{ psi} \leftarrow$$

$$P_\omega = S^1 A = 146.76\ (0.216)$$

$$= 31.7 \text{ lb/in.} \leftarrow$$

$$\text{Margin of Safety} = \frac{31.7}{19.07} - 1$$

$$= +\ 0.662 \leftarrow$$

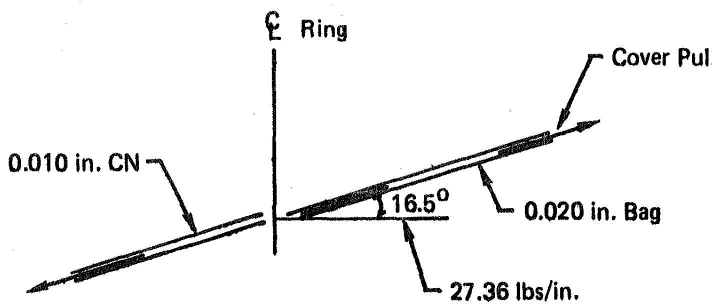
<u>Weight of Ring</u>

$$W = \rho V = \rho A \pi d$$

$$= 0.16\ (0.1728)\ \pi\ (28.8 + 0.644)\ (2)$$

$$= 5.115 \text{ lb} \leftarrow$$

BENDING IN RING DUE TO LINE LOAD MISMATCH



For cover folded flat against nozzle cover Pull = 27.36/cos 16.5 = 28.54 lb/in.

Mismatch Between 0.020 in. cover and 0.010 in. nozzle

$$= \frac{0.020 + 0.010}{2} = 0.015 \text{ in.}$$

Couple = 28.54 (0.015) = 0.428 in lb/in.

$$\sigma_{RING} = \frac{MR}{I/C}$$

$$\begin{aligned} I &= 0.00587 \text{ in.}^4 \quad (P.7) \\ C &= 0.628 \text{ in.} \quad (P.7) \\ R &= 28.8 + 0.628 = 29.428 \text{ in.} \end{aligned}$$

$$\sigma_{RING} = \frac{0.428\ (29.428)\ (0.628)}{0.00587}$$

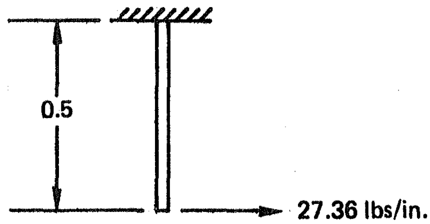
$$= 1348 \text{ psi}$$

Factor of Safety = 1.5

σ_{RING} = 1348 (1.5) = 2022 psi ←

M.S. = High

CHECK ADEQUACY OF ANGLE WEB AGAINST COVER PULL



Cover Pull = 28.54 lb/in.

Normal Force = 28.54 cos 16.5°

= 27.36 lb/in.

Ring angles are 1 in. deep. Assume connectors at mid-depth. Cantilevers portion of 0.060 in. t leg = 0.5 in.

M_{MAX} = 27.36 (0.5) = 13.68 in./lb

$$I = \frac{bd^3}{12} = \frac{1\,(0.06)^3}{12} = 0.0000\,18 \text{ in.}^4$$

$$J_b = MC/I = \frac{13.68\,(0.030)}{0.000018}$$

= 22,800 psi

Use Factor of Safety = 1.5 (Ult)

σ_{ult} = 22,800 (1.5) = 34,200 psi

σ_{ult} = allow = 130,000 psi (annealed)

$$M.S. = \frac{130,000}{34,200} - 1 = +2.80 \longleftarrow$$

The clamping action of the angle elements that constitute the ring section, must be metal to metal assured throughout the engine life. The ring joint clamps a 0.010 in. fwd nozzle insert and a 0.006 in. aft nozzle insert on either side of an 0.020 in. nylon cloth (rubber impregnated) insert. At operating temperatures, the nylon cloth insert will burn away. A gap of 0.020 in. cannot be tolerated.

REACTIONS AT CONV. NOZZLE/THRUST RING ASSY INTERFACE DUE TO EXTENSION FORCE AND THRUST FORCE DURING ENGINE FIRE

Max Cover Extension Force,

$P_{TOTAL} = 4951$ lb (P.3)

Reaction Radius = 19.9 in.

P/in. = $4951/2\pi\ (19.9) = 39.6$ lb/in. T ←

Max Thrust During Engine Fire

$T_{MAX} = 1300$ lb

P/in. = $1300/2\pi\ (19.9) = 10.4$ lb/in. C ←

STRESS IN NYLON CLOTH AT RING JOINT

Max Cover Pressure = 1.90 psi (P.3)

Cover Pull at Ring Attachment = 27.36 lb/in. (Parallel to ℄)

When cover is folded against nozzle
(Max. Bag Load/in.)

Cover Tension = 27.36/cos 16.5°

= 28.54 lb/in.

Stress = 28.54/0.02
= 1427 psi

Material tests on 16 oz Hypalon (0.020 in. t)

1 in. Strip Method
Tension Strength = 325 lb/in.

Grab Method

Tension Strength ⩾ 450 lb/in.

$$\text{M. of S.} = \frac{325}{28.54 \times 1.5} - 1 = +\ 6.59 \longleftarrow$$

(1.5 = F. of S.)

SUMMARY

Extension ring consists of 2 Ti-6Al-4V angles. Each angle is 1 in. deep with a 0.5 in. flange and has a uniform $t = 0.060$ in.

Angles connected by 1/4 in. ϕ rivets on ~ 1.25 in. spacing (148 rivets)

Element	Critical Load	Stress	Margin of Safety
Ring	External Pressure	88.3 psi	+ 0.66
Ring Web	Bending	34200 psi	+ 2.80
Nylon Cloth	Internal Pressure	2140 psi	+ 6.59*

Ring wt. = 5.12 lb

* Margin of safety at room temperature
Brittle point of Hypalon -40°F to -80°F.

HYPALON

Brittle point is the temperature at which stiffening becomes so severe that the elastomer breaks when flexed or shatters when struck.

Hypalon Brittle Point -40°F to -80°F

Ref. DuPont data on Eng. Properties of Hypalon.

APPENDIX II

LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

A	-	Area
AEDC	-	Arnold Engineering Development Center
Al	-	Aluminum
Aluminide	-	Diffusion Bonded Aluminum & Metals Slurry Coating
Cb	-	Columbium (Niobium)
CN	-	Convoluted Nozzle
e	-	Emmissivity
ε	-	Expansion Ratio (Area Ratio)
F	-	Force
F.S.	-	Factory of Safety
h	-	Heat Transfer Coefficient $BTU/ft^2hr°R$
Hf	-	Hafnium
HfO_2	-	Hafnia
I	-	Moment of Inertia of an Area
MMH	-	Monomethylhydrazine
M.S.	-	Margin of Safety
NASA	-	National Aeronautics and Space Administration
OTV	-	Orbit Transfer Vehicle
P	-	Structural Load
p	-	pressure
P&WA	-	United Technologies Pratt and Whitney Aircraft Government products Division
r	-	rolling radius (of CN shell)
Rad Y	-	CN contour radius in. from centerline

Silicide	-	Diffusion Bonded Silicone & Metals Slurry Coating
SDSTA2	-	Steady State Thermal Analyzer Program
Sta X	-	CN Contour Station, in. from Throat
T	-	Temperature, °R and °F
t	-	thickness
Ta	-	Tantalum
t_b	-	thicknes of shear spinning blank
Ti	-	Titanium
V	-	Vanadium
Velvet Black	-	Proprietary Carbon Coating
W	-	Tungsten
WSTF	-	White Sands Test Facility

End of Document