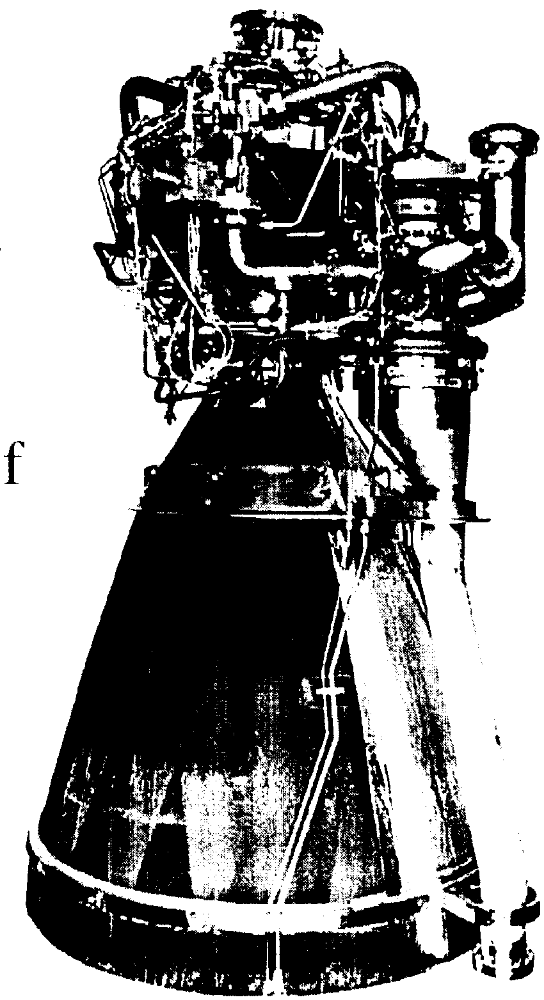
MC-1 Nozzle

I. INTRODUCTION

- Designed for a low cost engine for an expendable booster.
- Modified for use in the X-34 propulsion plant.
- Nozzle and chamber are one piece.
- The MC-1 Nozzle is the structural backbone of the engine.

PC	633 psi
Propellants	LOX/RP-1
Overall (Total) MR	2.34 (includes film cooling)
Wall Film Cooling	10% of total fuel flow
Ignition	Hypergolic, through wall
Thrust	60,000 lbs.
Area Ratio (Flight)	30:1



OUTLINE

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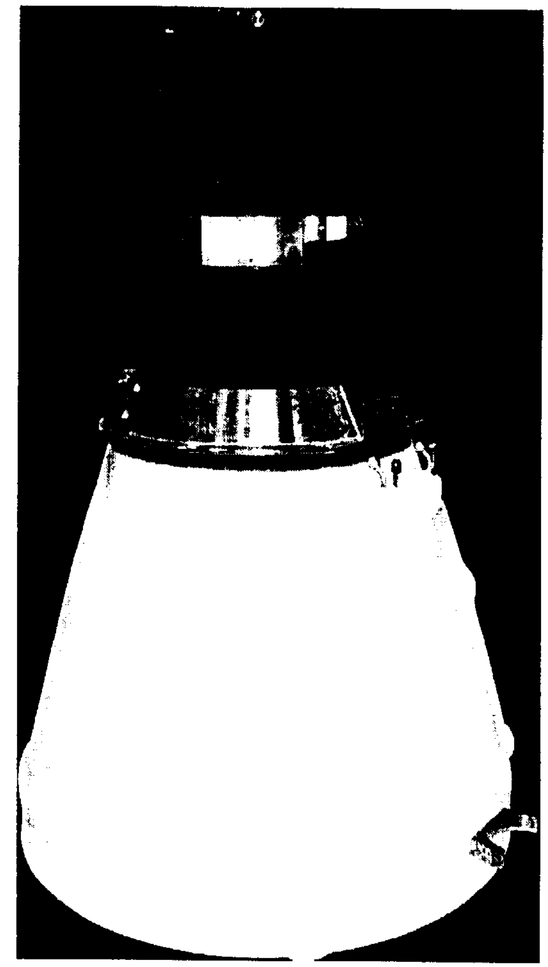


II. DESIGN GOALS

SIMPLIFY ENGINE SYSTEM

Using fuel film cooling with the ablative liner material allowed us to significantly simplify the engine system and nozzle by not requiring active, regenerative cooling.

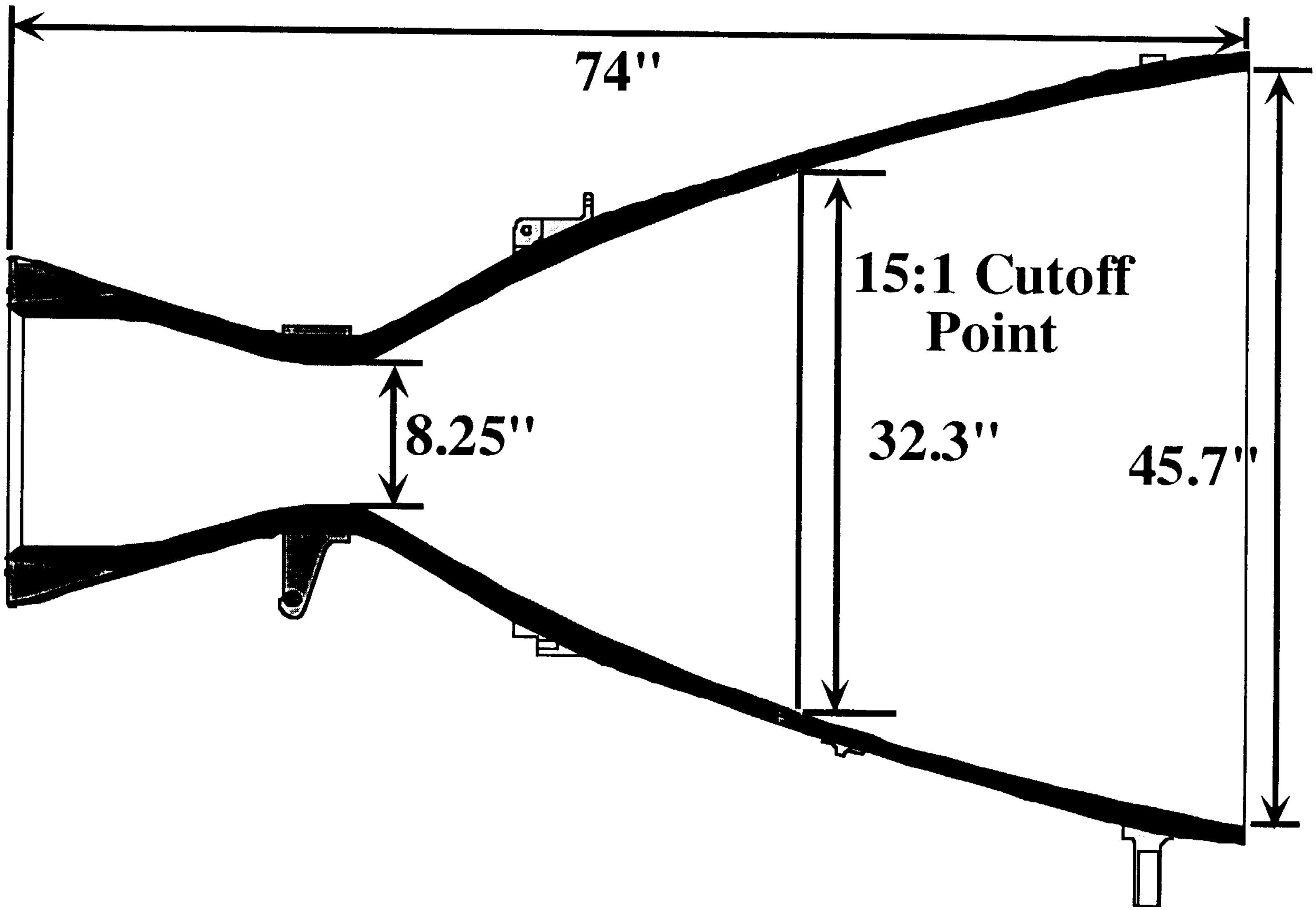
LOWER COST

The materials chosen for the nozzle are readily available, industry standards that are lower cost than traditional state-of-the-art materials. Fabrication processes were selected that used efficient processing techniques, which minimized the need for hand lay-up. Attachment of external hardware is performed by directly bonding to the external surface of the nozzle.

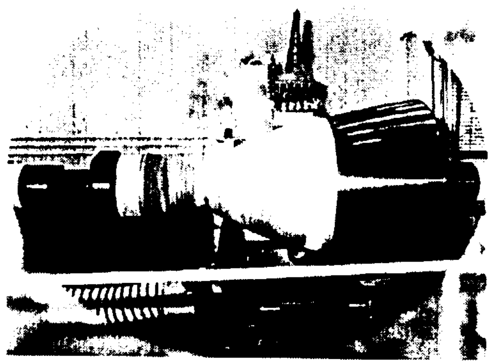
SHORT FABRICATION TIME

By choosing the processes mentioned above, the time as well as the cost of fabricating a nozzle was reduced. The time required to fabricate a complete nozzle, if brackets and materials are in stock, is only 6 weeks. If the nozzle assembly pipeline is full, nozzles are completed on 2 week centers.

A. Geometry

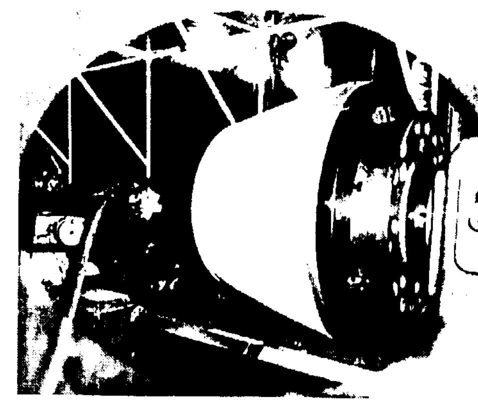


B. Materials and Fabrication

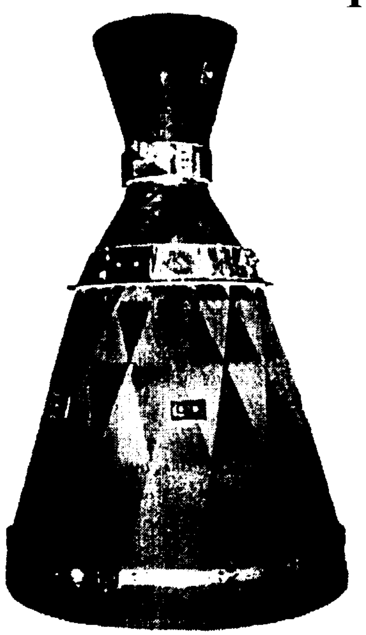


1. Tape Wrap Liner

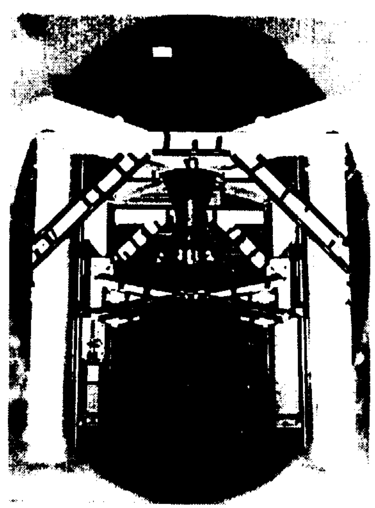
2. Cure Liner



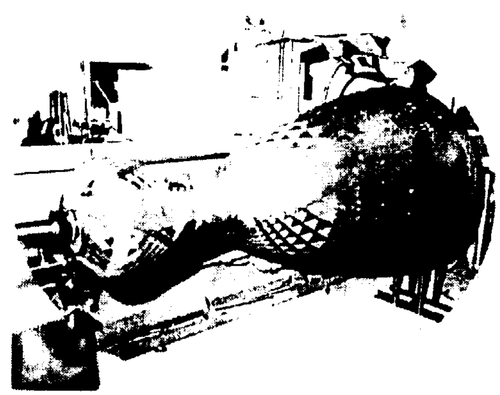
3. Machine Liner OD



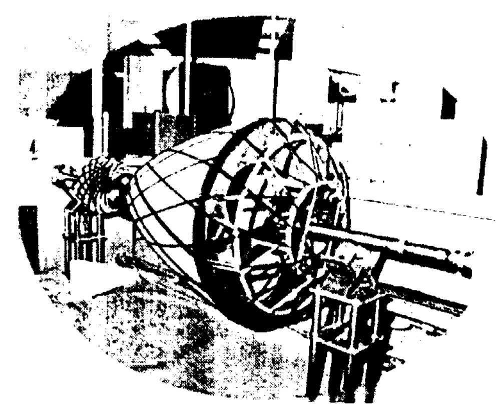
Fastrac Nozzle



6. Bond Brackets

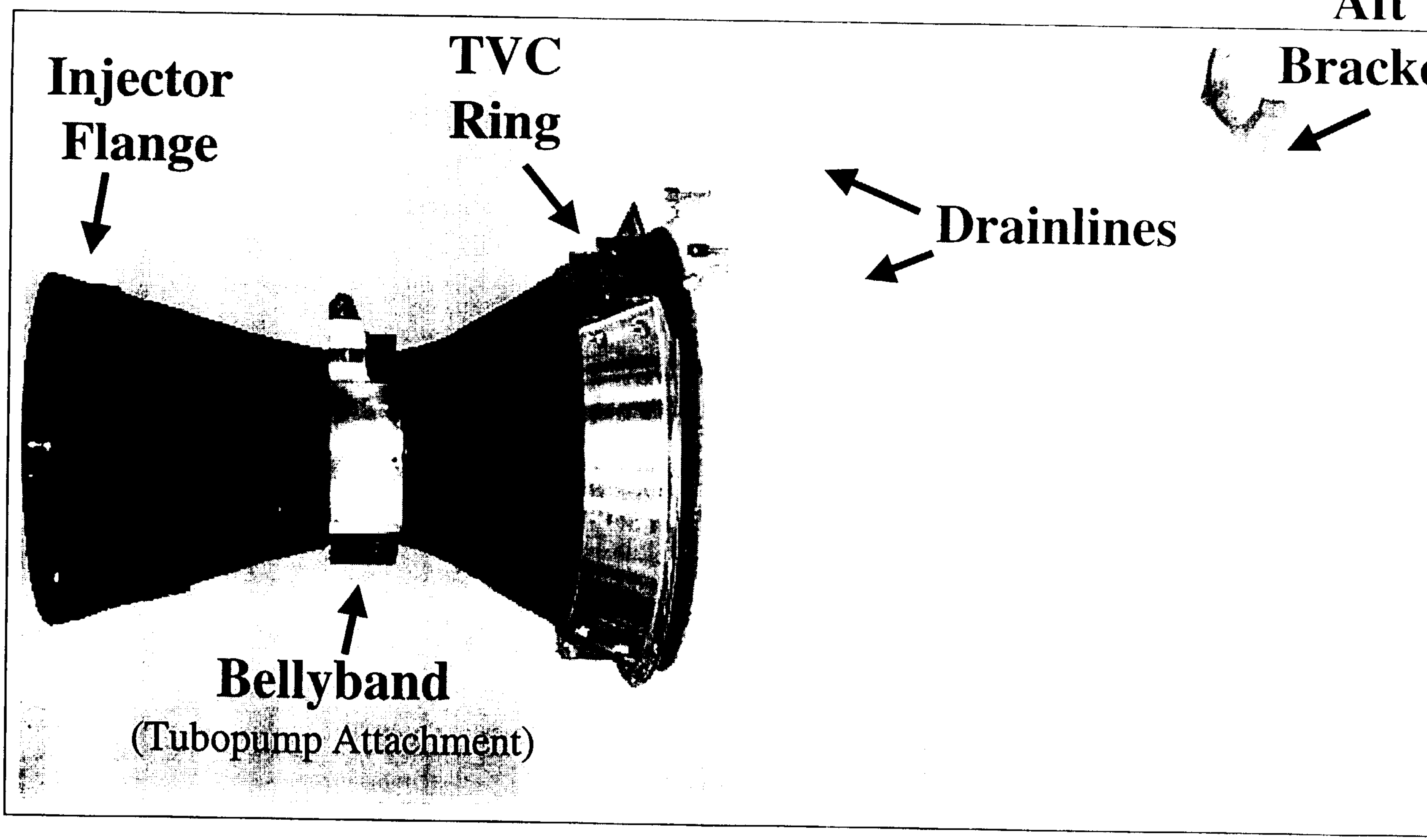


5. Cure Overwrap



4. Filiment Wind Overwrap

C. Brackets


Injector
Flange
TVC
Ring
Drainlines
Aft
Bracket
Bellyband
(Tubopump Attachment)

A. Hotfire Testing

- 66 total tests and 1803 seconds.
- 6 full duration tests.
- Multiple firings on single nozzle during development testing only.
- A Single 15:1 Nozzle has 4 starts and 342 seconds of hotfire.
- A Single 30:1 Nozzle has 7 starts and 282 seconds of hotfire.

	Component Test	Engine Test	Total
Tests	36	30	66
Seconds	1246	557	1803
Nozzles	12	6	18

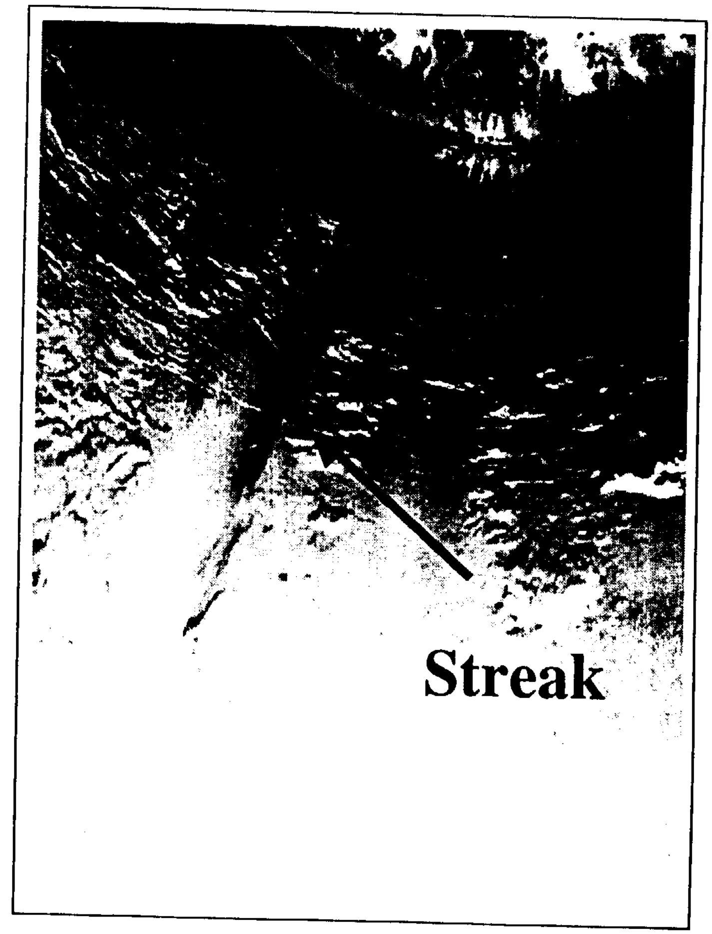
B. Erosion Rate

- An ablative liner pyrolizes, leaving a weak char layer.
- Viscous forces and abrasion typically remove the char layer during operation, and this is called erosion.
- After every nozzle test, the throat diameter has measured equal to or smaller than the original diameter.
- There is no erosion on the MC-1 nozzle liner.

  -Swelling of the liner and carbon deposition have been accounted for in the measurments.

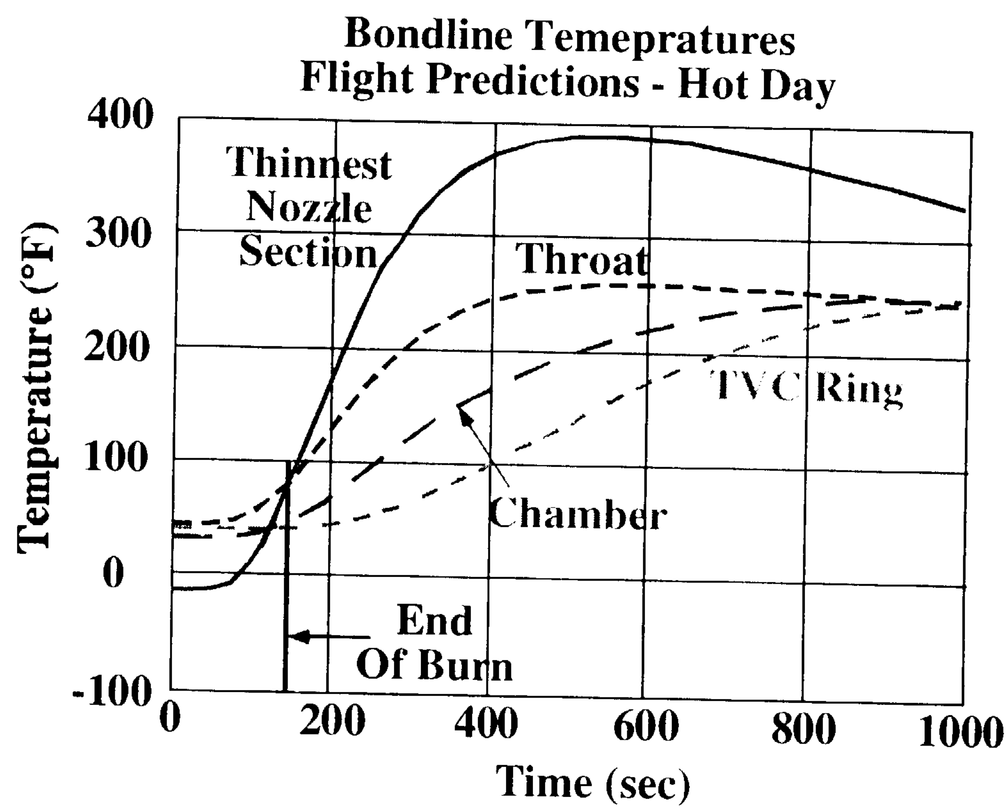
C. Injector / Wall compatibility

- A mal-distribution of the hot gas flow from the injector can cause local hot spots on the chamber wall.
- The liner material is an excellent insulator, and any localized heating can cause a deep removal of the ablative material. We define this removal of material as a "streak".
- Contamination of an outer fuel element did cause a shallow streak on one test (out of 66 total tests) . An additional 3 tests and 192 seconds were put on that same nozzle after the contamination was removed. There was no subsequent damage to the nozzle wall.



D. Thermal Analysis and Test

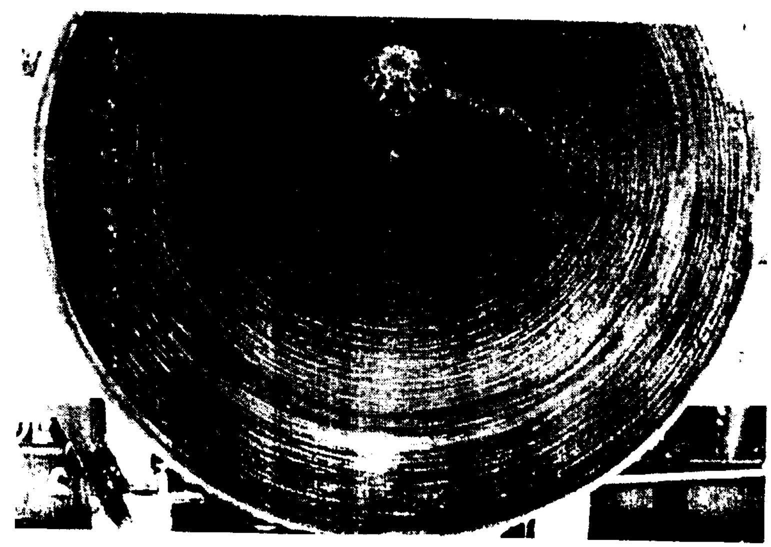
- Thermal predictions are generated from a thermal math model using a finite difference analysis software (SINDA) and custom Fortran codes
- The model accounts for the kinetic decomposition of the liner material and can predict char and heat affected depths.
- Model was calibrated with analog test data and through the thickness thermocouples during hotfire tests.



- The liner thickness was sized to keep all of the 'liner-to-overwrap' bondline below 200°F during operation, and below 300°F at the critical external attachment regions during the heat soak back after engine shutdown.

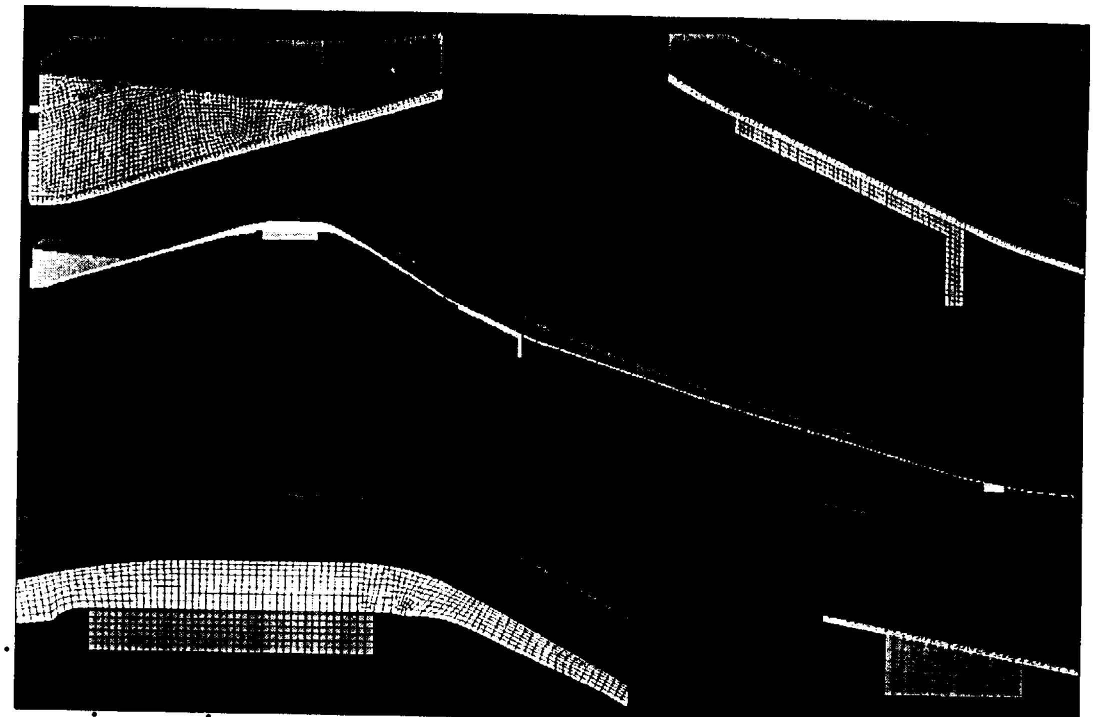
E. Side-loads Analysis and Test

- The Fastrac nozzle is optimized for a launch at an altitude of 30,000 ft. If tested at sea level, we predicted that the nozzle flow would separate from the wall and cause side loads. (Pe/Pa = .3)
- The magnitude of the side loads was predicted and the nozzle was tested on the component stand at sea level with no diffuser present. Successful testing at the component level has given us confidence to continue testing the engine using over-expanded nozzles at sea level.
- The side-loads measured during 30:1 HTF engine tests were 2000 lbs. maximum (translated to nozzle lip) at approximately 15 HZ. The peak side-loads occur during startup and shutdown, but do not induce any damage to the nozzle due to the high nozzle stiffness.



F. Thermostructural Analysis

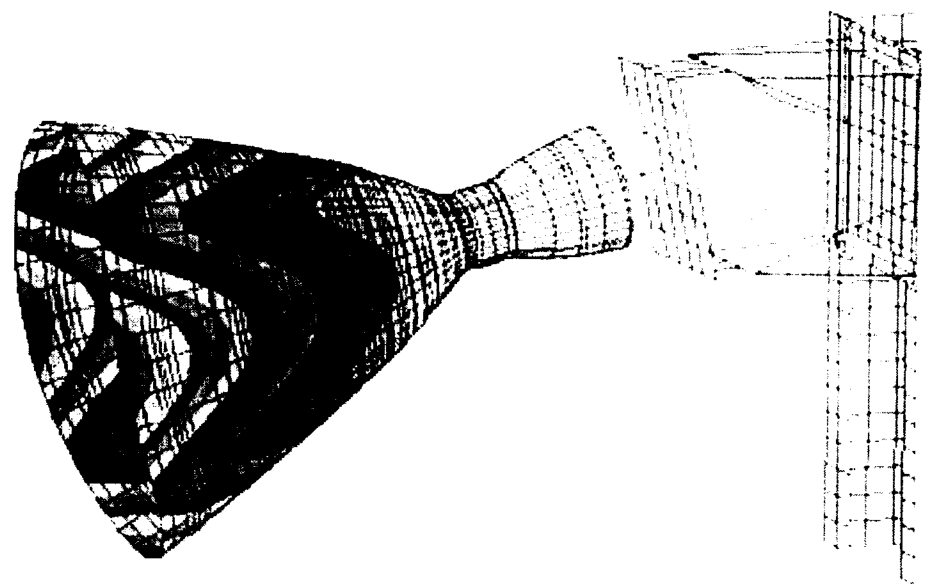
- We use Patran to pre-process (build) and, to some extent, post-process (interpret results from) our models.
- We use the ABAQUS finite element code to run the models, and make extensive use of internally developed FORTRAN codes and Excel spreadsheets to process composite material properties for input and to post-process the output analysis results.



- In order to approximate the continuous variance in overwrap material properties along it's length, there are over 40 different overwrap material property definitions for a 30:1 nozzle, and each set has to be pre- and post-processed individually.
- Liner material properties vary over temperatures from -50 to over 2500 degrees F.

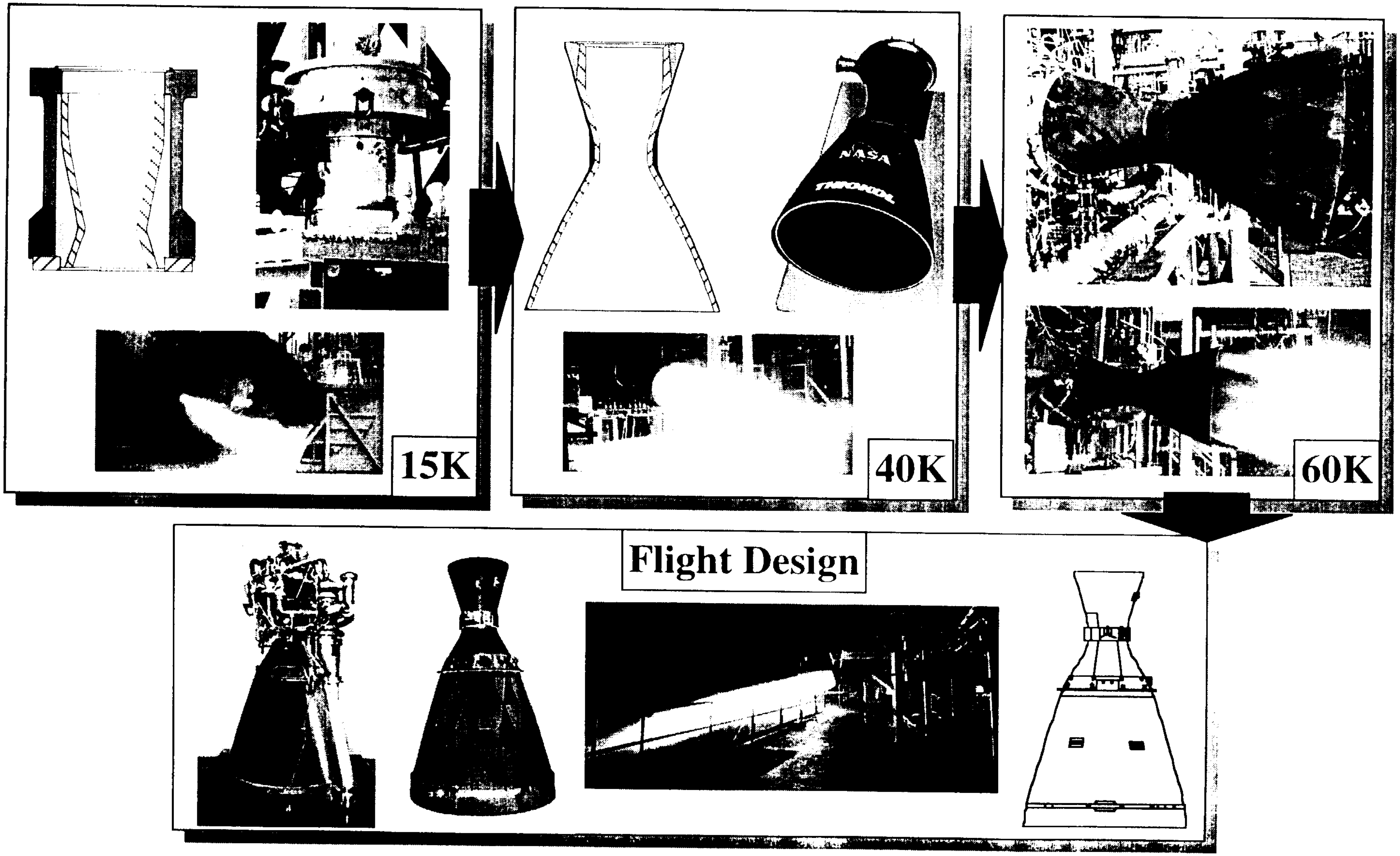
G. Dynamic Analysis and Test

- Because the nozzle is the structural backbone of the FASTRAC engine, its structural dynamic characteristics have a large influence on induced engine loads.
- A 360° MSC/NASTRAN plate element model was created with the plate elements incorporating the properties of each layer in the composite layup. Multiple material coordinate transformations are required.

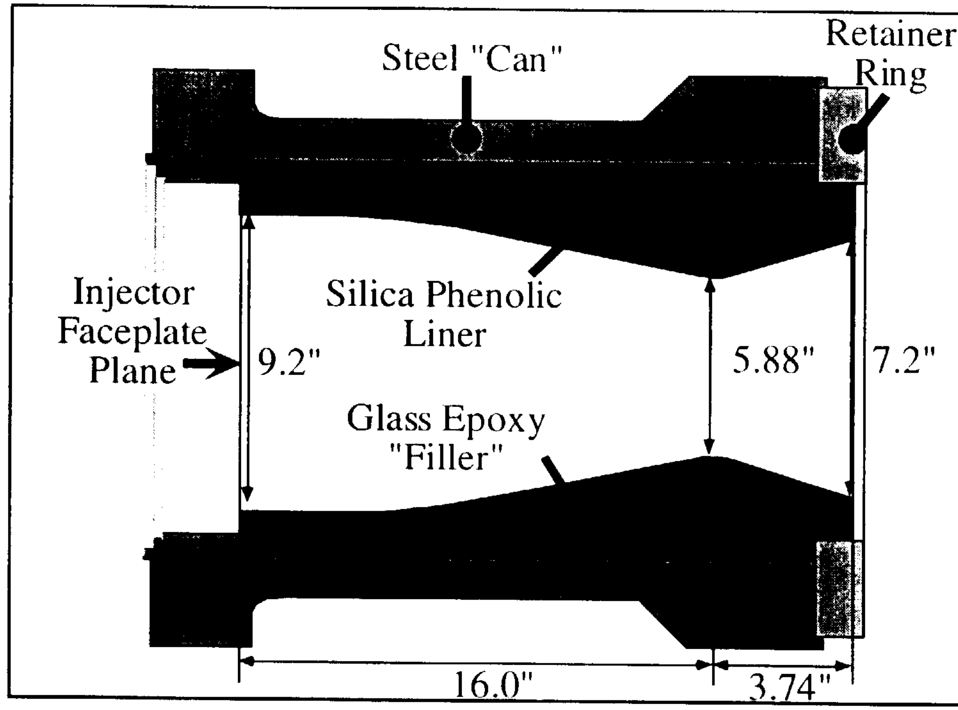


- A series of free-free modal tests of varying configurations of the nozzle was performed, along with a "hot" modal test, on which accelerometers were active during a full duration hotfire. These were used to correlate the dynamic models.
- The final results were very good, with the correlated model for the 30:1 nozzle having frequencies within 10% of the measured frequencies and MAC values greater than 0.9

V. DESIGN PROCESS



1. 15K Design



- We needed liner performance data using LOX/RP-1 propellants: injector/chamber compatibility, throat erosion and how the wall fuel film cooling would affect the TCA C*.
- We built a subscale materials tester that was modified from existing hardware left over from the STME program.
- We could make these liners quickly and inexpensively and slide them into the metal "can" for fast turn-around on the test stand.
- The injector had a flight like faceplate design to properly evaluate TCA performance along with the correct heating to the chamber wall.

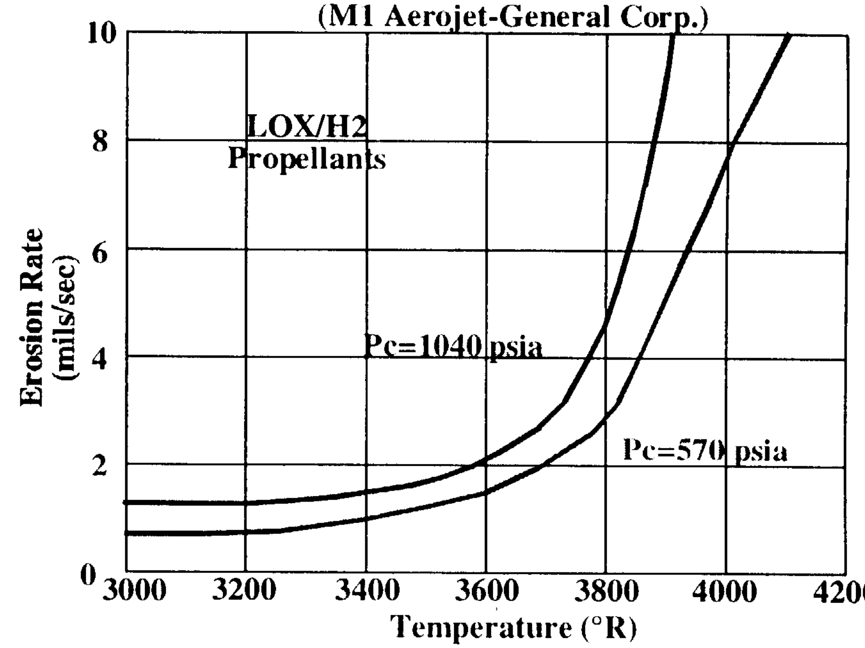
2. Operating Conditions

Propellants	LOX/RP-1
Mixture Ratio	2.34 (Includes fuel film cooling)
PC	350 - 500 psia
Wall Cooling	10% of fuel flow on nozzle wall

4. Film Coolant Study

- Wall cooling was necessary to keep the silica phenolic liner below its melting temperature (approx. 3200°F)
- The throat erosion requirement was 2 mils per second.
- The only erosion data that we had to base our calculations on was derived from the LOX/H2 M1 program conducted in the late 1960's (see AIAA 69-442)[1].

Erosion Rate of Silica-Phenolic
(M1 Aerojet-General Corp.)

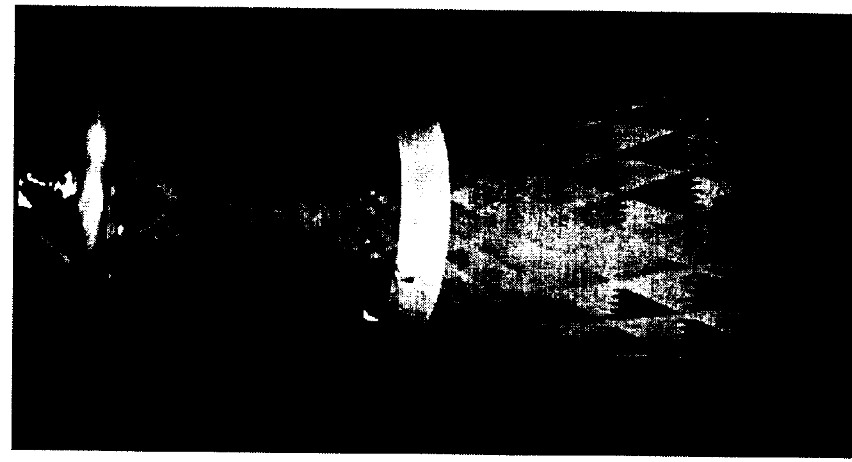


- The inner contour of the chamber was designed to maximize the affect of the fuel film cooling that is provided by the injector while optimizing the total efficiency of the TCA.
- A CFD trade study was conducted on the affect that different film coolant flowrates and chamber length had on throat erosion. 10% was the optimized value.

5. Hotfire Test Results

- 31 hotfire tests and 778 seconds were accumulated on 7 different 15K liners.
- No throat erosion was measured on any of the liners. The silica liner was charred but none of the charred material was removed.
- Chamber streaking was a consistent problem throughout the entire test program, and was solved by changing the injector element geometry to block LOX rich gas from flowing parallel to the injector face and against the wall.

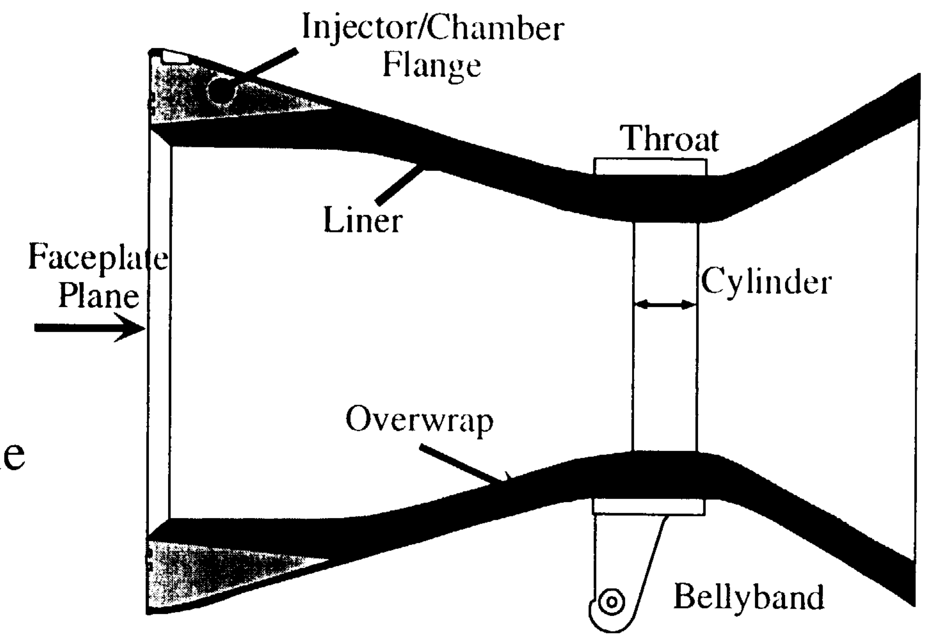
1. Fabrication and Test Goal



- The second portion of the program was the 40K flight-like TCA.
- It was named 40K because the TCA would produce approximately 40,000 lbs. of thrust at 400 psi.
- The goal was to demonstrate that a flight-like nozzle could be manufactured using the materials and techniques used in 15K.
- Manufacturing a continuous, hourglass shaped liner is not a common manufacturing method and had to be proven. Most ablative nozzles are manufactured in segments and joined by mechanical means, which significantly increases the cost and complexity of the nozzle.
- Three of these nozzles were manufactured and went on to successfully complete an accumulated 18 tests and 473 seconds of hot fire, with the longest test 150 seconds long.

2. Internal Geometry

- The 40K supersonic nozzle optimized for an area ratio of 30:1, but was truncated at an area ratio of 10:1 to keep from over expanding the exhaust gas. (Pexit/Pamb > .3 rule)
- The shape of the internal wall of the subsonic chamber was designed using the CFD analysis and hotfire data obtained from the Fastrac-1 (15K)

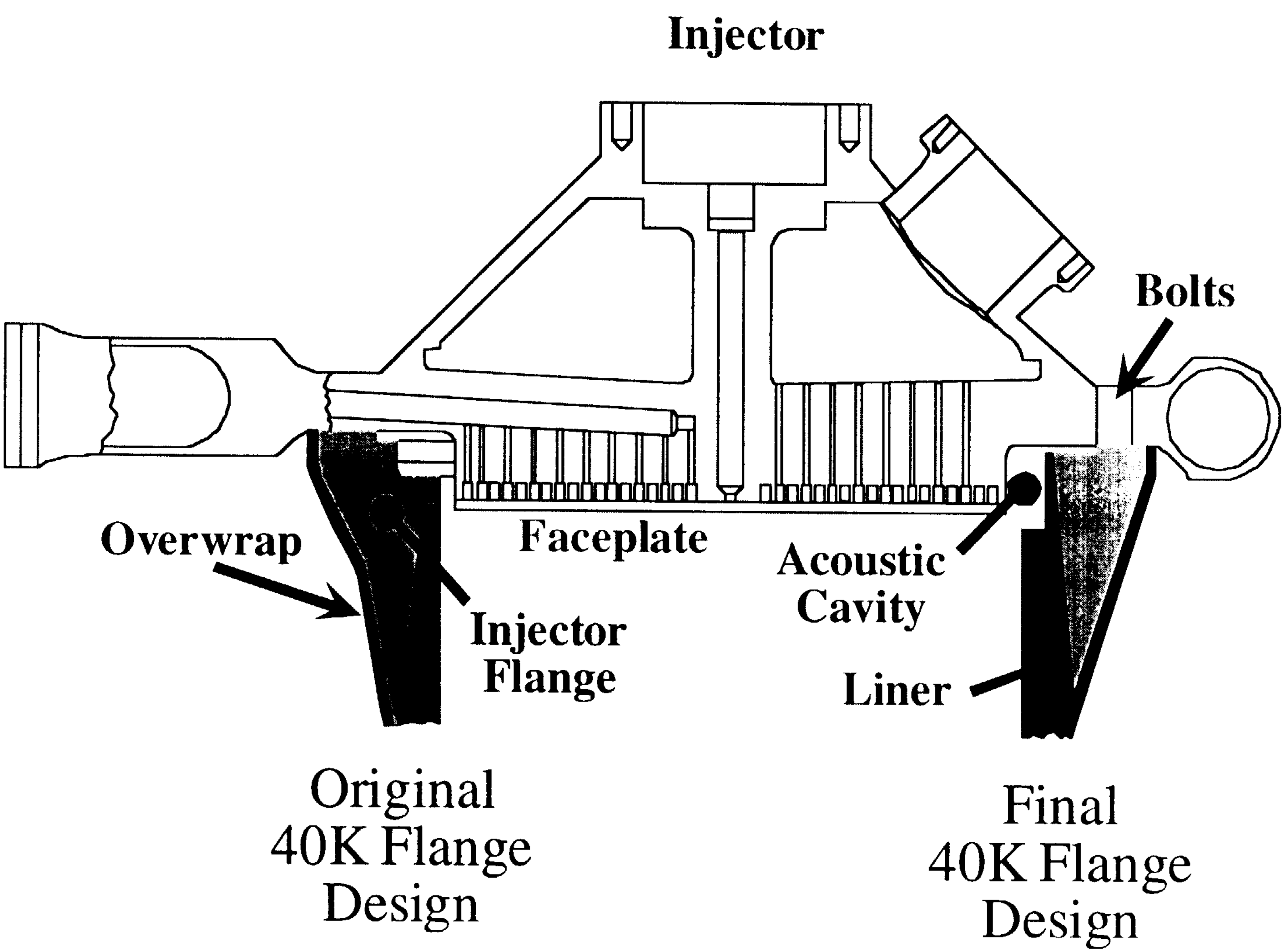


- Based on advice from industry experts, we also added a 1.5 inch cylinder section at the throat. The purpose of this addition was to try to reduce the effect that throat erosion would have on the performance of the TCA.

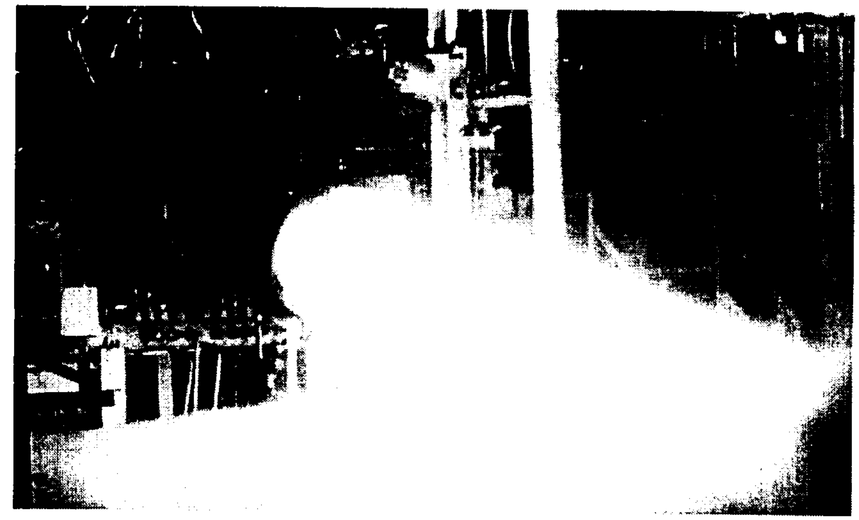
3. Initial Thickness of Materials

- The thickness of the liner is not arbitrary, but is constrained by manufacturing limitations.
- The initial liner thickness of the chamber and nozzle was driven by manufacturing guidelines, the geometry of the chamber/injector flange and the amount of char we saw in the 15K test series.
- The thickness of the overwrap is governed by the filament winding process.
- When you use a filament winding process you cannot independently change the thickness of the overwrap along the length of the nozzle. You choose the thickness at the largest diameter, and that drives the thickness at all other locations.

4. Injector Attachment Design



5. Hotfire Test Results



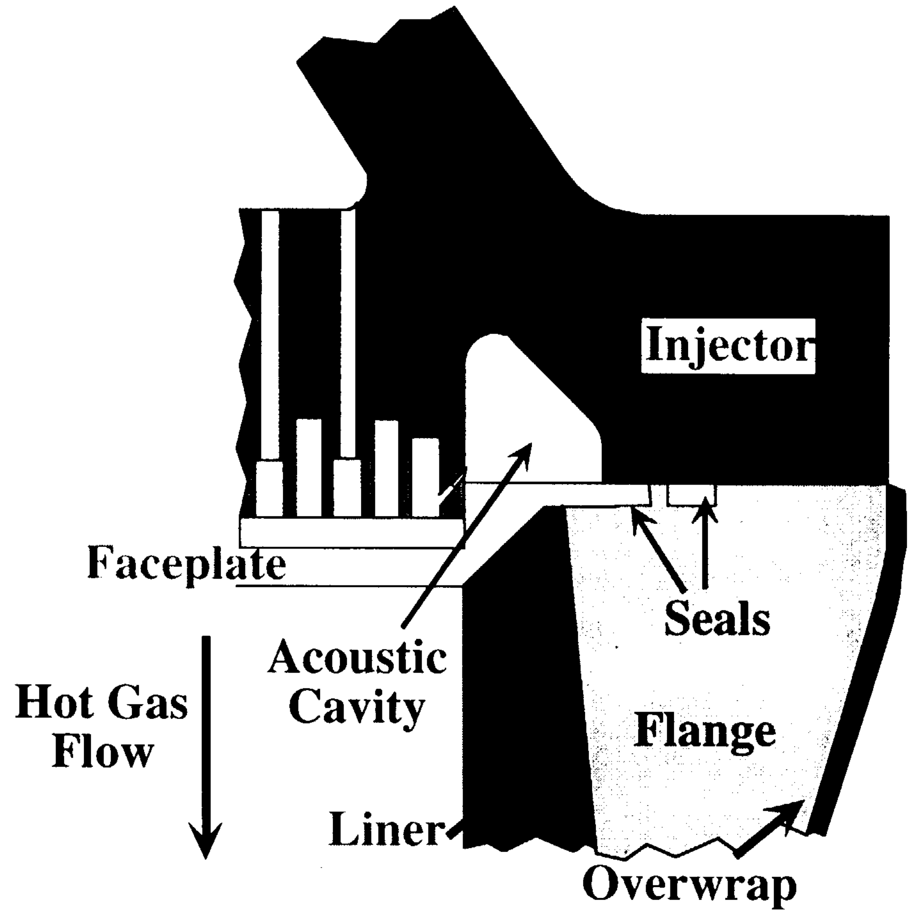
- A test matrix of 18 hotfire tests and 473 seconds was accumulated on three different nozzles.
- No net throat erosion was measured on any of the liners. The silica liner was charred but none of the charred material was removed during the tests.
- The chambers were cut into sections after testing was complete and the char layer depth measured.
- Heat damage in the acoustic cavity and some minor streaking occurred in the 40K testing. The streaking was solved with faceplate element geometry changes made on the 15K. No local overheating or streaking has occurred since these faceplate modifications were made.
- The test series ended with a successful 150 second test on 40K#2 (second 40K nozzle manufactured).

6. Transition to 60K

The last few tests of the 40K nozzles actually had a Pc above 600 psia (rather than 400 psia) as a pathfinder for the 60K hardware. No nozzle performance change was noted at the elevated operating pressures.

1. Injector Attachment Design

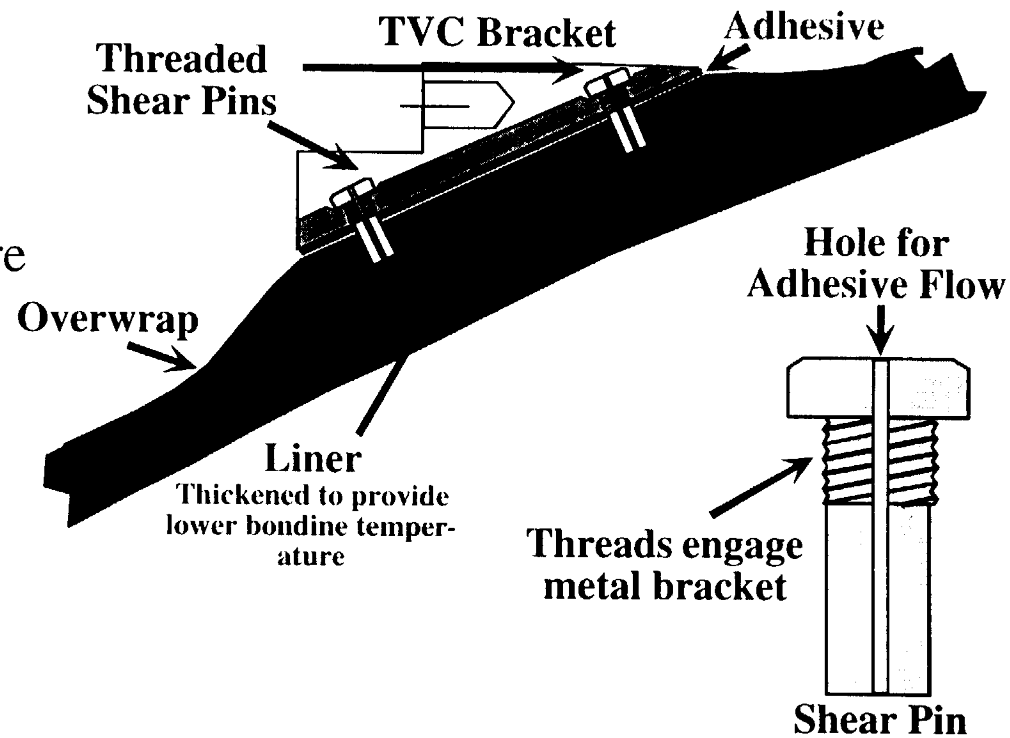
- The injector flange geometry changed slightly to accommodate the change from the 40K injector to the 60K injector.
- The chamfer on the silica leading into the acoustic cavity was changed to match the new acoustic cavity geometry desired for the new design.



2. Liner Thickness Change

- Liner thickness was kept almost identical to the 40K, with a small liner thickness increase at the locations where the brackets are bonded to the nozzle outer surface.

- This additional liner material was added to provide more thermal protection for the bondline under the external bracket attachments.



- Shear pins were also added at these locations to provide increased reliability of this attachment.

3. Materials and Processing

After two successful tests of the first 60K nozzle, the nozzle broke off just aft of the throat at the start of its third test. An investigation team was formed to explain the failure, and after the cause was found a "Tiger Team" was formed to correct and improve the materials and manufacturing process of the nozzle. The cause of the failure was a combination of the following:

- Low strain to failure of the "different but equal" silica phenolic material,
- Degraded bondline between the liner and overwrap,
- Induced stress from CTE mismatch between overwrap and liner,
- Repeated use of a single use nozzle.

3. Materials and Processing

- One primary reason for this failure can be traced to the change in silica phenolic material in the transition from 40K to 60K nozzle production.
- One "flavor" of silica phenolic was used in the 40K nozzles, but was discontinued, so a replacement material that met the identical RSRM spec was substituted.
- We found that this new material had a lower strength and was more brittle.
- We now use a silica phenolic "flavor" that is as close as the original material as can be manufactured at this time.
- Numerous changes and improvements were made to the processing flow of the nozzle based on the findings listed above, and no further anomalies have been found since these processing changes went into effect.
- We are also developing inspection techniques that allow us to judge the liner delamination depths and debonded areas caused by the post test heat soak through the nozzle wall. Using these techniques, we have been able to retest a nozzle up to nine times.

6. TPS

- The overwrap is limited to approximately 300°F temperatures due to the epoxy resin.

- In order to protect the overwrap from the plume radiation and convective environments at high altitude, TPS was applied to the surface of the nozzle aft of the TVC ring.

- No TPS is applied above the TVC ring because that portion of the nozzle is contained behind the Heat Shield on the X-34 vehicle.

VI. FUTURE WORK

"There comes a time in the life of every program when you must shoot the engineer and start production"

The time came when we had to freeze the nozzle design in order to meet the nozzle production schedule. We have identified several areas of improvement if another application for this nozzle is requested.

- Significant weight could be saved in the injector flange.
- A CMC (Ceramic Matrix Composite) nozzle extension would save a tremendous amount of weight, and would be easily attached to the ablative.
- Another area of interest that has been mentioned is a nozzle in the 250,000 lb. thrust category. The technology and design techniques developed on this nozzle will scale up to a nozzle of this size, and any booster application should result in a nozzle with an increased thrust/weight ratio over the current design.

VII. CONCLUSION

- We are nearing the end of the of this nozzle development, and have enjoyed great success.
- Although many of our current design requirements are driven by X-34, the philosophy, technology and hardware developed in this nozzle could be applied to other sizes and many applications.