AIAA 2000-3286
A REGENERATIVELY COOLED THRUST CHAMBER FOR THE FASTRAC ENGINE

Kendall K. Brown and Dave Sparks
NASA Marshall Space Flight Center
Huntsville, AL

Gordon Woodcock
Space America, Inc.
Huntsville, AL

36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference
16-19 July 2000
Huntsville, Alabama

A REGENERATIVELY COOLED THRUST CHAMBER FOR THE FASTRAC ENGINE

Kendall K. Brown* and Dave Sparks†
Space Transportation Directorate
NASA/Marshall Space Flight Center, AL 35812

Gordon R. Woodcock‡
Space America, Inc.
Huntsville, Al 35824

Abstract

This paper presents the development of a low-cost, regeneratively-cooled thrust chamber for the Fastrac engine. The chamber was fabricated using hydraformed copper tubing to form the coolant jacket and wrapped with a fiber reinforced polymer composite material to form a structural jacket. The thrust chamber design and fabrication approach was based upon Space America, Inc.'s 12,000 lb, regeneratively-cooled LOX/kerosene rocket engine. Fabrication of regeneratively cooled thrust chambers by tubewall construction dates back to the early U.S. ballistic missile programs. The most significant innovations in this design was the development of a low-cost process for fabrication from copper tubing (nickel alloy was the usual practice) and use of graphite composite overwrap as the pressure containment, which yields an easily fabricated, lightweight pressure jacket around the copper tubes. A regeneratively-cooled reusable thrust chamber can benefit the Fastrac engine program by allowing more efficient (cost and schedule) testing. A proof-of-concept test article has been fabricated and will be tested at Marshall Space Flight Center in the late Summer or Fall of 2000.

Introduction

The Fastrac engine program is part of the Bantam Low Cost Technology Program. Technical demonstrate that off-the-shelf products and commercial practices could be used to develop low-cost rocket engines. Initially, the Fastrac engine was intended for a ground launched expendable booster, but early in the

design cycle it was chosen as the propulsion system for the X-34 high speed research vehicle. Since moving into the flight development stage, the engine has been re-designated the MC-1.

Space America, Inc. (SAI) submitted a proposal under NASA Research Announcement 8-21, cycle 2 to develop a regeneratively-cooled thrust chamber for the Fastrac engine. The thrust chamber would be based on the design and fabrication processes demonstrated in SAI's 12,000 lb, thrust (12K), regeneratively-cooled, LOX/kerosene thrust chamber.

A regeneratively-cooled thrust chamber could benefit the Fastrac engine program by providing a reusable thrust chamber, thus allowing more cost efficient testing and operation. This paper will discuss the design and fabrication of the proof-of-concept test article and the test program that will be conducted with the chamber.

Research Objectives

The objective of the contract was to evolve the fabrication approaches used by SAI in the construction of the 12K thrust chamber to a higher fidelity unit which could undergo hot-fire testing with the Fastrac main injector. Specifically, the research objectives are the following:

- Design, develop, and fabricate a regeneratively cooled thrust chamber for the Fastrac engine using the low cost regeneratively cooled thrust chamber methodology developed by SAI for the 12K chamber.
- Develop conceptual layouts for integrating a regeneratively cooled thrust chamber into the Fastrac engine assembly, with specific application to integration of a regeneratively cooled Fastrac engine into the X-34 flight test program.
- Provide a proof-of-concept test article to MSFC for a 3-test series in TS 116. The test article will be tested at the same operating conditions as the current thrust chamber assembly testing. Thermal data will be obtained to measure the bulk coolant temperature increase and the temperature at the coolant tube/composite jacket

* Former Liquid Propulsion Engineer and Contract Monitor, Space America, Inc., currently Liquid Engine Systems Engineer, NASA/MSFC, Senior Member.
† Combustion Devices Engineer and COTR, NASA/MSFC, Senior Member.
‡ Chief Engineer, Senior Member.

interface. This test article will be examined to investigate life limiting hardware issues.

Background

The Fastrac engine was initially intended to be a booster engine for low cost expendable launch vehicles. A number of design approaches were taken to make the engine easier to produce to achieve the low cost objective. Primary among these was the use of simplified designs to enable fabrication with commercially available machining equipment. Using ablative nozzles provided a good solution to that problem. The Fastrac engine became the X-34 main propulsion system and final development was based on that application. A significant amount of the hardware design was essentially frozen, and redesign to increase the reusability would have adversely impacted the cost and schedule of the engine. The Fastrac ablative nozzles are designed for a 300 sec burn duration, or a 23 sec engine acceptance test and a full duration (155 sec) burn during a X-34 mission. It is a 30:1 expansion ratio nozzle, but the nozzles are often truncated at 15:1 for sea level development testing. The Fastrac engine operates at a chamber pressure of 633 psia and produces 60,000 lb, vacuum thrust.

Space America, Inc. is developing a family of low-cost commercial rocket vehicles including sounding rockets, military target vehicles, and light and medium class expendable launch vehicles. Regeneratively cooled thrust chambers are cost efficient for Space America's main propulsion systems by allowing additional development testing without having to replace disposable thrust chambers. The cost efficiency increases if the vehicle or stage is recovered.

SAI began evolutionary development of regeneratively-cooled lox/kerosene rocket engines at the 4000 lb, thrust level with partially-cooled thrust chambers. The 4K engines provided valuable experience and test data and led to development of a 12,000 lb, regeneratively-cooled engine. The 12K engine is fully regeneratively-cooled, using copper tubes hydraformed and shaped to fit together to form the nozzle and chamber contour. The graphite structural overwrap approach that had been entirely successful at the 4K level was maintained. A test apparatus was built to develop and prototype the net-shape hydraforming process. Figure 1 shows the chamber during assembly (photo on the left is the tubewall assembly partially welded, and the photo on the right is the fully assembled chamber after application of the graphite reinforced composite overwrap jacket).

Application to Fastrac Engine

A regeneratively-cooled thrust chamber can benefit the Fastrac engine development program in many ways. It allows increased development testing without the time and expense of replacing ablative nozzles. Regeneratively-cooled engines are generally expected to provide approximately 1% increased performance, although the counteracting real processes inside the combustion chamber may tend to dissipate that theoretical increase. In the X-34 program, or any reusable vehicle, a regeneratively-cooled engine also decreases program cost, schedule, and risk by eliminating the requirement to install a new nozzle after each mission.

Program Philosophy and Approach

An aggressive schedule was established in order to produce test hardware for an anticipated test stand availability approximately 6 months from contract start. Concurrent design practices were utilized to enable the design to progress based upon first-order calculations while higher-order analyses were being developed independently by consultants – when the higher order
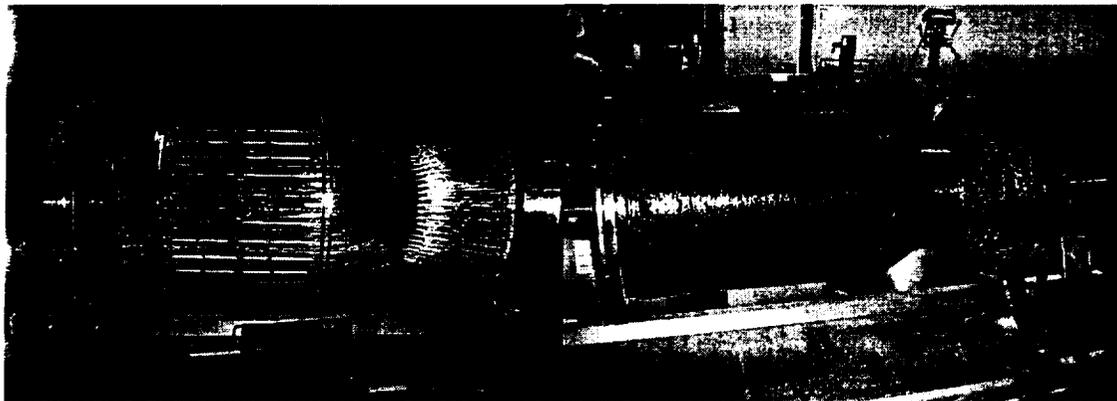
Figure 1 – Space America 12K Regen-Cooled Lox/Kerosene Engine
Left – During Weld-up; Right – After Composite Jacket Fab

analyses were obtained, that information was incorporated into the hardware design. The program was planned with four primary tasks: preliminary design, detailed design, fabrication, and testing. Reviews were held with MSFC at key milestones in the program.

Initially, the preliminary design focused on key areas of technical risk. A primary objective of this program was to demonstrate that fabrication of a regeneratively cooled Fastrac thrust chamber can be an economical alternative to the current ablative chambers. Therefore, the proof-of-concept test article needed to be representative of any eventual flight units. This presented a number of conflicting requirements, principally, the ability to design the chamber for testing as a thrust chamber assembly while maintaining the ability to integrate it into the engine system. The chief concern was the ability to develop designs and fabrication processes for the manufacture of a single production unit, while minimizing the design changes needed for increased production.

The Space America, Inc. 12,000 lbf rocket engine operates at 250 psia chamber pressure and is regenerative-cooled to an area ratio of approximately ?:1. It has a 6.9" diameter throat, a 10.5" combustion chamber diameter and is approximately ?" long. The 12K engine uses liquid injection thrust vector control and the side force the composite jacket must carry is relatively minor. By contrast, the Fastrac engine operates at 633 psia, has a ?.25" diameter throat, a 11.282" combustion chamber diameter, and the 15:1 area ratio nozzle is approximately 44" long. The Fastrac engine is gimbaled and uses two actuators to apply force to move the engine to direct the thrust. The increased operating pressure, larger nozzle, and the TVC loads are significant variations which were addressed during the design. Additionally, SAI identified that the larger nozzle necessitated the use of a bifurcation of the tubes to double the number of tubes in the divergent nozzle.

The test article fabrication ? and ? ? consisted of three separate, but parallel, activities: fabricating subcomponent and assembly tooling, fabricating the hydraformed tubes, and fabricating the manifold parts. Throughout fabrication of the test article parts, inspections and tests were conducted in accordance with specified procedures. ? tooling had to be designed and custom built for this project, partly due to the physical difference between the Fastrac chamber and Space America's 12K engine and partly to solve problems identified during fabrication of the 12K chamber. Fabrication tooling included hydraform molds, tube preshape and preform tools, a hydraulic hydraforming system, and

miscellaneous alignment and fixturing tools. The assembly tools included a horizontal assembly cart, a vertical assembly pallet, an assembly mandrel, and miscellaneous alignment and fixturing tools.

Design
The preliminary design effort defined the functional requirements, updated the conceptual designs, and reevaluated proposed manufacturing techniques. The contract required fabrication of a single thrust chamber for design verification testing. Fabrication of additional regenerative thrust chambers is highly uncertain, and depends upon the performance of the component during testing and upon the direction of the MC-1 engine and X-34 programs. Thus, design and fabrication approaches were reviewed during the preliminary design effort to determine the optimum approach for fabrication of the test article, and to define areas that could and would be improved if production of the regen-thrust chambers was needed. This section will present the derived requirements for design of the test article, design trade studies, and integrated engine concepts.

Design Requirements
Since future integration into the Fastrac engine assembly is the purpose of this development, defining the interfaces was the first priority. Two sets of interfaces and design requirements exist - first for the test article and its testing at MSFC, and second for the integration of a regen-chamber into the Fastrac engine assembly. Several trade studies were performed, including trades to determine the feed line configuration, the coolant circuit (one-pass or pass-and-a-half), and fabrication processes for tube-tube and tubewall-manifold joining and the composite jacket.

The coolant tubes must be primed with fuel prior to starting the main combustion chamber. The life of a coolant tube without coolant flow, at the heating rate predicted at mainstage pressure, is less than half a ? ? ? ? ? configurations must account for the coolant jacket priming requirement.

The test article structural jacket was structurally designed for the currently predicted Propulsion Test Article and X-34 thrust vector control actuator loading conditions. ? ? ? assumption. It was assumed that the composite jacket would be designed to carry all of the actuator loads.

The basic approach to developing concepts for integrating a regeneratively-cooled thrust chamber into the Fastrac engine assumes the major components stay the same, and most in the same positions, but all of the secondary components can be rearranged. Trying to

create a regen thrust chamber as a line replacement unit and interchangeable with the ablative nozzle seemed to be unrealistic. In effect, this produces two different Fastrac engines - a regeneratively cooled Fastrac and an ablative Fastrac, with the only difference between the two engines being the thrust chamber and the size of the fuel orifice. The engine must have a horizontal start capability, i.e. use in the X-34, so consideration of the coolant jacket priming is essential. Relocation of the main fuel valve became essential to integration concept development. The governing assumptions and ground rules for the new fuel flowpath in the regen-engine are the following:

- Turbopump relationships remain unchanged
  - Existing propellant inlets to the engine
  - Existing orientation with respect to the injector
  - Existing MOV position
  - Existing belly band
  - Maintain pressure drop within existing fuel orifice delta-P
- Horizontal start capability
  - coolant jacket primed at engine start
- MFV can be repositioned
- Existing ignition system
- Maintain injector feed (splitter block and steer horns) as similar to existing as possible
- Use existing TVC actuator bracket
- Ancillary engine components subject to relocation
  - igniter valves, bypass valves, purge valves, TCA igniter assembly, etc.

Integrated Engine Concepts

To demonstrate how the regeneratively-cooled thrust chamber can integrate into the engine system to provide a regeneratively cooled Fastrac engine, a couple of conceptual layouts were developed. A concept was developed for an altitude engine with a 30:1 expansion ratio nozzle, such as the X-34, and for a booster vehicle application. The conceptual layouts only show the major engine components – regen thrust chamber, turbopump, gas generator, main injector, main fuel valve, main oxidizer valve, turbopump bracket, TVC actuator bracket, lox feed line, and fuel feed line.

X-34 Application

Figure 2 shows a conceptual model of a regeneratively cooled Fastrac engine suitable for the X-34 research aerospace plane. One of the governing design requirements was the ability to have the coolant jacket fully primed at engine start, thus the coolant jacket needed to be between the fuel turbopump discharge and the main fuel valve. As part of the X-34 mission profile the vehicle is carried at an altitude of ~5,000 ft for about an hour prior to drop and engine
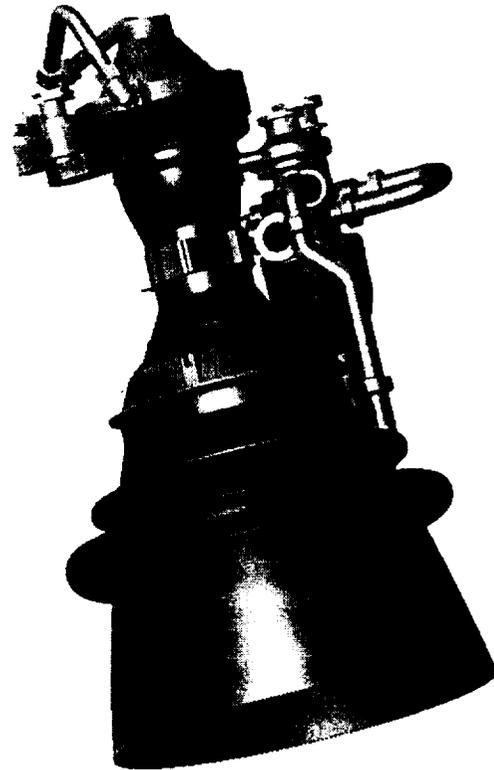

Figure 2 – Fastrac Engine with Regen-Cooled Thrust Chamber for X-34 Application

ignition. The ambient temperature at that altitude is near the freezing temperature of RP-1, thus a major system integration study will have to address that issue.

The MFV is moved to the opposite side of engine, moved up, and uses the same splitter block arrangement as the existing engine to distribute fuel to the two sides of the injector. The engine system is shown with a nozzle extension to provide the 30:1 expansion ratio nozzle. The thrust chamber is regeneratively-cooled to an area ratio of 15:1 and nozzle skirt is connected to a flange included as part of the lower fuel manifold. Shown is a nozzle skirt that is cooled by dump cooling or transpiration cooling with the gas generator exhaust, similar to that used on the Saturn F-1 engines. An ablative nozzle extension or an uncooled refractory metal nozzle could also be used. The low heating rate in that portion of the nozzle would allow a properly designed ablative nozzle extension to have a life of several full-duration tests. The high-temperature refractory metal nozzle extension probably would not be a good choice for the X-34 application because of the radiative heating load generated to the aft section of the vehicle.
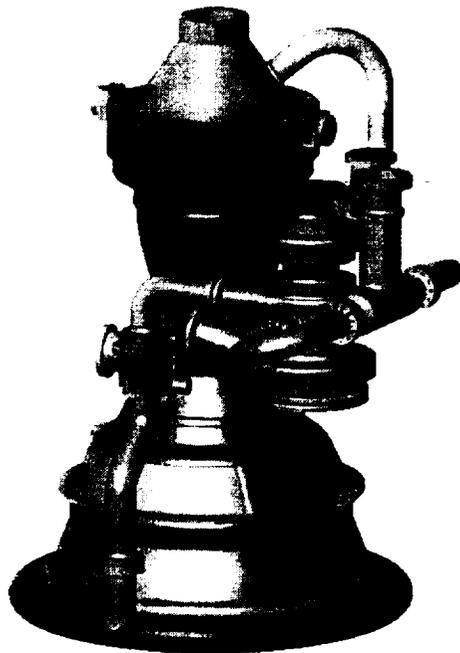
Figure 3 – Fastrac Engine with Regen Thrust Chamber for Booster Application

manually pre-primed, or the start sequence modified to fill the jacket as part of the start transient.

Figure 3 shows a conceptual layout for a booster application Regen-Fastrac engine. The fuel pump discharge is connected to the main fuel valve, which is rotated down 180° from its current configuration. The MFV feeds the lower manifold. The upper manifold feeds the injector directly through holes or slots in the thrust chamber flange and the injector. The concept model is shown with the 15:1 nozzle used for the test article design. The exact nozzle contour would have to be optimized for the specific booster vehicle application, but that has relatively minor implications on the hardware design.

Design Description

Figure 4 is a CADD model of the regen thrust chamber test article. The coolant jacket is fabricated by welding hydraformed copper tubes together to form a continuous tubewall. The regen thrust chamber contour is the same as the existing ablative nozzles - with one exception - the straight segment in the throat has been removed. A straight throat section is often used in ablative throats, but is unnecessary in a hardwall chamber. The major components of the assembly include the tubewall, the lower and upper manifolds, and the composite structural jacket.

Copper tubing, alloy C122, is hydraformed to obtain the correct widths at all axial positions along the thrust chamber contour to produce a continuous coolant jacket. It is formed using two sets of tubes: the first set comprise the combustion chamber and nozzle section to an area ratio of about 5.3:1. The second set of tubes form the nozzle from the 5.3:1 to 15:1 area ratios, and

Booster Applications

In the SAI 12K engine, the fuel flows from the upper manifold directly into the injector fuel manifold, thus avoiding piping to connect the upper fuel manifold to the injector. If it is assumed the Fastrac engine is started in a vertical configuration, as in a vertical takeoff launch vehicle application, this same type of system can be used. The coolant jacket could be
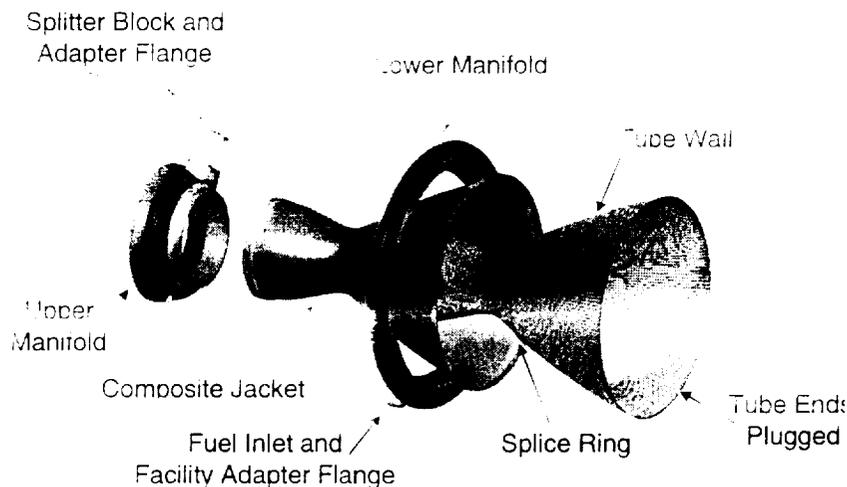

Figure 4 – Exploded View of Thrust Chamber

contain twice as many tubes as the chamber/throat tubes. A machined copper ring with pass-through slots is used to take the coolant flow from two nozzle tubes into one chamber/throat tube.

The fuel enters the thrust chamber at the nozzle exit with a single inlet duct. The inlet manifold, a toroid formed by rolling a piece of stainless steel tubing, distributes fuel to each tube through a slot in the top of each tube. The torroid is attached to rings welded to the tubewall, and the upper support ring serves as a transition to the composite jacket. The upper manifold contains the thrust chamber flange to attach to the injector. The injector interface design is exactly the same as the ablative design, with particular attention to ensuring the aperture to the injector acoustic cavity is the same. Fuel exits each tube through a slot in the top of each tube to the manifold. The upper manifold exit is located 180° from the inlet to provide as equal flow as possible through each tube.

The composite jacket is fabricated using the involute fabrication process, discussed in the next section. A graphite/phenolic preimpregnated fabric was selected due to the predicted temperature at the composite/tubewall interface.

Fabrication Process Selection

A number of trade studies were performed during the design phase to select the fabrication methods to be used on the test article.

In the SAI 12K thrust chamber, a GTAW (Gas Tungsten Arc Welding, often called TIG) process is used to join the tubes to form the tube wall and seal hot gas from the composite overwrap. The TIG weld was used because of problems with a silver-solder braze in the 4K regen-cooled chamber (only the cylinder section of that chamber was cooled). Using a torch-braze requires heating a much larger area, creating differential thermal expansion, contamination problems during the curing of the composite jacket, and possible metallurgical issues. The ... ... considered optimum. The two traditional methods used to join coolant tubes for rocket engine thrust chambers are furnace brazing and electroplating.

After reviewing the specifications for furnace brazing alloys, we determined that furnace brazing and ... ... appropriate ... ... temperature ... brazing temperature required and the added requirements of the assembly tooling.

Electroplating is a joining method for tubewall engines, and is used on SSME, Ariane V, and numerous other rocket engines, and seemed like a reasonable alternative for this application. It was concluded that electroplating would be an excellent candidate for a

production run of regen-chambers, however for a one-unit production the non-recurring engineering and tooling costs were prohibitive.

The SAI 12K engine has a graphite composite material structural jacket fabricated on top of the tubewall and tied into the upper manifold. The SAI 12K uses a liquid injection thrust vector control system, so the side force, and resulting bending moment, that the jacket must resist is small. The primary load the jacket must contain is the combustion chamber hoop stress. A composite jacket was proposed for the Fastrac chamber using an involute fabrication method. An involute composite lay-up is often used for ablative solid propellant rocket motor nozzles, so extension of the method to this application is somewhat unique. An alternative identified in the proposal was to fabricate the structural jacket by electroplating nickel on top of the tubes.

An involute lay-up technique means that a composite part is fabricated using individual panels of composite fabric laid on top of each other, each offset by some amount. One can envision an involute by taking a deck of cards and spreading it out on the table with each card offset parallel to each other by a set amount. Then take the cards and bend them around a mandrel and tuck the end of the spread out cards underneath the beginning to form a cylinder. A composite jacket can similarly be fabricated for a rocket engine by taking axial strips and individually forming each to the contour of the thrust chamber using graphite fiber fabric pre-impregnated with resin. An involute fabrication technique requires very little tooling and is an excellent option for prototyping.

A design trade study was developed to weigh fabrication of the composite jacket with an involute jacket versus the more conventional method winding or fiber placement. The review determined three critical disadvantages to the conventional method. First, in order to use a winding machine for the composite jacket ... transition in the upper ... all to the ... ... radial ... and, tooling would be needed at the nozzle exit and the injector interface flange to allow the fibers to wrap around the ends (material which would be later cut off), and this tooling would be large and could be outside the costs budgeted for composite jacket tooling. Finally, the availability of a government winding machine was subject to the priorities of the government's use, and as such, could create a schedule problem affecting test article delivery. The primary advantage of the fiber winding machine is that the jacket would be applied in essentially the same design as the existing ablative chambers, thus minimizing technical risk.

The third alternative evaluated for the structural jacket was electroplating a nickel jacket on top of the tubewall. Nickel offers a high strength, high modulus material and brackets could easily be added by welding them directly to the nickel. The attractiveness of the nickel jacket exists only if the tubes are joined by electroplating. Once it was determined that electroplating the tubewall was prohibitively expensive, a more detailed investigation of the nickel jacket was abandoned. Issues which need further investigation are differential thermal expansion and the resulting thermal stresses, and crack propagation caused by the preferential grain growth direction.

Prototyping

A number of prototyping activities occurred during the design phase in order to completely understand the processes required for fabrication. All processes were prototyped which were significantly different than used in the 12K thrust chamber, or where the process used in the 12K thrust chamber could be improved. Prototyping was conducted in three areas, tube welding and brazing, tube hydraforming, and composite jacket fabrication.

Design Analyses

Fluid dynamic and structural analyses were conducted as needed to support the test article design and to predict the performance of the hardware. Lower order calculations and analyses, empirically based and simple analytical equations, were generated to begin the design while higher order analyses were being developed. Computational fluid dynamic analysis of the flow through an individual tube was conducted to obtain a higher resolution of the fluid behavior in the individual tubes. Finite element method structural analysis software was used to support the mechanical design of the test article.

Fluid Dynamic Analysis

Thermal analyses were developed to predict the temperature at the tubewall-composite jacket interface, the bulk temperature rise in the fuel, and the coolant circuit pressure drop. The analyses were anchored against test data from the SAI 12K thrust chamber. A hot-gas side prediction was made using the Bartz equation, with correlations to the 12K data, and is shown in Figure 5.

A 2-D transient model was developed to predict the heat transfer in and through the copper tube. The transient analysis shows that the engine reaches thermal steady-state after 2 seconds of mainstage operation (the simulation ignored the engine start transient). Figure 6 is a plot of the temperature distribution through the tube
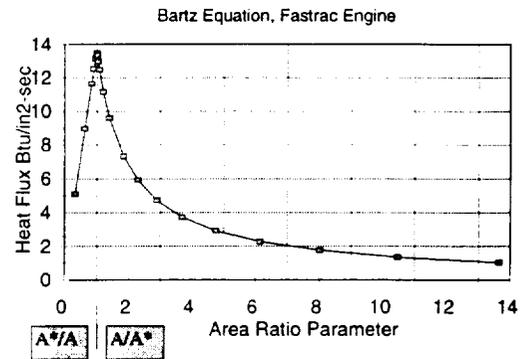

Figure 5 – Predicted Heat Flux for Fastrac Engine

wall as a function of the position along the tube from the center of the tube inside the chamber to the center of the tube at the interface to the composite jacket. This plot shows the predicted temperature across the tube is approximately 70°F. It also shows that the temperature at the composite jacket interface is approximately 260°F. The heat conduction through the tube and predicted inside wall temperature is used with a liquid-side convection model to predict the temperature rise in the fuel coolant. The predicted bulk temperature rise is approximately 160°F. A pipe-flow, friction factor method was used to predict a 22 psid pressure drop in the coolant tubes minus the inlet and exit effects.
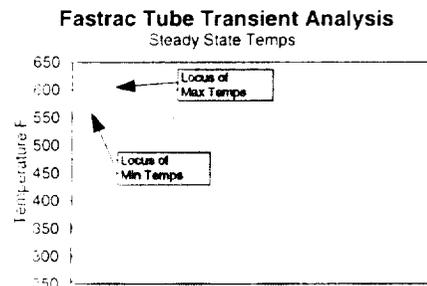

Figure 6 – Coolant Tube Temperature Profile at the Throat

The computational fluid dynamic (CFD) model simulated the flow in each of the tubes, but not the inlet, exit, or the tube splice ring. The CFD study included the effects of variable properties (density, viscosity, specific heat, etc., as a function of temperature) and used predicted tube wall temperatures generated by the analytical models. The CFD results correlated very well, predicting a total temperature rise of 158°F and a pressure drop of 24 psid. The CFD analysis modeled the boundary layer of the flow at the hot wall and determined that the conditions required for coking of the RP-1 propellant do not exit.

Structural Design and Analysis

As with the fluid dynamic analyses, the structural analyses were conducted in two phases, initial hand calculations and low-fidelity finite element method (FEM) models were used to size the hardware while more detailed FEM models were being developed. The structural jacket design requirements were based upon the loads from an integrated engine with maximum TVC actuator loads. Problems with developing the detailed FEM model prevented having the final result until after the detailed design was complete. As will be discussed, the final FEM analysis indicates the test article has sufficient structural margin for engine testing, but may not be able to support the predicted TVC actuator loads. The composite jacket was sized using the initial assumption that the jacket carried all of the combustion chamber pressure and maximum predicted TVC actuator loads. The predicted TVC actuator loads are quite high and include peak dynamic loads as static loads - a conservative assumption. Using vendor data for typical graphite/epoxy composite materials, a conservative design was chosen to provide a wall thickness of 0.25" in the combustion chamber and through the TVC actuator position on the nozzle. Beyond the TVC actuator the design thickness was reduced to 0.20 in because little load is present and further thickness reduction would have been a manufacturing problem.

The cross-sectional geometries of the coolant tubes as a function of axial position, and the associated wall thicknesses, were developed using the low-level FEA software. The analysis was validated against the proven 12K geometry. The design criteria assumed the copper tubing had fully annealed strength properties, even though a significant, but variable amount of cold-working is present in the tubes after the hydraforming. Thus, any grain growth, and subsequent reannealing, caused by the heat introduced during the assembly welding is essentially irrelevant. The 2-D transient heat transfer model was used to estimate the thermal response of the can and indicates [...] locally in high heat transfer areas, but that life due to thermal cycle fatigue is of the order of 100 cycles (starts to mainstage).

The detailed model included the internal chamber pressure, the internal tube pressure, and the TVC actuator loads. The detailed [...] individual tubes, the welds, the splice ring, and the composite jacket were limited by the software. A plane of symmetry down the center of the thrust chamber was defined and half of the chamber was modeled. Initial results of the model seemed to confirm the initial design results, however when all of the loads were combined, and the meshing problems solved, the model

predicted negative margins in the tubes in the divergent portion of the nozzle between the splice ring and the throat. The final model included updated property data for the graphite-phenolic jacket. Since the stiffness modulus for the composite jacket is less that the stiffness of the tubewall, the bending moment from applying the TVC actuator load is restrained by the tubing instead of the jacket.

When the graphite-phenolic fabric was received, tensile test articles were designed and fabricated in an attempt to gather property data for the involute jacket. Two tensile test samples were designed – one to obtain the bond strength between the jacket and the upper manifold and the other to obtain the bulk tensile strength in the as-laid configuration. The bond test specimen provided results representative of the matrix being used. However, the tensile test specimen data was inconclusive due to insufficient fiber length.

Composite materials experts at MSFC were consulted to review the tensile test data and its impact on the involute jacket design. It was determined that without significant additional testing, the involute jacket may not be able to support the design requirements. However, since structural testing with TVC actuator loads was not in the test plan, and since the actuator loading is the critical load, the involute jacket was redesigned using updated design criteria and designed for the internal chamber pressure as the critical load. The test objectives for the test article can still be met with the chamber, however the design had to be further iterated to account for fabrication issues.

The negative margin predicted in the tubewall as a result of the tubewall, splice ring, and composite jacket design indicate the structural design needs to be significantly readdressed as a follow-on project.

Fabrication

Special tooling had to be fabricated for the tube forming and chamber assembly due to the significant differences between the XAI 12 and the Fastrac chambers. This tooling includes hydraulic hydraforming equipment, a segmented assembly mandrel, and miscellaneous assembly fixtures.

The assembly mandrel and horizontal assembly cart is shown in Figure 7. The sections in the combustion chamber, the convergent nozzle throat, and the initial divergent section of the nozzle are separate parts fabricated from low-carbon steel. The remaining section of the nozzle was fabricated by applying a thin layer of low-carbon steel on top of a special polyurethane foam and metal structure. The foam was machined undersized to the desired contour and the nozzle and thermal arc-spray metal deposition was used to build up a steel shell to the final dimension. The
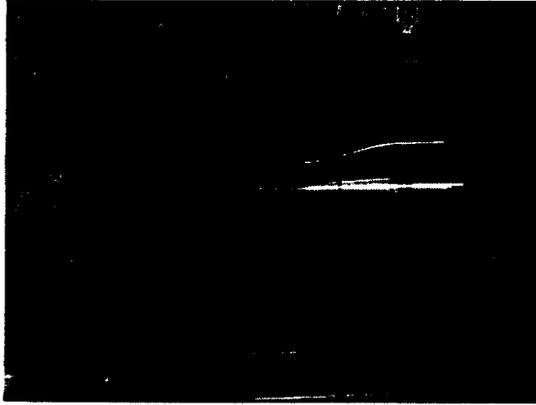
Figure 7 – Thrust Chamber Assembly Mandrel

fabrication process for the nozzle mandrel was significantly less expensive, than building it by rolling and machining steel plate. There was also the added benefit of lower weight and easier to handling.

Each of the two tube sections were fabricated using a hydraforming process developed by Space America, Inc. for their commercial propulsion systems. After each tube was formed to the final shape it was inspected for defects and dimensions. An end plug was GTAW welded into each tube and proof tested to approximately 130% of the nominal operating pressure inside the tube.

The assembly was dry-fit on the assembly mandrel and the fit in the critical regions of the combustion chamber and the nozzle throat was excellent with virtually no gaps. Figure 8 hows the tubewall assembly during dry-fit.

GTAW was selected for the tubewall welding because the single item production and firm fixed price contract precluded development of the electroplating or other joining process. Deoxidized copper filler rod was used for the tube-to-tube welds and aluminum-bronze filler rod was used to join the copper tubewall to the stainless steel manifolds. During welding of the nozzle some of the tubes were overheated, which in turn caused partial (local) disintegration of the mandrel steel ... complete ... ...

... nozzle had to be reinforced with steel disks at circle axial locations. This left unsupported gaps between the disks, which compromised the desired dimensional tolerances of the nozzle.

Torch brazing was selected for joining the tubes to the splice ring. A silver-bearing braze filler rod was determined ... test ... material ... application. Prototype braze joint tests indicated the joint design would allow the braze material to flow between the adjacent tubes and provide a strong joint with no leakage. After brazing of the splice ring tubes, a significant amount of repair had to be made, and accepted deviations ... the splice ring further
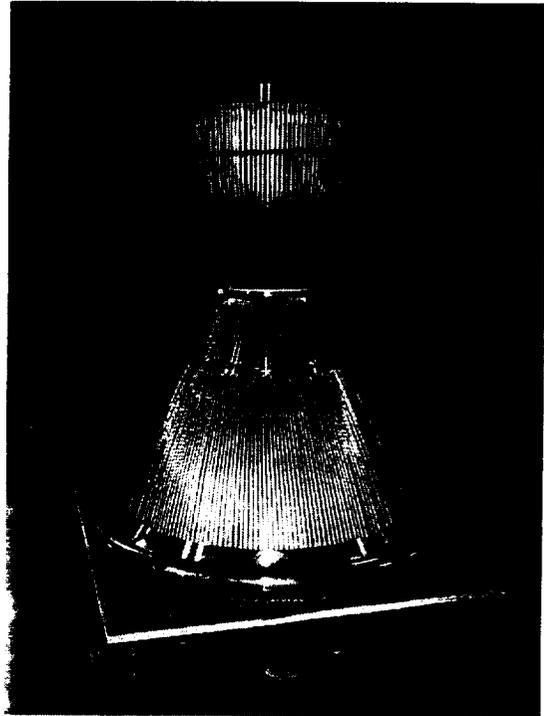

Figure 8 Dry-fit of Tubewall Prior to Welding

exacerbated the brazing. The resulting braze joint is cosmetically poor. It contains local high spots which may generate small disturbances in the nozzle flow, however they are not expected to generate shock induced hot-spots.

While these mechanical flaws exist, they will not affect meeting the test objectives for the thrust chamber and are major lessons learned for subsequent chambers. Any performance decrease from the non-optimum nozzle shape should be minor, but thrust cannot be measured at the test facility, so the performance loss cannot be determined.

The original composite jacket design used fabric pieces cut on the bias with respect to the fiber direction, thus allowing it to be conformed to the convex and ... ... When ... composite jacket was ... oriented ... future aligned ... ... the direction of the hoop stress in the combustion chamber – the governing load for the test article – the involute design had to be modified to build up the throat region to reduce the amount of contour change. Figure 9 shows the chamber during fabrication of the involute jacket.

... ... prior to the hand lay-up of the involute pieces to help secure the pieces during the lay-up and to help bond the jacket to the tubewall. Thermocouples and strain gages were attached to the metal tubewall prior to applying the resin and involute lay-up to provide test data during ...
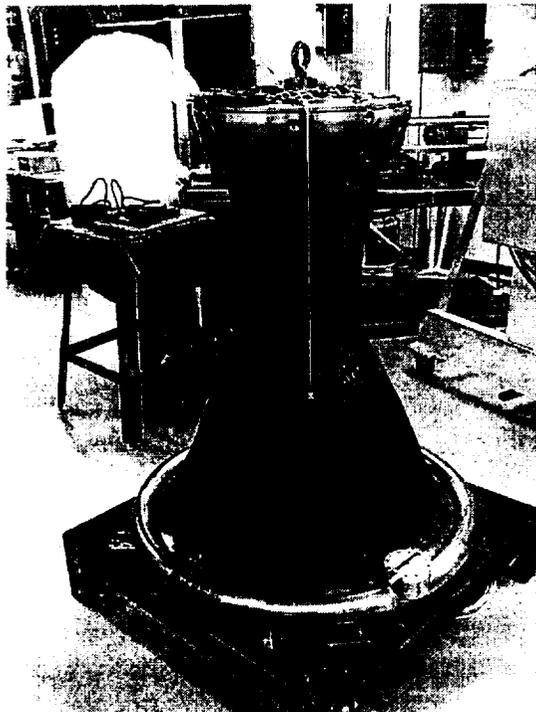
Figure 10 - Chamber During Composite Jacket Fabrication

The build-up regions were vacuum bag debulked as layers were applied and the final involute assembly was debulked prior to the vacuum bag cure cycle.

The completed thrust chamber is shown in Figure 11. Also shown is the upper manifold elbow block and the fuel adapter block.

Design/Process Improvements and Future Work

Depending upon future applications of the Fastrac engine, and the need to take advantage of the regeneratively cooled thrust chamber, a few remaining issues must be worked before fabrication of additional thrust chambers can begin. Lessons learned during the fabrication of the test article indicate that design and process improvements are needed in the coolant circuit tube brazing processes, as these are difficult to control, and the composite jacket design and fabrication process.

While the test article was not designed to be a light weight test article, it is approximately the same weight as the 15:1 ablative nozzle. The design of the upper and lower manifolds could be modified to save weight, and optimizing the tube joining process and composite jacket fabrication would also save weight. Conservatively, a light-weight version of the regen thrust could save 10%-20% of the weight of the ablative nozzle.

Design Improvement Areas

A laser brazing technique for joining the tubes has been experimented with, and appears promising. This process could significantly improve the time associated with the coolant circuit fabrication. Since the involute composite jacket design does not appear to have adequate strength, a new design and associated fabrication technique is needed.

The bifurcation joint must be redesigned due to the problems encountered during the brazing. The major problem was the ability to machine a large piece of copper into a small, relatively low mass part. It became difficult to control, and copper is notoriously hard to machine because as it is cut with the machine tool it becomes dimensionally unstable. A second problem with the current splice ring design was the difficulty in sealing the vertical intratube leakage, i.e. the leakage between the vertical sections of two tubes. Here, the torch braze material could not flow together from the top and bottom to form a good seal. Ironically, this problem was a result of the tubes fitting together too well.

Future Work

At this time, there are no plans to integrate a regeneratively-cooled thrust chamber into the MC-1 engine as the propulsion system for the X-34. A regen thrust chamber could reduce program risk by

Figure 11 – Regeneratively-Cooled Fastrac Engine Thrust Chamber Test Article

eliminating the need to replace thrust chambers after each flight. A comprehensive development program is needed to develop the technology and design to produce an integrated regeneratively cooled Fastrac engine. The path is defined by four major steps: thrust chamber process improvements, detailed integration layout, detailed integration design, and component and engine testing.

Test Article Testing

Tests are expected to be conducted at MSFC's test facility in October 2000, depending on test stand availability and MSFC priorities. The test objectives are:

- To demonstrate integrity of the test article and assess practicality of upgrading the Fastrac engine to a fully reusable engine by incorporating a regeneratively cooled thrust chamber into the design.
- To determine pressure drops in the fuel circuit and therefore assess ease of integrating the regeneratively cooled chamber into the Fastrac engine and power balance. Overall pressure drop in the fuel circuit is estimated to be less than the pressure drop in the current calibration orifice between the fuel pump discharge and the injector.
- To compare measured temperatures on the combustion chamber structure with analytical predictions. to confirm predicted temperatures and heat transfer rates. and to assess cooling margin for the regeneratively cooled chamber.

The chamber wall is instrumented with 41 thermocouples attached to the outside of the copper tube wall. These were installed before the overwrap was put on the chamber. Thermocouple probes are located in the fuel inlet and outlet manifolds to measure bulk fuel temperature rise in the cooling jacket. Pressure taps are located on the fuel inlet and outlet manifolds. in the injector. and located in the thrust chamber head-end manifold to measure combustion chamber pressure. Strain gages are also located on the tube wall.

All hot-fire tests will use the standard start sequence for a component-level, thrust chamber assembly test. Following checkouts, three hot-fire tests are planned:

- 10-second test with LOX flow at stage 1 and full fuel flow. In this condition, the LOX flow is metered by the LOX valve and the fuel flow is metered by the facility cavitating venturis. Chamber pressure is predicted to reach about 400 psia.
- 30-second mainstage test, targeting nominal chamber pressure 633 psia.
- 150-second (full duration) mainstage test, targeting the same condition.

Summary

A low-cost regeneratively-cooled thrust chamber has been developed for the Fastrac engine, and a proof of concept test article is awaiting test stand availability. The cost of the regen chamber is expected to be approximately 2.5 to 3.5 times the cost of the current ablative nozzles, but it is expected to have at least 3 times the life. The exact cost is difficult to determine until the identified process improvements are completed and a nozzle skirt designed. The future of the Fastrac engine and the Fastrac engine is unknown, so further development of this thrust chamber is unknown.