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New Method of Making Advanced Tube-Bundle Rocket Thrust Chambers

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NEW METHOD OF MAKING ADVANCED TUBE-BUNDLE ROCKET THRUST CHAMBERS

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ABSTRACT

An advanced rocket thrust chamber for future space applications is described along with an improved method of fabrication. Included are fabrication demonstrator and test chambers produced by this method. This concept offers the promise of improved cyclic life, reusability, reliability, and performance. The performance is improved because of the enhanced enthalpy extraction. The life, reusability, and reliability is improved because of the enhanced structural compliance inherent in the construction. The method of construction involves the forming of the combustion chamber by a tube-bundle of high conductivity copper or copper alloy tubes, and the bonding of these tubes by a unique electroforming operation. Further, the method of fabrication reduces chamber complexity by incorporating manifolds, jackets, and structural stiffeners while having the potential for thrust chamber cost and weight reduction.

INTRODUCTION

The design of future rocket engines will be done for a variety of missions and for a variety of requirements. In assessing the future requirements of space engines, one set of needs seems to dominate the picture; that is, for an engine that will be space-based, man-rated, and capable of many reuses, without severely compromising its thrust performance. This engine is expected to be very robust and reliable. In order to satisfy these requirements, the present candidate configurations involve the use of the expander cycle to drive the propellant pumps, and as such, encourage the development of combustion chambers with enhanced ability to extract enthalpy into the coolant from the combustion. The high chamber pressure of the proposed configurations result in high heat fluxes. As is the case for the space shuttle main engine (SSME), these configurations will require that the chamber be made of high conductivity copper or copper alloy.

This paper addresses these requirements by describing an advanced method of fabricating these advanced combustion chambers. This fabrication method and its benefits are not limited to just the engines described above but have potential for benefiting a wide variety of engines and missions.

FABRICATION METHOD

In the course of pursuing advanced fabrication techniques for producing rocket combustion chambers, several innovative and novel techniques have been developed at NASA Lewis Research Center. These techniques are employed to enhance the combined issues of performance, reliability, weight, and cost. These techniques are incorporated into the fabrication process described below. The fabrication steps are diagramed in sequential order and are shown in Fig. 1 as a general road map of the process. The individual fabrication steps will be described in detail below.

The fabrication starts with the production of tubes of high conductivity copper or copper alloy. These tubes will provide the passages for the coolant in the regeneratively cooled combustion chambers. The round tubes are individually roll formed on their outside surface while pressurized on the inside and stretched axially. The result is the production of a tube that is straight and of round cross section, but is of varying cross-sectional area and of varying wall thickness. The tubes are produced with a "double-taper," meaning that the tube diameter necks down to a minimum near the middle and then flares out to the larger diameter towards the end again. Figure 2 is a pictorial representation of the various fabrication steps. Figure 2(a) is an illustration of a double tapered tube as it would appear after a roll forming operation.

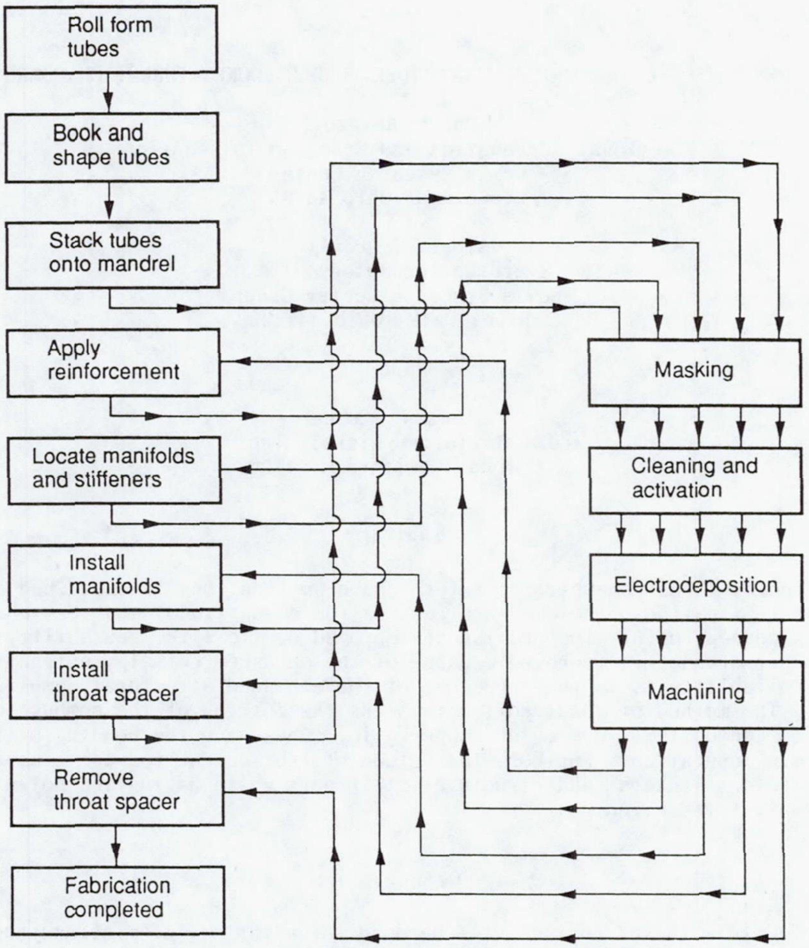


Figure 1.—Fabrication process diagram.

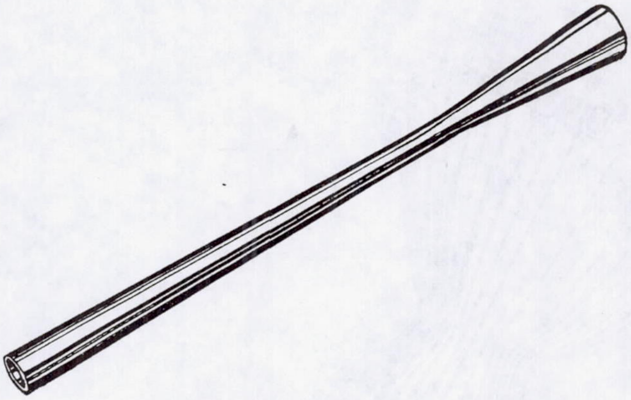
The next operation takes these straight tubes and bends them to a specified "S" shape to accommodate the combustion chamber contour. Figure 2(b) is an illustration of how a tube would look after a bending operation. The final tube forming operation is a booking operation. Here the round S shaped tubes are pressed in a die to a somewhat eliptical cross section to satisfy the tube width requirement. Figure 2(c) shows how the tube would look after a booking operation.

The tubes are then stacked around a mandrel to form the tube bundle shape of the contoured combustion chamber. The tubes are selectively fitted to accommodate the manufacturing tolerances without excessive accumulation of clearance. Figure 2(d) shows how the tubes would look stacked around a contoured mandrel. On the mandrel the tubes are held in place by holding fixtures as required. The tube assembly is now ready for the electroforming process. The electroforming process consists of four specific steps. These steps are a reoccurring process and are shown in the fabrication process diagram of Fig. 1. They are:

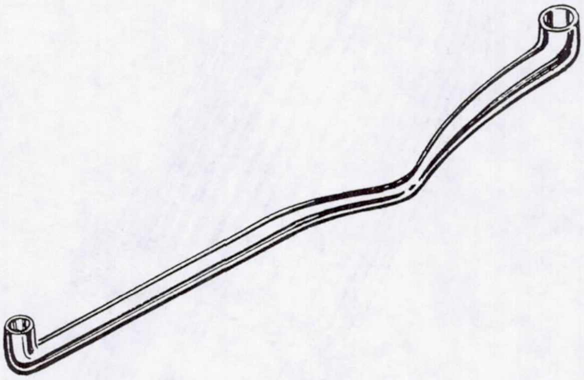
(1) Masking
(2) Cleaning and activation
(3) Electrodeposition
(4) Machining

The masking step involves the careful shielding of those areas of the tube and mandrel assembly where electrodeposition is not needed. The shielding is done by a variety of materials including machined plastic pieces, plastic tape, and molten wax or plastic coatings.

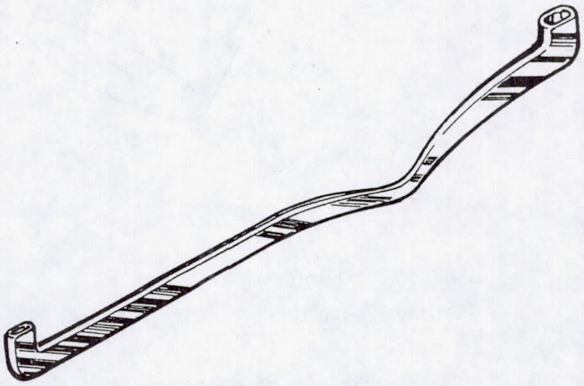
The second step is the cleaning and activation step. In this step the surfaces that will be electrodeposited are physically, chemically, and electrically cleaned in preparation for electrodeposition. The surfaces must be completely free of all oil, grease, wax, or masking material, along with any surface oxide on the metal surface; the metal must be clean down to its nascent surface. Any nonconductive surfaces onto which electrodeposition is desired must be activated by a conductivization process.



(a) ROLL FORMED TUBE (STRAIGHT, DOUBLE TAPERED).

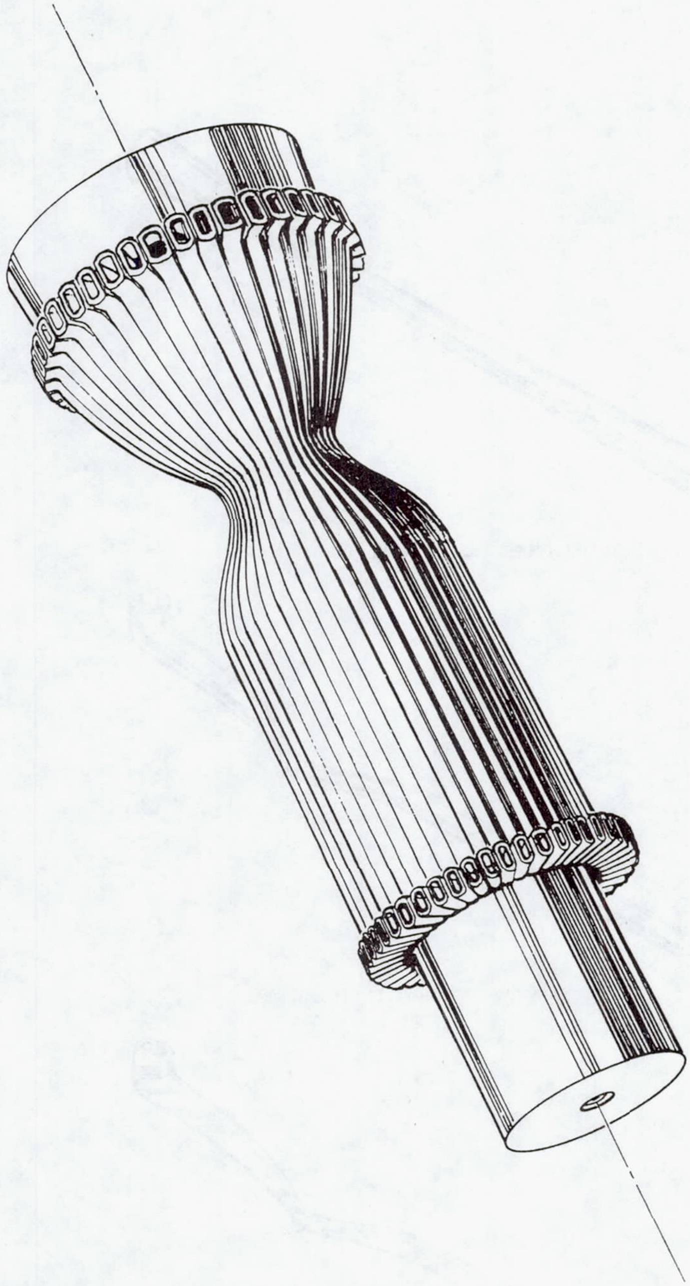


(b) "BENT" TUBE ("S" SHAPE TO FIT CONTOUR).



(c) "BOOKED" TUBE (FLATTENED TO WIDTH SPECIFIED).

FIGURE 2. - FABRICATION PICTORIAL.

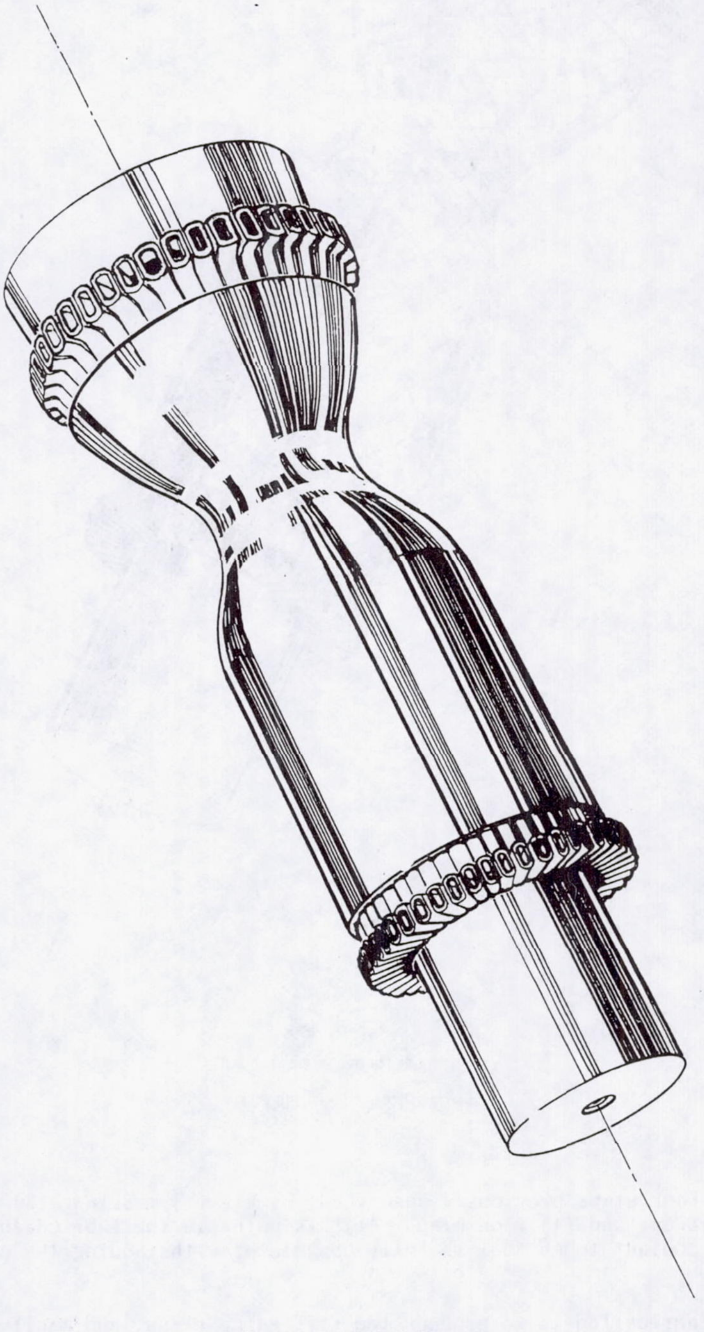


(d) TUBES STACKED ONTO MANDREL.

FIGURE 2. - CONTINUED.

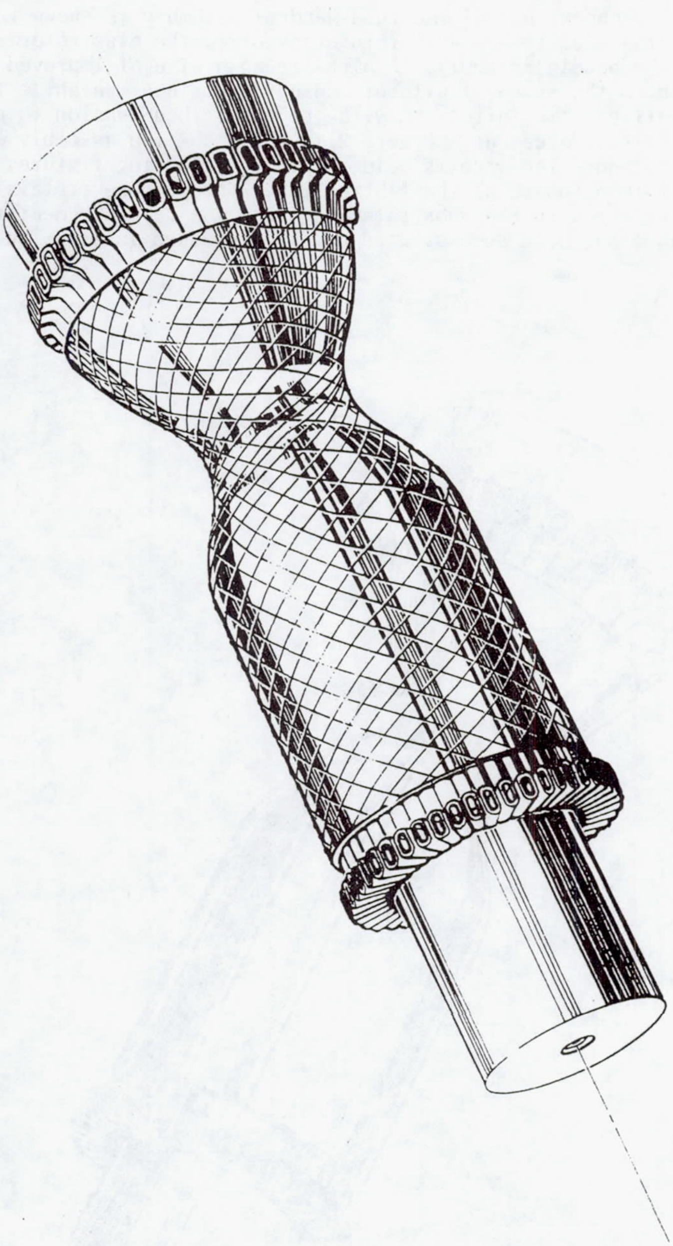
The third step is the actual electrodeposition of material onto the prepared surfaces. For this step the tube and mandrel assembly are submerged into an electroplating bath and a controlled current imposed that then causes the deposition of metal onto the exposed surfaces. Care must be exercised in this step to insure proper control of the current and adequate circulation of the electrolyte along with proper adjustment of the electrolyte chemistry. When done properly, deposition rates on the order of 0.001 in per hour can be achieved. During this process the individual tubes are bonded together and a gas tight seal is affected between them.

When enough material has been deposited onto the surfaces the assembly is ready for the fourth and final step of electroforming. The fourth step is machining. Periodically during the electroforming the assembly is put into the machine shop and the electrodeposited material is machined to specified dimensions. This allows the forming of intricate geometrical details as needed in the fabrication. Once machined to specified dimensions the assembly has completed one trip through the electroforming phase. The appearance of the tube-Mandrel assembly is shown in Fig. 2(e). The next phase of fabrication is the addition of wire reinforcement to the electroformed jacket being formed on the outside of the tube bundle assembly. A high strength wire of improved tensile properties can add significant strength to the assembly without adding significant weight. The wire is wound on the assembly in the specified orientation and with the prescribed tension to provide the desired prestressed condition to the reinforcement. Figure 2(f) shows how the assembly would appear after the reinforcing wire was attached. The wire is held in place by holding fixtures and the total assembly returned to the electroforming phase of the fabrication. The purpose of this electroforming effort is to intimately bond the wires to the substrate and cause the reinforcement to "load share" with the substrate. This technique has been demonstrated and is discussed later. The electroforming effort



(e) ELECTROFORM BONDED TUBES.

FIGURE 2. - CONTINUED.

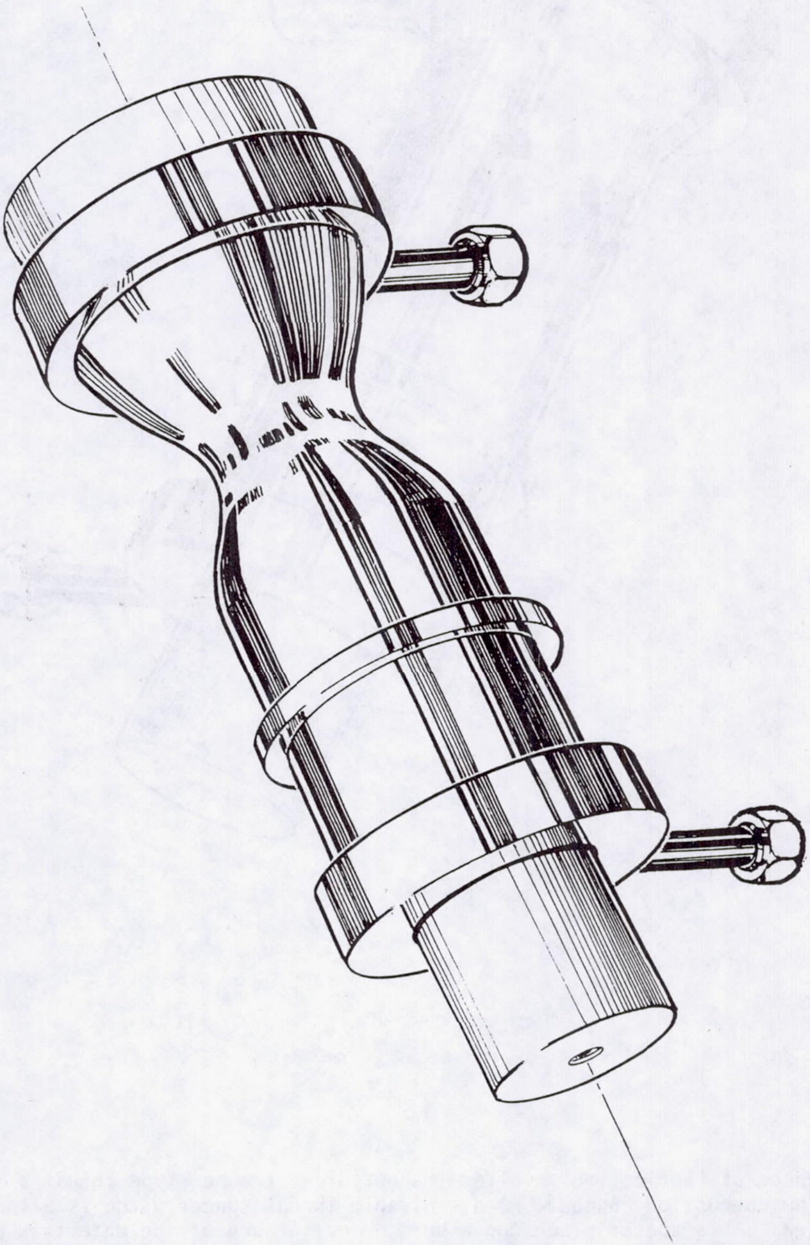


(f) WIRE REINFORCING ATTACHED.

FIGURE 2. - CONTINUED.

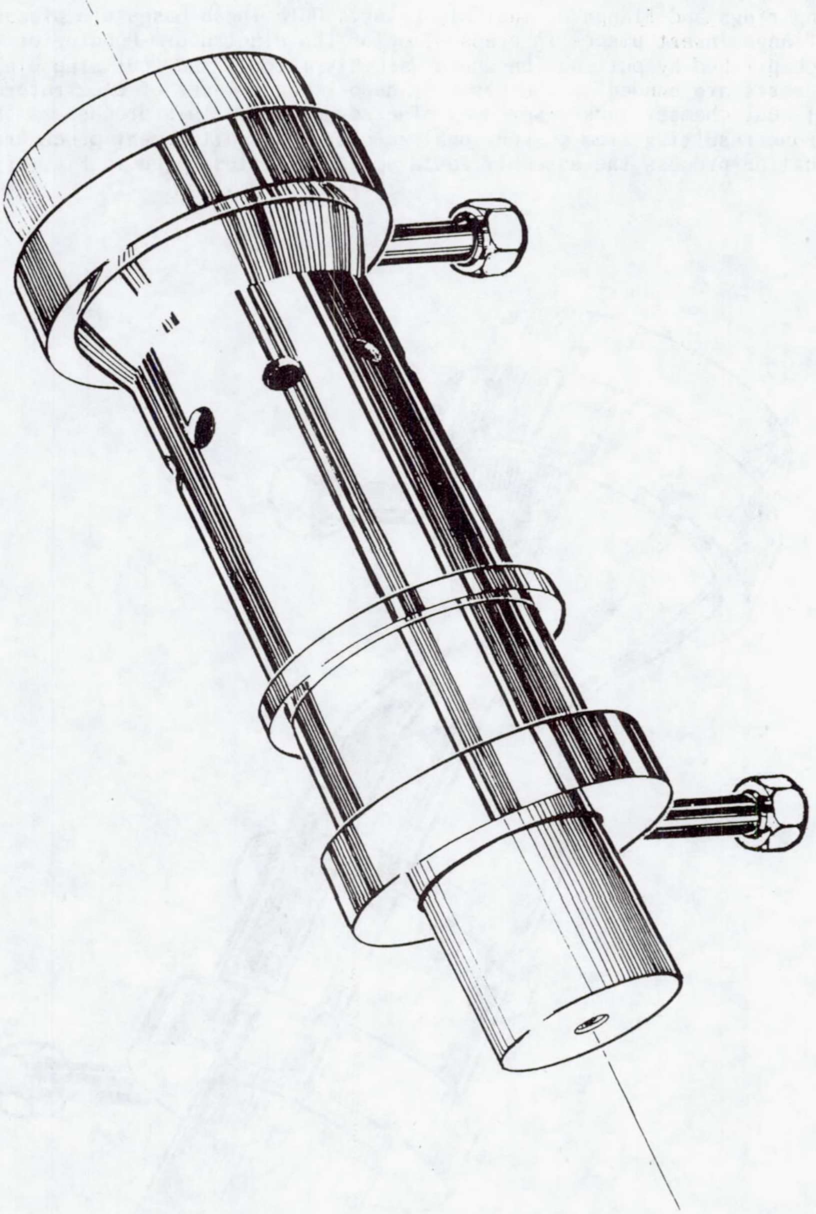
again goes through the four steps previously described, namely (1) masking, (2) cleaning and activation, (3) electrodeposition, and (4) machining. At this point in the fabrication the assembly has a jacket formed over the coolant tubes that is fully capable of withstanding the combustion pressures anticipated.

The next step in fabrication is to produce the stiffening rings, and manifold and flange bases to which the flange and manifold prefabs can be attached. Their locations are marked onto the assembly and the four step process of electroforming repeated. The masking is done over the entire assembly except where the markings indicate the location of the stiffeners and flanges or manifolds. When the four step electroforming process is completed for the third time the chamber assembly will have completed stiffening rings and flange or manifold bases. Onto these bases are placed the prefabricated manifold or flange insert pieces in preparation of the electroform bonding of these inserts. This bonding is accomplished by putting the whole assembly through the four step electroforming process again. The inserts are bonded to the bases by depositing a layer of electroformed metal over the inserts and adjacent chamber jacket surface. The advantage of this process is the avoidance of any heat affected zone resulting from conventional weld or braze attachment procedures. At this point in the fabrication process the assembly would appear as illustrated in Fig. 2(g).



(g) MANIFOLDS AND STIFFENING RINGS ATTACHED.

FIGURE 2. - CONTINUED.



(h) THROAT "BOX-TYPE" THRUST STRUCTURE IN PLACE.

FIGURE 2. - CONCLUDED.

The final phase of fabrication involves the building of a box-type thrust structure around the throat area of the combustion chamber. A dissolvable throat spacer piece is attached to the outside of the throat area. This spacer piece could be made out of any of the materials previously described for masking purposes. Once attached to the throat, the entire assembly is put through the electroforming process for a fifth and final time. During the electroforming process a layer of metal is deposited over the throat spacer piece and bonded to the chamber at both ends of the spacer piece. When the building and machining of this box-type thrust structure are complete the internal throat spacer piece is melted or dissolved and drained out of the cavity through several vent holes machined into the thrust structure. The completed assembly is shown in Fig. 2(h).

BENEFITS OF PROPOSED FABRICATION TECHNIQUES

The proposed method of making a rocket combustion chamber is intended to produce a configuration that will replace the currently popular milled copper alloy liner combustion chamber, an example of which is the SSME (space shuttle main engine). The proposed method would produce an engine that has many advantages over the milled liner type configuration. The advantages are performance, weight, cost, life, and reliability and will be addressed one at a time.

PERFORMANCE

In applications where the engine uses an expander cycle the attainable combustion chamber pressure is limited by the energy of the turbine drive gas. The energy of the turbine drive gas is limited by the enthalpy obtained while flowing as a coolant through the coolant passages. According to Ref. 1, a 34 percent increase in heat extraction is expected as a result of the corrugated wall surface of a tube-bundle configuration as compared to a smooth walled liner configuration. A corresponding increase in combustion chamber pressure is expected and with it an increase in engine specific impulse.

WEIGHT

Because all of the joining operations are to be done at room temperature by electroform deposition instead of conventional weld and brazing operations, no thermal degradation is expected in material properties. As such no increase in cross-sectional thickness is needed for the heat affected zones. Furthermore, improved structural properties are possible with wire reinforcing, allowing thinner cross-sectional thickness.

COST

A significant contribution to the cost of a conventional milled liner (smooth walled) chamber involves the continued high precision, match-machining of components that have to be brazed or welded to the assembly. By "growing-on" many of the components a substantial number of these precision match-machining operations can be avoided. These precision machining operations involve labor intensive inspections and some scrapping or reworking of parts, all of which are costly and will be reduced in the above proposed procedure. Further, the proposed method lends itself to iterative type assembly line operations.

LIFE

The conventional milled liner configuration suffers a fatigue problem because of the thermal expansion of the inner liner in a highly constrained structural shell. With a tube bundle configuration the circumferential constraint is substantially reduced because of the structural compliance of the tube bundle, with a corresponding decrease in thermal strain. Conservative analysis predicts a 100 percent increase in fatigue life by using the tube bundle configuration (Ref. 2).

RELIABILITY

Because of future space-basing and man-rating requirements, the need for engines of high reliability is obvious. An engine configuration that operates at lower stress levels because of the inherent structural compliance is expected to be more robust and more forgiving of condition excursions, and as such to be more reliable. The method of fabrication also has inherent potential for further reliability improvement. By having limited number of joints and reduced number of critical inspection steps, there are fewer potential failure sites to monitor.

DEMONSTRATED FABRICATION CAPABILITIES

Of the innovative fabrication techniques discussed above many have been demonstrated alone or in combination with other techniques, and are discussed below.

Roll forming of tubes. Although the roll forming process sounds difficult and involved it is a technique that is well established. The process has been in use for decades and has been used to produce tubes of nickel alloys for all of the brazed tube bundle engines such as the F-1 and J-2 (Saturn), the RL-10 (Centaur), and the LR87-AJ and LR91-AJ (Titan). The application of this technique to tubes of copper alloy is not expected to be a problem, in fact it is anticipated that copper because of its high ductility, will roll form more easily than the nickel alloys.

<u>Booking and shaping</u>. Compared to roll forming this is not nearly as challenging an operation. Booking and shaping has been successfully accomplished for all of the brazed tube bundle engines already mentioned. Booking and shaping has also been successfully accomplished on copper tubes for several "plug and spool" cylindrical combustion chambers for fatigue testing at NASA Lewis, see Fig. 3.

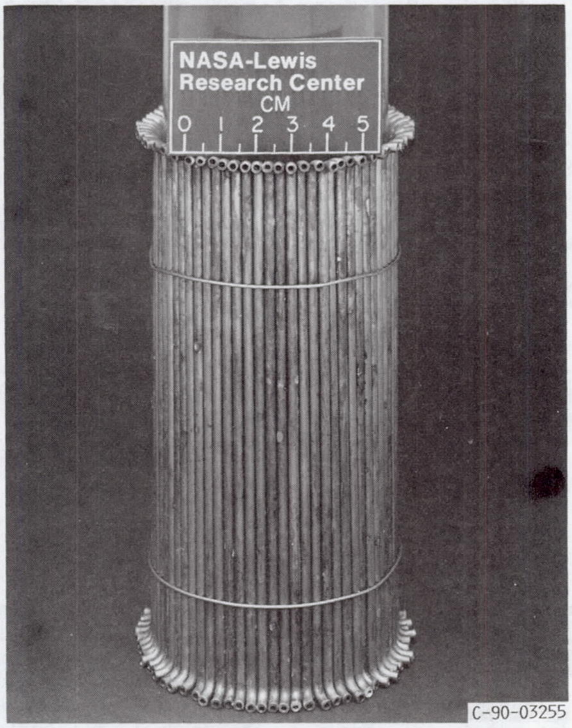
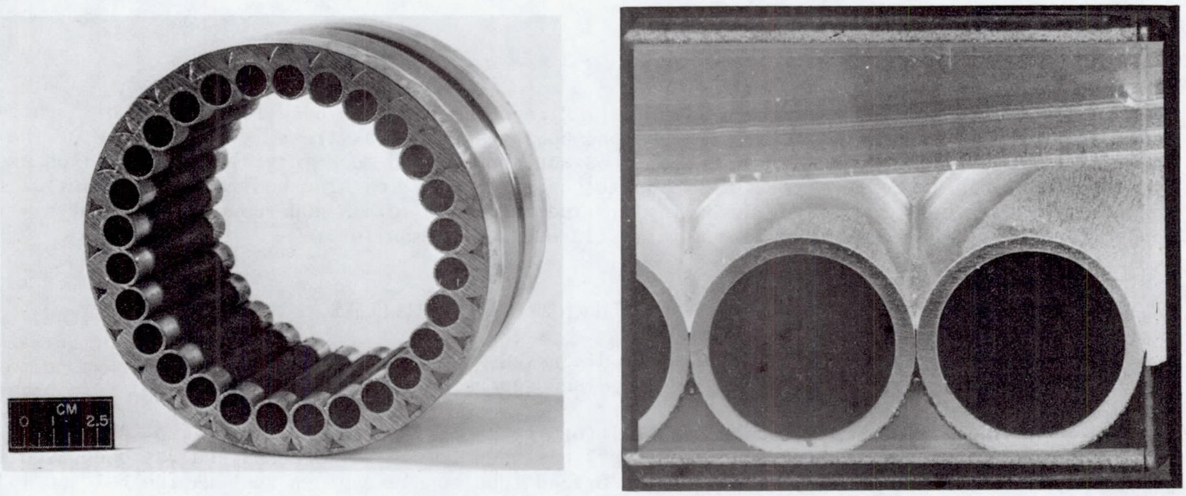


FIGURE 3. - PHOTOGRAPH OF FORMED AND BOOKED COPPER TUBES STACKED ON A MANDREL.

<u>Electroform bonding of tubes</u>. This technique has long been recognized as the enabling technology for this fabrication effort. As such, early work was started back in the 1960's and successful bonding has been demonstrated for stainless-steel tubes (with nickel electroformed close-out). The results of this early work is shown in Fig. 4 which is two photographs of a successfully bonded assembly. More recently, successful bonding of copper tubes with electroformed copper close-out has been demonstrated (Ref. 3). Figure 5 is a photograph of a section through a successfully bonded copper-tube assembly.



(a) ELECTROFORM BONDED TUBES.

(b) ENLARGED VIEW.

FIGURE 4. - ELECTROFORM BONDING OF STAINLESS STEEL TUBES WITH ELECTROFORM DEPOSITED NICKEL.

Wire reinforcement of an electroform deposited matrix. The concern with this technique was whether the wire reinforcement could be fully involved in carrying its share of the structural load. In other words could the wire be intimately bonded to form a metal matrix composite with the electroform deposited material. Results of early work have shown that this is indeed possible (Ref. 4). A photomicrograph of a section of this early work is shown in Fig. 6, which shows 2 layers of "D" shaped wires intimately bonded to the matrix.

"Grown" in place stiffening rings. The technique of electroform depositing a stiffening ring directly to a tube assembly provides many advantages of cost, time, strength (no thermal degradation) and weight. It has been fully demonstrated in our work reported in Ref. 3. Figure 7 is a photograph of two copper tube assemblies produced and reported in Ref. 3. Shown are two different styles of stiffening rings that were fully "grown on" to the tube assembly.

Attachment of manifolds and flanges. Two techniques, both proven, are in contention for use in applying manifolds and flanges to the tube bundle assembly. The first is to simply grow the entire manifold in place similar to the grown in process used for the stiffening rings. The second technique is to grow in a base and then to place a prefabricated insert piece onto the base to be electroform bonded to the base. The electroform bonding of these insert pieces is accomplished by depositing a layer of electroformed metal over the inserts and onto the adjacent chamber surface. Both of these techniques have been demonstrated and are reported in Ref. 3. Photographs showing the progress during fabrication are shown in Figs. 8 to 10. Figure 8 shows the manifold base detail as machined into the surface of the electroformed assembly. Figure 9 shows the prefabricated manifold inserts installed in position and the start of the masking process. Figure 10 shows the assembly in the electroforming bath at the start of electroform bonding of the manifold inserts.

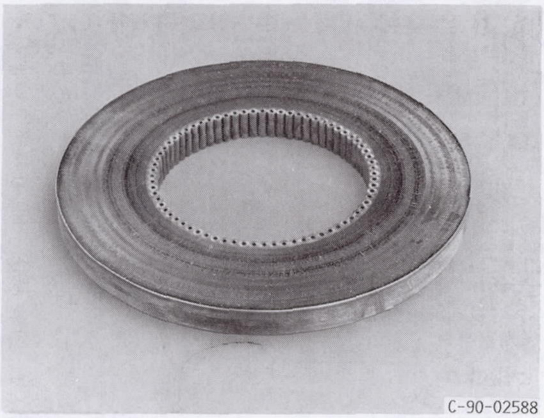


FIGURE 5. - ELECTROFORM BONDING OF COPPER TUBES WITH ELECTROFORM DEPOSITED COPPER.

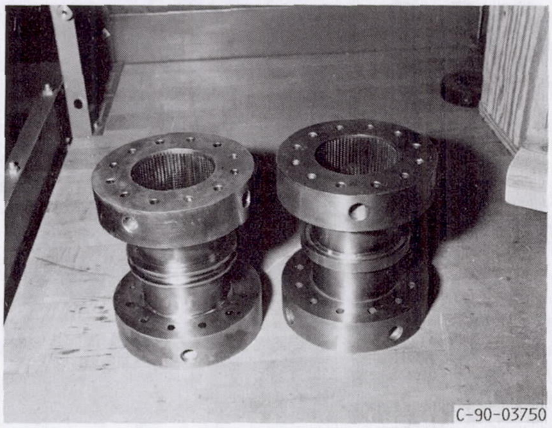


FIGURE 7. - PHOTOGRAPH OF "GROWN ON" STIFFENING RINGS.

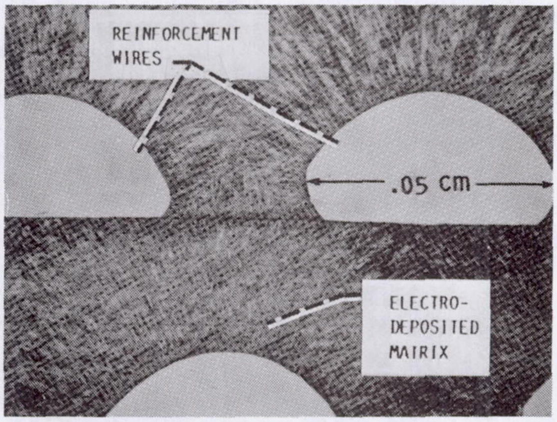


FIGURE 6. - PHOTOMICROGRAPH OF WIRE REINFORCED ELECTROFORM DEPOSITED NICKEL.

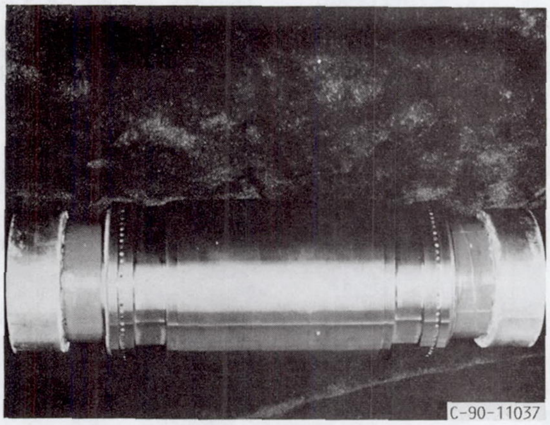


FIGURE 8. - PHOTOGRAPH OF TUBE ASSEMBLY WITH MANIFOLD BASES MACHINES.

FIGURE 9. - PHOTOGRAPH OF TUBE ASSEMBLY WITH PREFABRICATED MANIFOLD INSERTS INSTALLED.

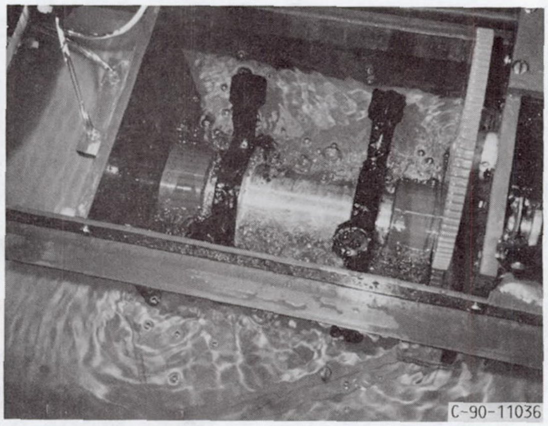


FIGURE 10. - PHOTOGRAPH OF TUBE ASSEMBLY IN ELECTROFORMING BATH HAVING MANIFOLD INSERTS ELECTROFORM BONDED TO ASSEMBLY.

CONCLUSION

Described is a method to produce a rocket combustion chamber with copper or copper alloy tubes. Until now this has not been considered as feasible because of copper's particular vulnerability to the severe thermal degradation expected as a result of the furnace braze operation needed to bond the tubes together. However, in the procedure described herein, the tubes are bonded together by electroform deposition at essentially room temperature, and no thermal degradation occurs. This allows production of a combustion chamber that has the high thermal conductivity of a milled liner with the structural compliance of a tube-bundle configuration. In addition, the electroformed tube configuration will be less costly, more reliable, and increase heat transfer. Higher chamber pressures can be obtained due to the improved enthalpy extraction to the coolant provided by the increased wetted surface area (tubes instead of smooth liner). The cost is reduced by the elimination of many of the precision match-machining requirements on the jacket, along with fewer fabrication steps. Weight is reduced by not needing thicker cross sections to compensate for heat affected zones caused by welding and brazing, and by thinner cross sections by virtue of wire reinforcing. Life is enhanced by both the strain reductions achieved by the compliant nature of the construction, and also the absence of material degradation caused by the heat of the weld and braze cycles.

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16. Abstract

An improved method of fabricating advanced rocket chambers for future space applications is described. Included are fabrication demonstrator and test chambers produced by this method. This concept offers the promise of improved cyclic life, reusability, reliability, and performance. The performance is improved because of the enhanced enthalpy extraction. The improved cyclic life, reusability, and reliability is improved because of the structural compliance inherent in the construction. The method of construction involves the forming of the combustion chamber by a tube-bundle of high conductivity copper or copper alloy tubes and the bonding of these tubes by a unique electroforming operation. Further, the method of fabrication reduces chamber complexity by incorporating manifolds, jackets, and structural stiffeners while having the potential for thrust chamber cost and weight reduction.

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