Development of Core Cladding Fabrication Techniques for Phase I Fission Propulsion Systems

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Abstract. Phase I fission propulsion systems focus on safety, timely development, and affordability. Prototype and flight units can be tested at full thrust, using resistance heaters to closely simulate heat from a fission reaction. In Phase I ground testing, one goal is to establish a reliable and affordable manufacturing technique for fabricating a flight-like core. A refractory metal (Mo) has been suggested for the core substrate, primarily due to the existence of a significant database for Mo/UO_2 fuel. The core can be fabricated by bundling Mo tubes with a bonding system that meets preliminary test goals. These criteria include materials compatibility, ability to maintain thermal and structural integrity during 10,000 hours of operation, and fabrication with existing facilities. This paper describes an effort to investigate several fabrication techniques in a cost-effective manner. First, inexpensive materials were tested at low temperatures to determine the relative effectiveness of such techniques as welding, brazing, plating, and vacuum plasma spraying (VPSing). Promising techniques were chosen for further evaluation, including thermal and structural studies, using ceramic tubing at intermediate temperatures. The most desirable technique will be tested on actual Mo tubing at anticipated operating temperatures. This work is being performed by the National Aeronautics & Space Administration (NASA) at George C. Marshall Space Flight Center (MSFC), Los Alamos National Laboratory (LANL), and Advanced Methods & Materials (AMM), Inc.

INTRODUCTION

Initially, an investigation was planned concerning the feasibility of brazing or welding Ta tubing to a W simulator supplied by LANL. After a stainless steel manifold was introduced for fueling cycles, more readily available materials were investigated, such as Nb, Ni, and 304 stainless steel (304SS). Modules were prepared from different materials using various assembly methods, which included brazing, electron beam (E-beam) welding, spot welding, mechanical bundling, VPSing, and plating techniques. Research was conducted with stainless steel, as well as ceramic and refractory materials, such as Mo, Nb, Nb/1% Zr, Ti/Zr/Mo-base (TZM) alloy, and Mo/Re.

MANUFACTURING ALTERNATIVES

Baseline data had been established using a seven-cavity model that was electrical discharge machined (EDMed) from consolidated powder metallurgy W. This model was capable of withstanding elevated temperatures under simulated flight conditions. While research was being conducted for refractory and ceramic materials, work proceeded in parallel to demonstrate the feasibility of this approach. LANL and AMM fabricated several modules from 304SS tubing, with and without tricusps. Each module was fabricated as one heat pipe surrounded by four fuel pipes brazed into position. This configuration constituted the actual 30 kW core. The modules generated test results that have been addressed in papers written by members of the Safe Affordable Fission Engine (SAFE) team (REFERENCES).

Meanwhile, manufacturing techniques evolved for alternate modules. One was fabricated from 304SS tubing that was gas W arc welded. During fabrication, it was tack welded using a standard 308-L stainless steel rod with an Ar shield (Figure 1). Smaller tubes were used to allow preliminary testing of candidate heaters, which provided data comparable to the W element.

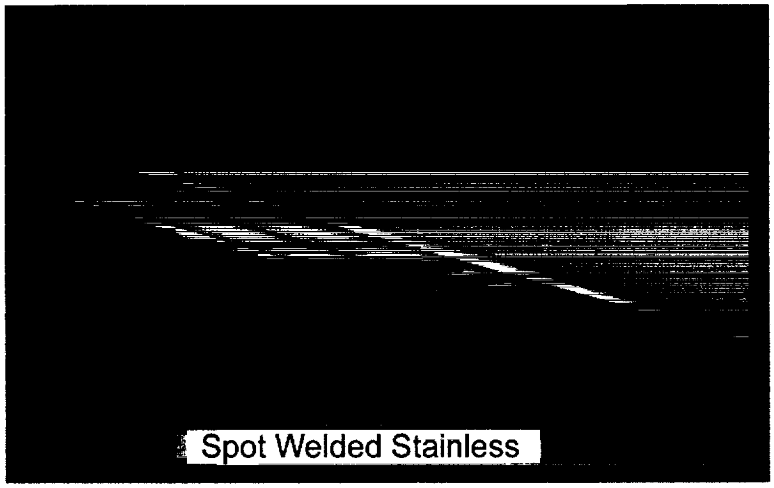

FIGURE 1. Spot-Welded Stainless Steel Module (1.27-cm O.D. Tubing).

Next, 304SS tubing sections were joined with Wood's Ni strike followed by an electroless plating process using Ni sulfamate. During the first attempt, the module only plated near the tubing ends. At increased amperage, the plating was more complete, but thickness variations were produced (Figure 2). In addition, this module debonded after sectioning. A third attempt was made using an electrolytic cycle. This process produced better uniformity and bonding, but the module tended to spall when sectioned.

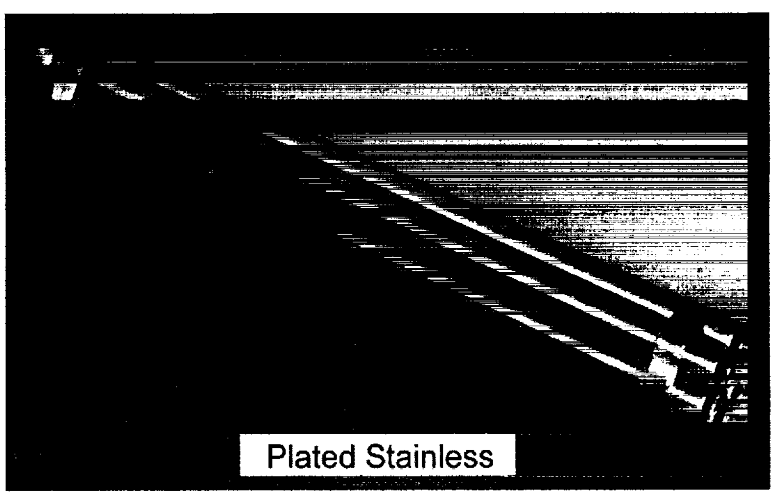

FIGURE 2. Plated Stainless Steel Module (1.27-cm O.D. Tubing).

A VPSed module was produced at MSFC. Here, 304SS tubing was used with a compatible, but proprietary, stainless steel powder (Figure 3). The module was sufficiently coated in a thermally conductive manner. However, each module had to be machined before testing to ensure a uniform coating. Although this technique showed promise, it was not pursued further due to financial and schedule constraints.

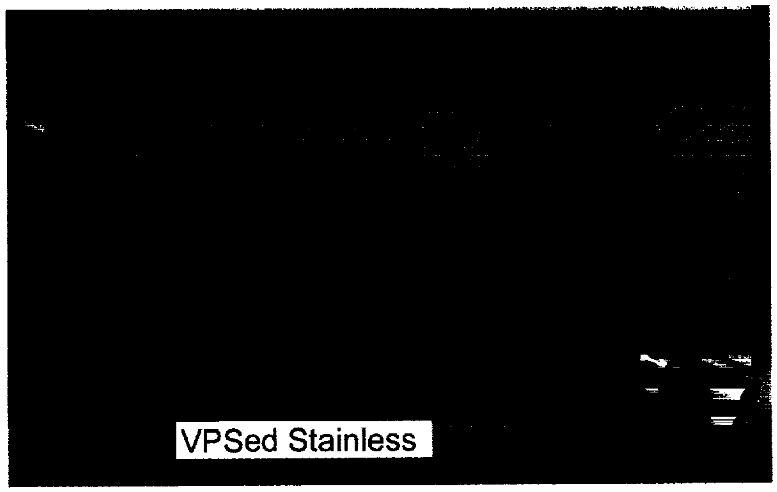

FIGURE 3. VPSed Stainless Steel Module (1.27-cm O.D. Tubing).

A mechanically bundled 304SS module was also fabricated. It consisted of seven sections of tubing that were secured with 304SS wire (Figure 4). This module lacked structural integrity, but otherwise behaved as intended by the original design.

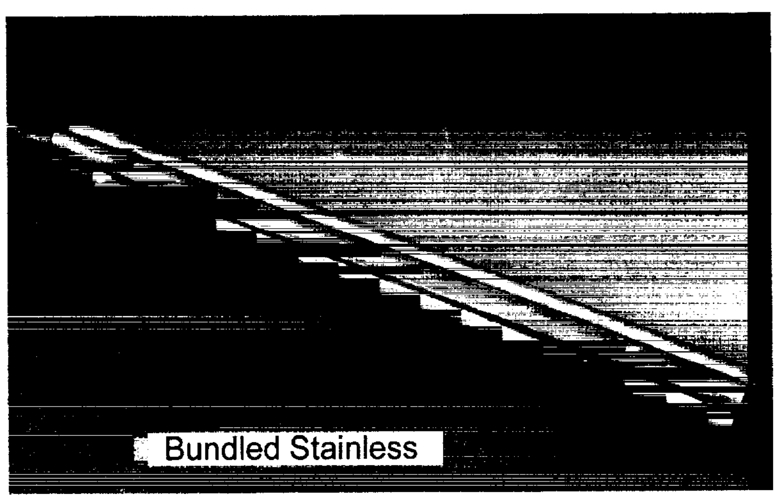

FIGURE 4. Mechanically Bundled Stainless Steel Module (1.27-cm O.D. Tubing).

A bundled ceramic module was fabricated in a similar manner. The first module was primarily used to verify temperature limits. A second module was fabricated using an alumina adhesive developed at MSFC (Figure 5).

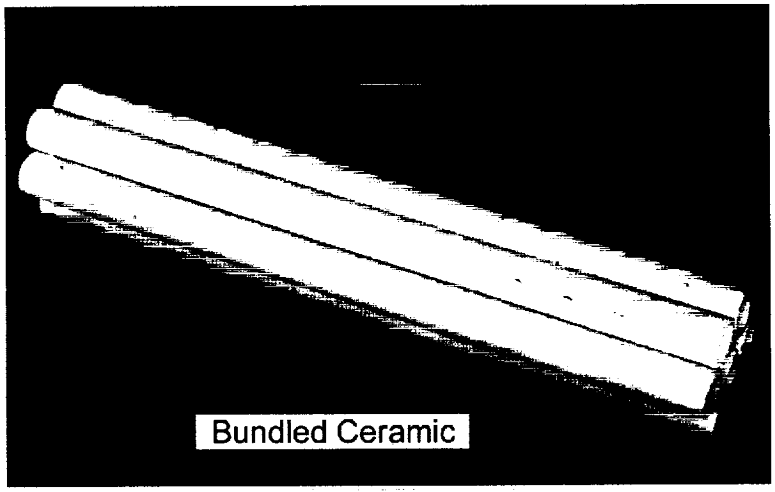

FIGURE 5. Bundled Ceramic Module (1.59-cm O.D. Tubing)

Meanwhile, LANL and AMM were optimizing methods for brazing tubes fabricated from Mo (Figure 6), a material that is not readily welded or brazed. To optimize its strength and thermal conduction, AMM and Scarrot Metallurgical Company made considerable efforts to ensure that all braze joints had maximum metal contact. Several iterations were required, due to problematic temperatures and vacuum levels. Many of these modules were used to study the homogeneity necessary for parent, braze, and fixturing materials. Several were shipped to MSFC for destructive and nondestructive evaluation. Some were thermally cycled in vacuum and atmospheric furnaces. Others were tested in the core chamber. Another group was sectioned (Figure 6) for mechanical testing (Table 1).

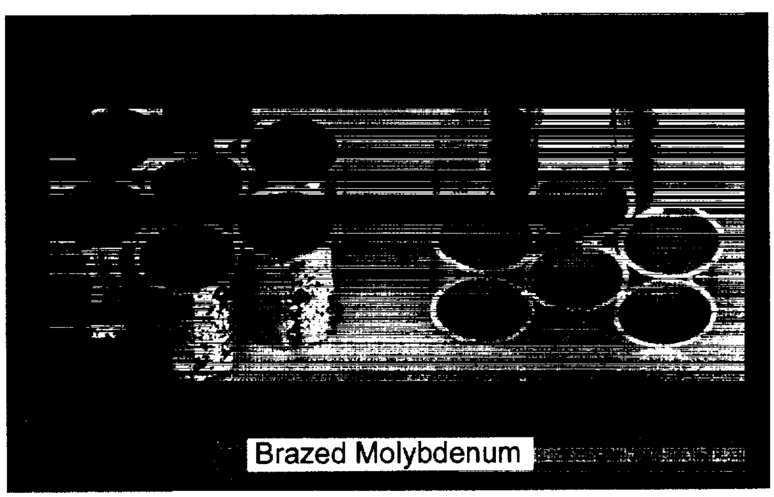

FIGURE 6. Brazed Mo Tensile/Shear Specimens (1.27-cm O.D. Tubing).

TABLE 1. Tensile Results for Brazed Mo Module.

Set	Sample	Top Length	Bottom Length	Ultimate Tensile Strength
1	1	1.54 cm	1.60 cm	0.58 MPa (84.0 psi)
	2	1.58 cm	1.54 cm	0.74 MPa (107.0 psi)
	3	1.54 cm	1.61 cm	0.62 MPa (90.0 psi)
2	1	1.54 cm	1.60 cm	0.35 MPa (50.0 psi)
	2	1.58 cm	1.54 cm	0.58 MPa (84.4 psi)
	3	1.54 cm	1.61 cm	0.53 MPa (76.3 psi)
	4	1.38 cm	2.49 cm	*Broken as loaded into test fixture*

Note: In Set 2, Samples 2 and 3 were oversized samples.

The first seven-tube Mo module was 0.43-m long (Figure 7). It underwent thermal and mechanical testing at MSFC (Table 2). AMM then used graphite tooling to assemble enhanced modules with a length of 0.43 m, which were brazed using V foils and powders to improve their structural properties. They are being tested at MSFC, with promising initial ambient tensile results (Table 3).

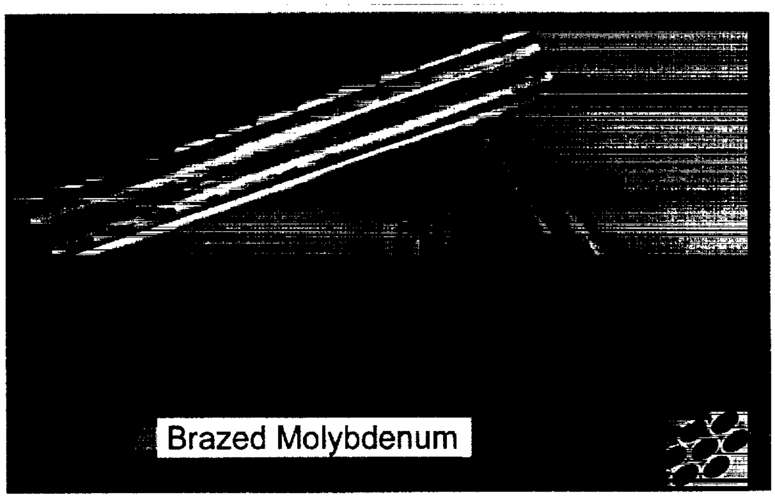

FIGURE 7. Enhanced Mo Modules (1.27-cm O.D. Tubing). Upper Section Brazed With V Foil, Lower Section Brazed With V Foil and Powder.

TABLE 2. Tensile Data for Enhanced Mo Module Brazed with V Foil.

Set	Sample	Top Length	Bottom Length	Ultimate Tensile Strength
18A	1	1.92 cm	1.91 cm	0.32 MPa (47 psi)
	6	3.06 cm	3.06 cm	*Broken as loaded into test fixture*
	7	2.12 cm	2.11 cm	0.78 MPa (113 psi)
	8	2.12 cm	2.21 cm	0.77 MPa (112 psi)
	9	2.42 cm	2.43 cm	0.41 MPa (60 psi)

TABLE 3. Tensile Data for Enhanced Mo Module Brazed with V Foil and Powder.

Set	Sample	Top Length	Bottom Length	Ultimate Tensile Strength
18B	1	3.06 cm	3.07 cm	*Broken as loaded into test fixture*
	2	1.93 cm	1.94 cm	0.91 MPa (132 psi)
	3	---	---	*Broken during assembly*
	4	---	---	*Broken during assembly*
	5	2.28 cm	2.28 cm	1.21 MPa (175 psi)
	6	2.37 cm	2.28 cm	1.63 MPa (237 psi)
	7	2.37 cm	2.37 cm	0.69 MPa (100 psi)

SUMMARY

This paper explored various manufacturing techniques for fabricating modules from Mo tubing for use in core assembly. Several candidates were not pursued, due to constraints such as feasibility, costs, and schedules. Brazing is considered the most promising approach to date. The SAFE team is experimenting with brazing practices, as well as alternative techniques made possible by new configurations and additional financial backing. Future work requires detailed studies of intermetallic structure, braze adherence and uniformity, and strength and cyclic characteristics. Lessons learned during the 30 kW effort indicate that core assembly is feasible and module configurations can be altered for effective integration of a test article. Less complex fabrication may be possible with bonded and unbonded tricusps. The same modules can be used to ascertain compatible baseline data for the 30 and 300 kW cores.

ACKNOWLEDGMENTS

The SAFE team wishes to acknowledge invaluable contributions made by AMM, Inc. of San Jose, CA and Scarrot Metallurgical Company of Los Angeles, CA.

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