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AN EVALUATION OF THE FEASIBILITY OF JOINING TITANIUM ALLOY TO HEAVYMET TUNGSTEN ALLOY

MASTER

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June 7, 1978

SANL-507-019

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FINAL REPORT

on

AN EVALUATION OF THE FEASIBILITY OF JOINING TITANIUM ALLOY TO HEAVYMET TUNGSTEN ALLOY

to

UNIVERSITY OF CALIFORNIA
LAWRENCE LIVERMORE LABORATORY
LIVERMORE, CALIFORNIA 94550

by

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June 7, 1978

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Columbus, Ohio 43201

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This constitutes Battelle's final report covering the research performed under SANL 507-019. The objective of this program was to select and evaluate methods of brazing and/or explosively welded Ti-6Al-4V titanium alloy to Heavymet, a tungsten-base metal containing up to about 20 percent alloying elements (nickel, copper, etc.) to improve its ductility and other mechanical properties. Designs permitting the reliable production of joints between these base metals were of interest too. While this investigation was primarily concerned with an engineering study of the problems associated with joining these base metals in the required configuration, limited experimental studies were conducted also.

The joining methods are reviewed individually in the sections below. Recommendations for developing a viable titanium-tungsten joining procedure are discussed in the concluding section.

Brazing

Filler Metals

Before considering candidate filler metals for brazing titanium to tungsten, a computer search of the literature holdings of various Government information centers was conducted with the objective of taking advantage of prior work in this area. However, the search produced largely negative results because this is an unusual combination of metals to braze or join by any conventional method. The output of the search was reduced to nil when it was limited to the brazing of Ti-6Al-4V to Heavymet. In fact, the instances of brazing Heavymet to itself or to a dissimilar metal are rare. In work conducted by Battelle, Heavymet was successfully brazed to a molybdenum-base alloy for a nose cone application with a gold-palladium-nickel alloy and with pure copper as well. It is quite likely that titanium-to-tungsten joints could be produced with these filler metals; however, both filler metals melt at temperatures higher than those normally used for brazing titanium-base alloys.

The choice of filler metals for the LLL application is limited by the following constraints in addition to those that must be considered in establishing any dissimilar metal brazing procedures (e.g., compatibility of the filler metal with the respective base metals, filler metal wetting and flow properties, etc.):

- To avoid embrittlement, loss of ductility, and other adverse effects on the metallurgical and mechanical properties of titanium-base alloys, brazing must be done at temperatures below that at which the beta phase forms (that is, below the beta-transus temperature). Transformation of titanium-base alloys occurs at various temperatures, depending on the alloy content of the base metal; for Ti-6Al-4V, the transformation temperature is about 1825 F. Thus, filler metals that can be used for brazing at temperatures below 1825 F should be selected for this application. It should be noted that transformation occurs when the parts comprising the LLL structure are welded together. However, transformation is confined to a narrow band by using a low heat-input welding process that does not produce a wide weld bead or heat-affected zone.

- Filler metal selection can be complicated by prior brazing operations. In this instance, a tube was brazed to the tungsten member with a gold-base alloy (Au-18Ni) that melts at 1745 F. The remelt temperature of joints made with some filler metals is higher than that at which brazing occurs. However, it is unlikely that the remelt temperature of this joint will be appreciably higher than 1745 F, because there is little reaction between the filler metal and base metal. To avoid disturbing the original joint, subsequent joints should be brazed with filler metals that melt no higher than 1745 F. However, if the first joint was made with a higher melting filler metal (e.g., the Au-Pd-Ni alloys), the titanium-to-tungsten joint could be made with brazing alloys that melt at temperatures up to about 1800 F.

Candidate filler metals are discussed in the following sections with the above constraints in mind; these metals are grouped according to the major alloying element. Efforts were concentrated on the selection of alloys for brazing titanium, because these alloys should be generally suitable for brazing tungsten to titanium as well. Many of the filler metals used for brazing tungsten were not considered in this study because they melt above the beta-transus temperature of titanium.

Silver-Base. Silver-base filler metals, particularly those suitable for vacuum brazing, were among the first and most widely used alloys for brazing titanium base metals; such filler metals have also been used for brazing tungsten. However, as joint demands increased, these alloys fell into disfavor because joints brazed with them did not possess the required strength, oxidation resistance, etc. Also, when titanium was brazed with silver-base filler metals, a silver-titanium intermetallic compound with little ductility formed and detracted from the soundness of the joint, the thickness of this compound increased with the temperature and time of brazing. Further, joints brazed with these alloys were subject to a crevice-type corrosion.

Despite these handicaps, silver-base filler metals may be used to braze titanium if the joint requirements are not severe, or if a barrier layer of metal can be applied to the titanium joint member (e.g., by explosive welding). For example, a Ag-9Pd-9Ga filler metal has been developed to eliminate problems with silver-titanium intermetallic compounds and the lack of corrosion resistance. However, experience with this alloy is limited.

Experimental titanium-tungsten tee-joints were brazed with Ag-28Cu and Ag-9Pd-9Ga. These filler metals wet both base metals well. However, the flow properties of Ag-28Cu were much superior to those of Ag-9Pd-9Ga. Additional studies of the Ag-9Pd-9Ga alloy could not be conducted at this time due to the lack of sufficient filler metal; however, this alloy should be examined further in an extension to this program.

Titanium-Base Filler Metals. The need to obtain filler metals with improved properties for brazing titanium led to the development of alloys based on titanium itself. Such alloys are of interest since titanium-base filler metals have been used to braze refractory metals and ceramics. Alloys of the following types were evaluated first: Ti-28Ni, Ti-48Zr-4Be, and Ti-15Ni-15Cu. All of them melt below the beta-transus temperatures for most titanium alloys; however, their wetting and flow properties differ appreciably, depending on the particular alloy being brazed. With Ti-6Al-4V, the Ti-48Zr-4Be filler metal had generally superior wetting and flow properties. The strength, oxidation resistance, corrosion resistance, and other properties of joints brazed with the Ti-48Zr-4Be filler metal were shown to be much improved over similar properties of joints brazed with silver-base alloys.

Ti-6Al-4V/tungsten Heavymet tee-joints were brazed with Ti-28Ni and Ti-48Zr-4Be filler metals. The Ti-28Ni filler metal did not appear to melt completely at the brazing temperature and did not wet both base metals with equal facility. This may have been caused by a slight increase or decrease in the nickel content of this alloy and a subsequent increase in its melting temperature. The joint made with Ti-48Zr-4Be was acceptable. The filler metal wet both base metals and adequate flow was achieved.

In recent years, alloy development efforts (Solar Division of International Harvester Company) have been concentrated on the Ti-Zr alloy system. The most promising of these experimental filler metals are the following: Ti-27.2Zr-15Ni-7Cu and Ti-28.8Zr-28Cu. Experimental quantities of both should be obtained for study on this program.

Other Filler Metals. Gold-base filler metals can be used to braze tungsten alloys (e.g., the tubing-to-tungsten joint in the LLL configuration); however, there is little evidence that they would be useful to brazing titanium so such alloys were not considered further. Similarly, tungsten joints have sometimes been brazed with nickel-base alloys. However, all but one of the commonly-used alloys (Ni-10P) melt at temperatures above the beta-transus of titanium alloys and are thus unsuitable for this application.

Eutectic diffusion brazing has been used to join titanium honeycomb sandwich structure with a thin layer of electroplated copper serving as the diffusion aid. This technique might be useful for joining titanium to tungsten, but we believe that the same results could be achieved by conventional brazing methods.

Joint Design

Joint designs for brazing dissimilar metal joints are influenced by the shape of the parts, the expansion characteristics of the respective base metals, the form in which the filler metal is available (wire, foil, or powder), and other considerations. Joint design will be discussed in general terms later in this report, since all of the constraints associated with the LLL application are not immediately evident.

Explosive Welding

In determining the feasibility of the explosive welding approach for joining the titanium to tungsten, it was first necessary to consider several important aspects of the process and the materials combination. Through the years, Battelle has had considerable experience with the explosive welding of Ti-6Al-4V alloy to itself and to many other metals or alloy systems. While the explosive welding process is capable of welding this titanium alloy directly to other metals, it is often preferable to use a thin interlayer of a third metal in some combinations. Tantalum and niobium are most often utilized as interlayer materials for explosive welding titanium alloys. Experience has shown that it is also preferable to weld the Ti-6Al-4V alloy in the annealed condition to minimize the potential for cracking and to follow the welding operation with a stress-relief heat treatment to remove the hardening and stresses introduced by the explosive welding process.

In general, there has been very little experience with explosively welding tungsten and its alloys and this has mainly been limited to tungsten-rhenium alloys. The major reason for the lack of experience with the tungsten alloys has been their susceptibility to cracking during the explosive welding operation due to their low impact resistance. Experience has shown, however, that sufficient impact resistance can oftentimes be gained to prevent cracking by explosively welding these metals at an elevated temperature. The preheat temperature must, however, be below the temperature at which rapid oxidation of the tungsten alloy occurs.

The approach selected for the cursory explosive welding experiments to be conducted in this program was to utilize a 0.25 mm (0.010-inch)-thick interlayer of tantalum between the titanium and tungsten alloys being welded. Welding would be accomplished in two steps with the tantalum first being explosively welded to the 2.54 mm (0.1-inch)-thick titanium. Following stress-relief treatment, the tantalum-clad titanium would then be welded to the preheated tungsten alloy in the second step.

The first series of experiments were directed toward explosively welding the tantalum interlayer material to the titanium alloy. In a series of five experiments the impact energy during welding was varied from 42 to 81 joules/cm^2. This was accomplished by varying the standoff distance from 1.27 to 2.34 mm (0.050-0.042-inch) while holding the explosive loading constant. Following welding, each explosively welded tantalum-titanium sample was vacuum stress-relief annealed at 649°C (1200°F) for one hour. Peel testing and metallographic examination of the bonds in each sample revealed that a minimum of 55 joules/cm^2 was required to produce a consistant, high strength weld. While high-strength welds were obtained at an impact energy of 81 joules/cm, it was found desirable to keep maximum impact energy below 75 joules/cm in order to minimize hardening and distortion of the Ti-6Al-4V alloy during the explosive welding operation.

The second series of experiments then involved explosively welding the tantalum clad titanium to the Heavymet alloy. The 6.4 mm (0.250-inch)-thick Heavymet plate stock for these experiments was provided by LLL. The sample size for these experiments was 5-x 15.2-cm (2 x 6 inch). Prior to welding the Heavymet components and its support plate was preheated. The initial experiment was conducted with a calculated impact energy of 192 joules/cm^2. Following welding the sample was sectioned for metallographic examination and chisel testing. Metallographic examination of the welds in this sample (Figure 1) revealed the titanium-to-tantalum weld to have essentially a flat interface, thus indicating that the impact energy was near the minimum allowable to achieve consistant welding. The tantalum-to-Heavymet weld, however, had a rather sizable wave pattern with melt pockets indicating that the impact energy was slightly higher than necessary. In

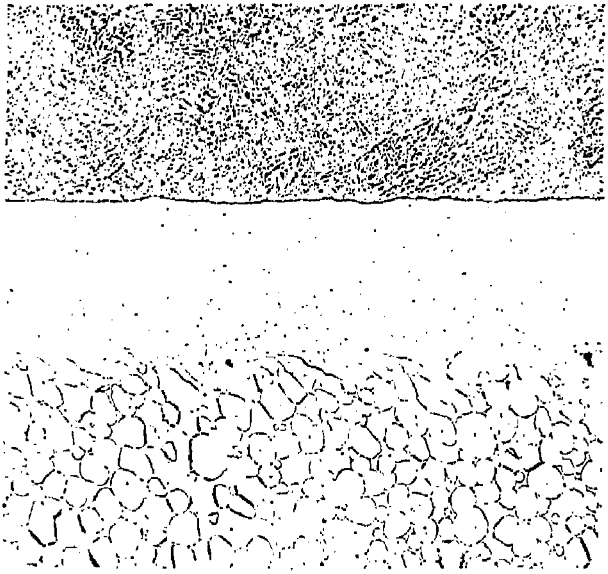

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FIGURE 1. METALLOGRAPHIC SECTION OF EXPLOSIVE WELDS IN FIRST Ti-6Al-4V/ TANTALUM/HEAVYMET SAMPLE. IMPACT ENERGIES WERE:

Tantalum to Ti-6Al-4V - 55 Joules/cm^2
Tantalum clad Ti-6Al-4V to Heavymet - 190 Joules/cm^2

chisel testing the sample sections were always found to fail along the tantalum-to-Heavymet weld interface, thus indicating that this was the weakest of the two weld interfaces. Of great importance in the results of this experiment was the fact that the Heavymet withstood the welding operation without any damage.

The second Heavymet welding experiment was conducted with a reduced impact energy calculated to be 175 joules/cm^2. The resulting metallographic appearance of the weld (Figure 2) revealed that the wave size in the tantalum-Heavymet weld had been reduced considerably. The increased impact energy to weld the tantalum to the titanium alloy resulted in that weld interface having a small wave pattern. The reduced impact energy for welding to the Heavymet did result in improved chiseling characteristics for the weld. Again, the Heavymet was not cracked or damaged during the welding operation.

Joint Designs

Brazing

Since the LLL structure must be furnace brazed, the fixturing of the Ti-6Al-4V and tungsten Heavymet joint members and the placement of the filler metal in the joint area are keys to success of the brazing efforts. Also, the respective parts must be assembled and brazed in such a manner that subsequent joining operations can be conducted with the least difficulty.

Fixturing is required to hold the parts in registry during brazing and to maintain proper joint clearances. Fixturing of the LLL assembly is difficult because the titanium member is thin and highly stressed by the forming operation. As a result, its contour changes during brazing when these stresses are relieved and movement of the joint members relative to one another is difficult to control. Movement can also occur because of the difference in the coefficients of expansion of the titanium and tungsten parts. Thus, efforts should be made to develop a self-fixturing joint design.

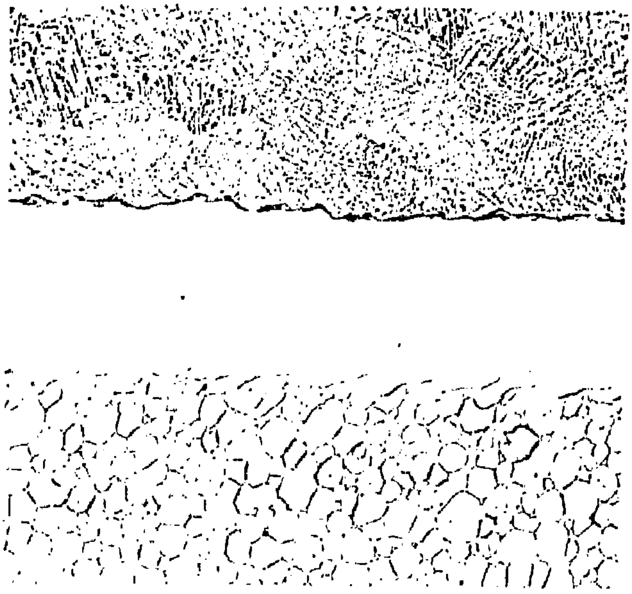

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FIGURE 7. METALLOGRAPHIC SECTION OF EXPLOSIVE WELDS IN SECOND Ti 6Al 4V/ TANTALUM/HEAVYMET SAMPLE. IMPACT ENERGIES WERE:

Tantalum to Ti-6Al-4V - 73 Joules/cm^2
Tantalum clad to Ti-6Al-4V to Heavymet - 175 Joules/cm^2

The form in which the filler metal is available also affects joint design, since its placement must be considered. The most promising filler metals for this application are indicated below:

Ag-28Cu
Ag-9Pd-9Ga
Ti-48Zr-4Be
Ti-27.2Zr-15Ni-7Cu (experimental)
Ti-28.8Zr-28Cu (experimental)

The silver-base alloys can be obtained in many forms because they are ductile; foil or wire appears most attractive for this application. Filler metals based on the Ti-Zr alloy system are available as powders only so they must be applied as a slurry.

With these considerations in mind, several joint concepts are discussed below:

- In its present form, the ILL joint design is not self-fixturing and cannot be made so. However, if a silver-base alloy is used for brazing, the assembly of the joint components and placement of the filler metal could be simplified by explosively welding a narrow strip of thin brazing alloy foil (~0.003-inch thick) to the titanium part before it is formed. This would insure that the filler metal was correctly located and that the titanium surface was clean and receptive to wetting.

- A self-fixturing joint concept is shown in Figure 3. This would require the machining of a slot in the tungsten part (to a depth of about twice the thickness of the titanium part) and the use of a titanium part formed as shown in Figure 3. Alternatively, a short titanium section or stub could be formed as required and brazed to the tungsten part first. Then, the assembly could be completed by attaching the remainder of the titanium section to the stub using previously developed fusion welding procedures. In either case, brazing would be simplified by the elimination of fixturing.

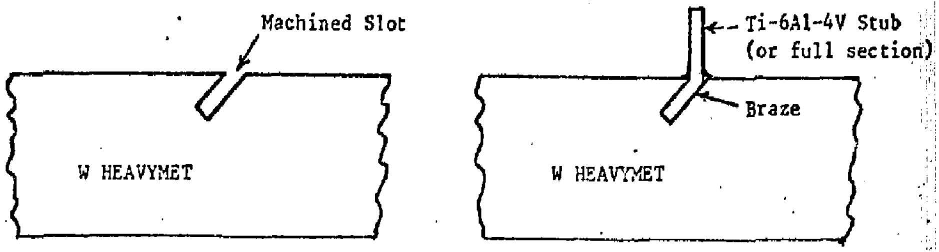

FIGURE 3. SELF FIXTURING DESIGN FOR BRAZING

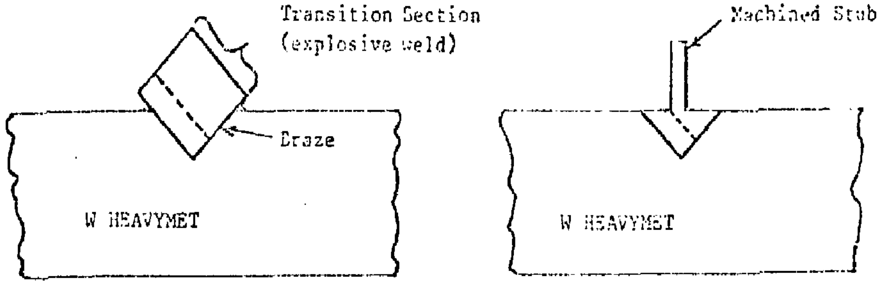

FIGURE 4. TRANSITION SECTION DESIGN USING COMBINATION OF EXPLOSIVE WELDING AND BRAZING

- Another self-fixturing concept is shown in Figure 4. This involves the use of a tungsten/titanium transition section that would be brazed to the tungsten part and machined to form a stub to which the remainder of the titanium part could be attached by fusion welding. The transition section would consist of flat plates of tungsten and titanium that would be explosively welded together with a tantalum interlayer using procedures discussed earlier in this report. Then, the transition section would be machined to fit a recess in the tungsten joint member and a tungsten-to-tungsten braze would be made (Figure 4a). Following brazing, the transition section would be machined to form the stub required for the subsequent attachment of the remainder of the titanium part (Figure 4b).

Explosive Welding

Explosively Welded Joint Design

The approach for making the titanium alloy-tungsten alloy joint by explosive welding is shown in Figure 5. This would essentially involve the explosive welding of a section of the titanium alloy having a thickness of approximately 3 mm to a solid blank of the tungsten alloy (Figure 5a). Following explosive welding, the titanium component would be machined to provide a section or stub for attachment of the remainder of the titanium component by fusion welding techniques.

Incorporated in the explosively welded joint would be a tantalum interlayer approximately 0.25 mm thick. In this instance the explosive welding would be accomplished in a single step or operation as opposed to the two step approach utilized in the preliminary flat plate experiments described earlier in the report. Welding would be conducted with the components at $\sim 204^{\circ}$C (400°F) as before to improve the impact resistance of the tungsten alloy in particular. Following welding and prior to final machining, the explosively welded component would be heat treated at approximately 980°C (1800°F). This would assure that all stresses induced

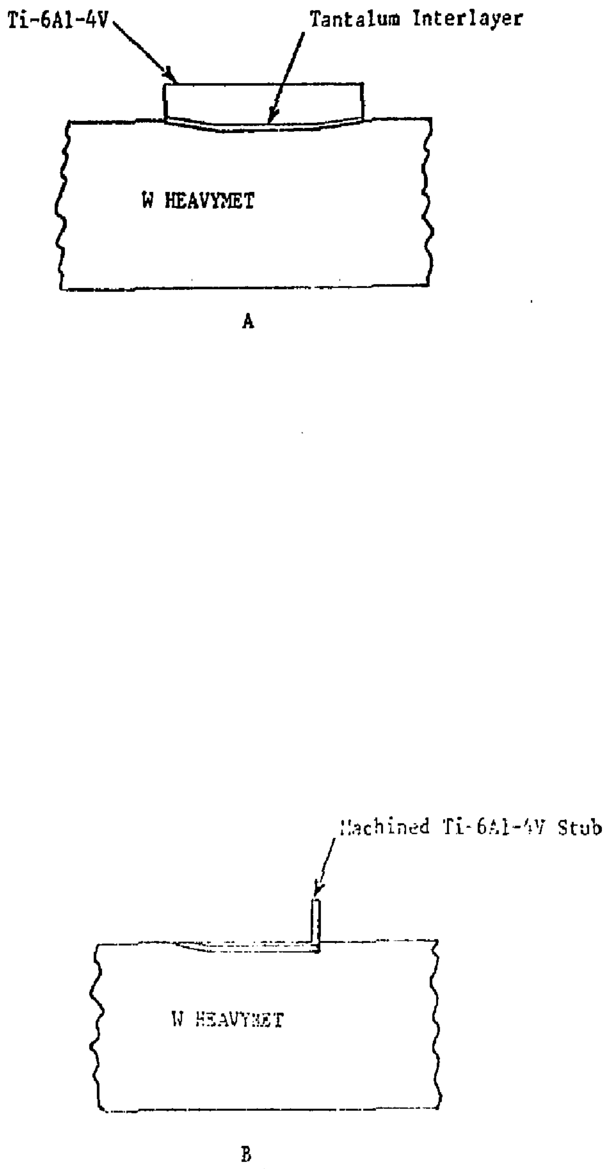

FIGURE 5. APPROACH FOR EXPLOSIVELY WELDING TITANIUM ALLOY TO TUNGSTEN ALLOY COMPONENT (A) SECTION IN AS-WELDED CONFIGURATION AND (B) FOLLOWING FINAL MACHINING

by the explosive welding operation would be removed and that the titanium section of the machined component would remain dimensionally stable during the subsequent brazing of the tube at approximately 954°C (1750°F).

The final titanium alloy-tungsten alloy joint (with the tantalum interlayer) is essentially a lap joint that results from the fact that the tantalum-tungsten alloy and titanium alloy-tantalum weld interfaces are depressed slightly below the final machined surface of the tungsten alloy component. This provides a joint of sufficient length to assure a leaktight, high strength bond.

A positive advantage of the explosive welding process is that the titanium component does not have to be made to the precise dimensional tolerances that will be required for brazing. The most critical aspect of the explosive welding process will be minimizing and controlling the distortion of the tungsten alloy component due to the extremely high forces generated on it during the welding operation. With the proper support tooling, however, it is expected that sufficient control can be maintained. Once the explosively welded component is stress relief annealed, its dimensional stability and control during the machining and subsequent operations should be excellent.

Recommended Research

A meeting at LLL should be scheduled at the start of the second phase of this program to (1) review the results obtained to date, (2) determine the constraints of the LLL application, and (3) define areas where experimental research is needed before proceeding to the fabrication of prototype joint assemblies. We believe that work on the brazing and explosive welding approaches should be conducted concurrently until such time as it becomes clearly evident that one or a combination of these approaches is most suitable for this application.

With respect to brazing, studies should be initially undertaken to evaluate the two candidate classes of filler metals (silver-base alloys and those based on the Ti-Zr alloy system) in order to select the optimum alloy for this application. Once this decision has been made, work can proceed immediately to a consideration of various joint designs and the fixturing required for each. In the course of these studies, joints duplicating that in the LLL structure will be assembled and brazed.

For the combination of brazing and explosive welding, a transition section of titanium-tungsten alloy will be required. This section would be fabricated by explosive welding. The techniques and parameters developed in this program would be extended and optimized for this approach. The brazing development for this design would be directed toward fabricating a tungsten-to-tungsten joint.

The explosively welded joint design would be immediately directed toward welding a transition section directly to the actual full-scale tungsten part. The titanium component with the tantalum interlayer would be explosively welded to the tungsten member in a single operation. Particular emphasis will be placed on fixturing the tungsten part to maintain its structural integrity and dimensions during explosive welding.