EXPLOSIVE TUBE-TO-FITTING JOINING OF SMALL-DIAMETER TUBES

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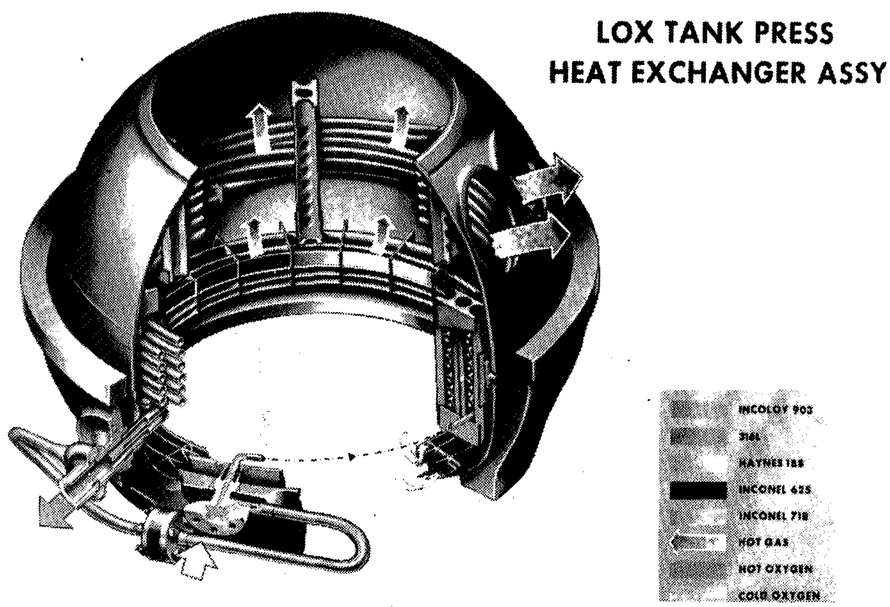
An effort is currently under way by NASA Marshall Space Flight Center to upgrade the Space Shuttle main engine through the use of improved materials and processes. Under consideration is the use of the Langley Research Center explosive seam welding process, as stated in the objective.

<u>OBJECTIVE</u> - DEMONSTRATE THE FEASIBILITY OF JOINING SPACE SHUTTLE MAIN ENGINE TUBE-TO-FITTING COMPONENTS IN AN OXYGEN HEAT EXCHANGER, USING THE NASA LaRC EXPLOSIVE SEAM WELDING PROCESS

The Space Shuttle Main Engine liquid oxygen tank pressurization heat exchanger assembly is shown in this figure. Located at the output of the oxygen turbopumps, just prior to the engine's main combustion chamber, this assembly's function is to convert a liquid oxygen supply to gaseous oxygen to pressure the oxygen vessel of the external tank. Liquid oxygen enters a 0.260-inch O.D. stainless-steel tube (inboard-directed arrow, lower left). The tube is wrapped around the inside of the heat exchanger, expands to a 0.5-inch O.D. in a split internal fitting, and penetrates the wall of the assembly at the outboard-directed arrow, lower left. The explosive joining effort described in this presentation was directed at joining the 0.260 and 0.500-inch diameter tubes to their respective fittings.



This figure details the materials, sizes, and temperature extremes at the input and output of the heat exchanger. All materials are refractory; each material has individual advantages and disadvantages in terms of strength, fracture toughness and the ability to be fusion welded.

Should the tube fail, the high-pressure oxygen pumped through the turbine would overpressurize the external tank with catastrophic results.

SHUTTLE HEAT EXCHANGER CONDITIONS/HARDWARE

- 316 L CORROSION-RESISTANT STEEL SEAMLESS TUBING
- AT INLET:
  - $-260^{o}F$
  - .260 O.D., .026-INCH WALL
- HEATED BY $+800^{o}F$ TURBINE GASES
- AT OUTLET:
  - $+390^{o}F$
  - .500 O.D., .035-INCH WALL
- THREE CANDIDATE MATERIALS FOR SHROUD FITTINGS:
  - HAYNES 188, INCONEL 625, INCOLOY 903
- MOST CATASTROPHIC FAILURE MODE IN ENGINE IS FAILURE OF TUBING

The explosive joining goals of this program are listed here.

1. Make the tube-to-fitting joint only through the mouth of the tube inserted in each fitting. No other external tooling or access would be required.

2. All other joining processes would be complete prior to the explosive joining of the tubes to the fittings.

3. Simplicity in tooling and process with easily inspectable assembly of all components of the tool and explosive materials would be required.

4. The output of the explosive, yielding the explosive joint, would have to be highly predictable and controllable.

5. The explosive joining process, which generates very high pressure, short-duration impulses, must not damage surrounding structure or fusion welds.

6. The bond between the tube and the fitting must have at least twice the strength of the tube.

7. The joint must be completely inspectable once made.

8. The joint shall exhibit absolute sealing capability with no indication of helium leaks at any required differential pressure across the joint.

9. No loss in strength or sealing capability will be allowed due to exposure to system temperature extremes in any cycle.

10. Reliability is paramount in all aspects of material preparation, tool assembly, the joining process, and the final joint.

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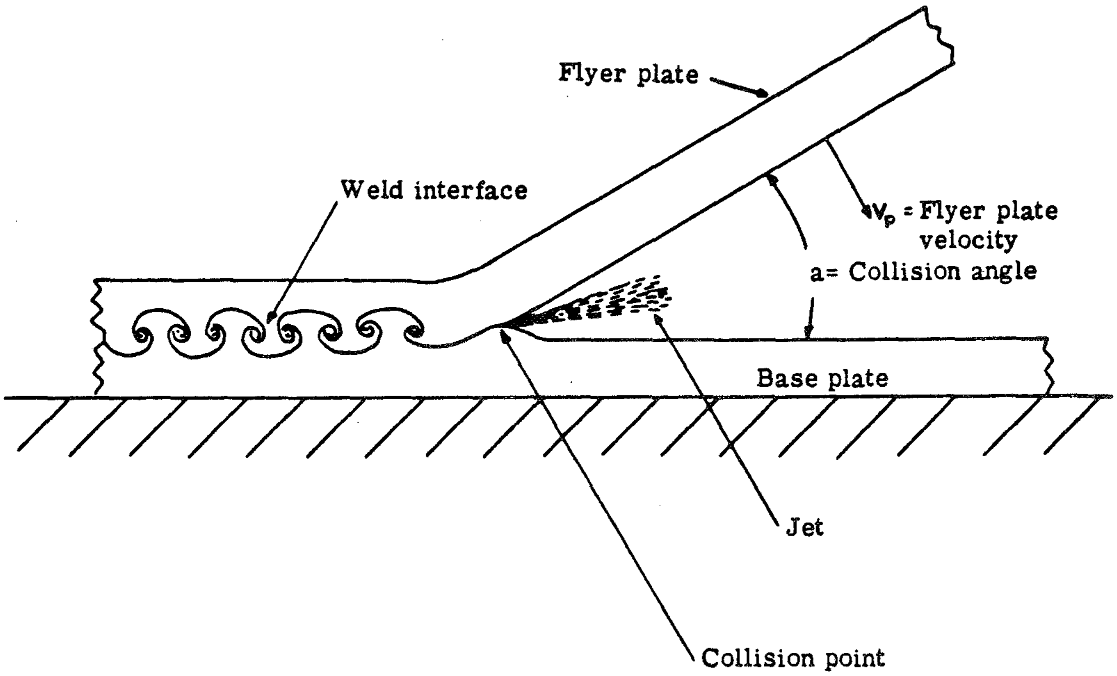
JOINING GOALS

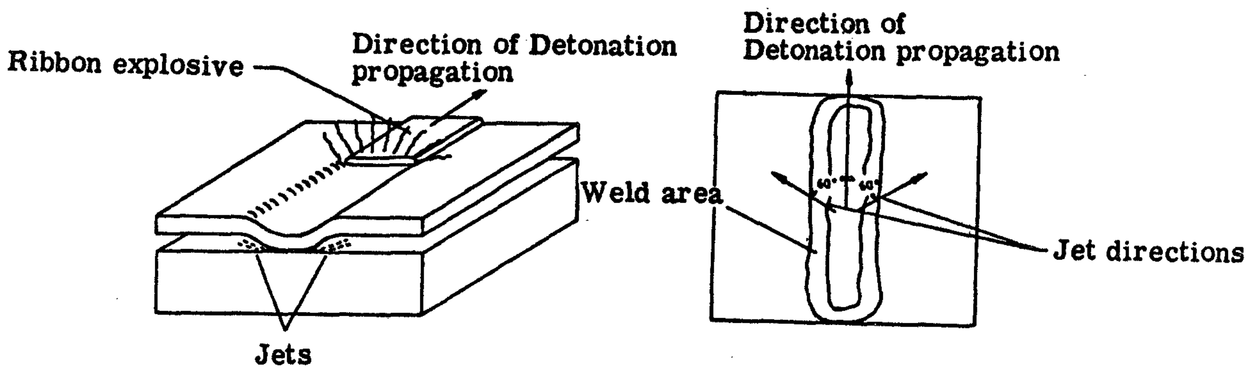
1. EXTERNAL ACCESS (MOUTH OF TUBE)
2. LAST STEP IN ASSEMBLY
3. SIMPLE
4. HIGHLY PREDICTABLE/CONTROLLABLE
5. NO DAMAGE TO SURROUNDING STRUCTURE/WELDS
6. JOINT HAVE LARGE STRUCTURAL MARGINS
7. INSPECTABLE
8. ABSOLUTE SEALS
9. UNAFFECTED BY THERMAL EXTREMES
10. RELIABLE

This figure describes the explosive joining process, which produces metallurgical bonds that are impossible to achieve by any other joining process. A several million psi explosive pressure wave accelerates the flyer plate into a high-velocity, angular collision with the base plate. On impact, the kinetic energy is converted to skin-deep melts, which are stripped from the surface and squeezed out (ejected) by the closing angle. The pure surface allows interatomic linkup through electron sharing. Bulk powder explosive is spread over the flyer plate and detonated along the line entering the plane of the paper to sweep from left to right (See "Practical Small-Scale Explosive Seam Welding" by L. J. Bement, NASA TM 84649, April 1983).



High-velocity angular collision of metal plates in an explosive welding operation.

This figure describes the Langley explosive joining process. A "ribbon" explosive is placed on separated plates and detonated at one end. The explosive pressure wave drives the plate downward, contacting in the center, producing two high-velocity, angular impacts outward at 60° angles from the centerline of the indentation. This process is ten times more efficient in terms of bond area produced by equivalent explosive quantities. Very small quantities of explosive are used.

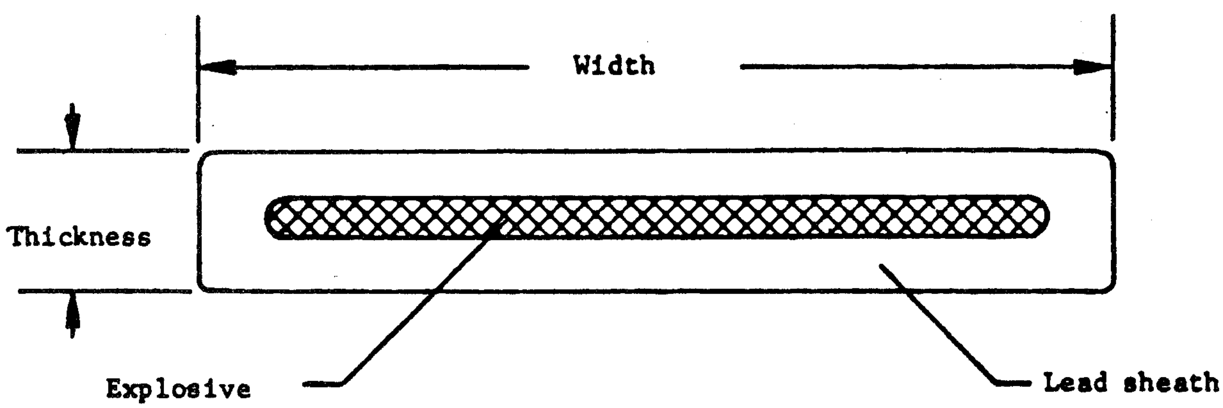


Mechanisms involved in small-scale explosive seam welding process.

The "ribbon" explosive, a lead-sheathed, flattened tube filled with RDX (cyclotrimethylene trinitramine) explosive, is shown here for six different loads. A grain unit is small: there are 7,000 grains in a pound, 15.4 grains in a gram.

Cross-sectional Dimensions of Linear Ribbon RDX Explosive

Explosive Load, grains/foot	Thickness, inch	Width, inch
7	0.020	0.220
10	0.020	0.300
15	0.025	0.315
20	0.030	0.365
25	0.035	0.370
30	0.035	0.510



This table lists the metals and range of thicknesses in which 100% strength joints can be obtained. The plates to be joined were placed in parallel (except as noted), separated by 0.015 inch. The ribbon explosive was placed on the outer sides of the plates, directly opposing and simultaneously initiated.

Like Metals Joinable by Explosive Seam Welding (100% Strength Joints)

Metal	Range of Thickness (inch)
a. Iron/steel Low-carbon to 300 and 400 stainless	0.001 to 0.050
b. Aluminum - any fully annealed alloy and all age and work-hardened alloys except 2024 and 7075	0.010 to 0.188
c. Copper/brass	0.010 to 0.150
*d. Titanium (Ti-6Aℓ-4V)	0.005 to 0.050

*Each plate prebent 5°

This process can metallurgically join a wide variety of metal combinations, as well as different tempers and conditions.

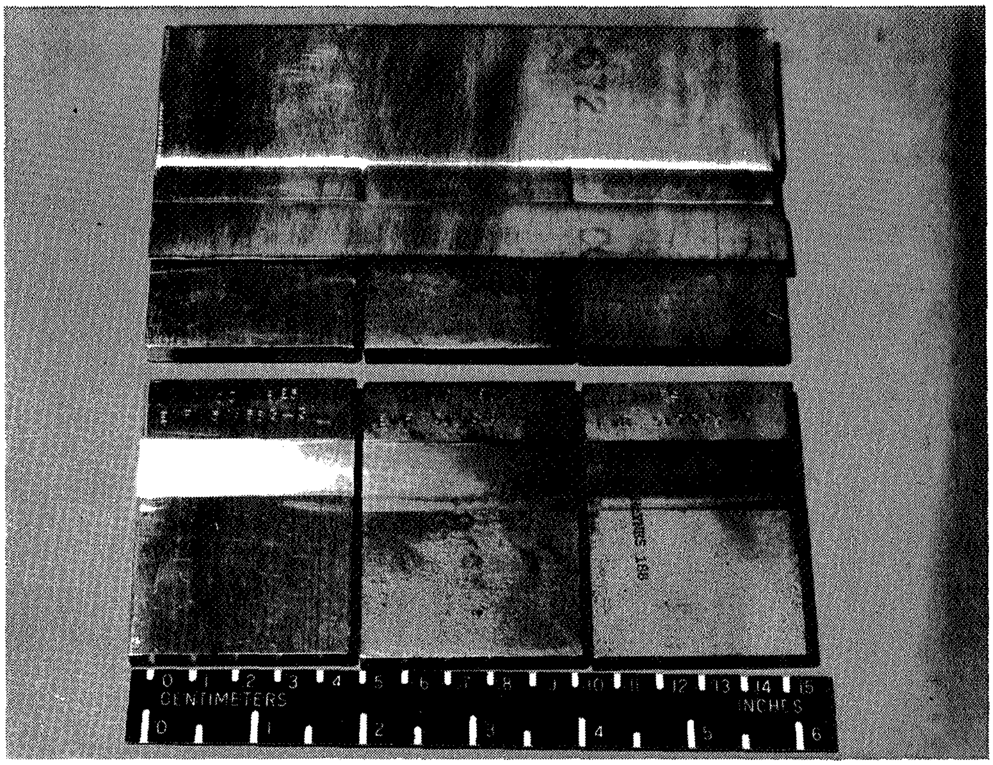
Metal Combinations Joinable by Explosive Seam Welding

a. Low-carbon to series 300 and 400 stainless steel are joinable in any combination

b. All aluminum alloys and conditions are joinable to any other alloy and condition, except a combination of 2024-T3, T4, etc. and 7075-T3, T6, etc.

c. Any combination of copper, aluminum, and brass can be joined

The explosive joining compatibility of the 316L stainless steel was first evaluated using flat stock. A 0.035-inch sheet of 316L stainless steel (top of figure) was joined to the three alloys of interest: Inconel 625, Incoloy 903, and Haynes 188. The base plates were machined with a V notch to allow the flyer plate (316L) to be in full contact and maximize the explosive joining efficiency. The lower plates show the machined notch, which is dimensionally described on the next figure. The upper figure shows the indent in the 316L, which was driven into the notch by the ribbon explosive. The vertical indents are where the 316L was driven into the small spaces between the base plates. The top joints were cross sectioned, pull-tested, and examined microscopically. The bond area for all three plates was several times that needed to support the full strength of the 316L.



This figure shows the dimensions of the "V"-notch, which was cut into the flat plates and the internal circumference of the fittings for the tube joining operation. The "V" immediately establishes the necessary collision angle for explosive joining. The tube outside diameter matched the fitting inside diameter to less than 0.002-inch tolerance. Past tests with 8-inch diameter tubes indicated this match was not critical. A joint was successfully made with a 0.060-inch diameter undersized tube. See "Explosive Seam Welding Application to Reactor Repair" by A. E. Aikens and L. J. Bement, presented at the 3rd Annual Conference of the Canadian Nuclear Society, Toronto, Canada, June 9, 1982.

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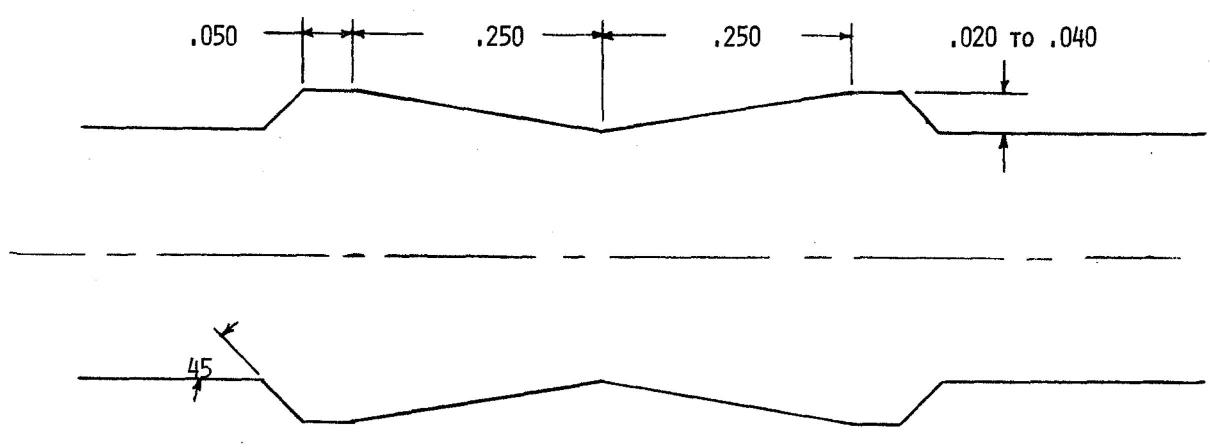
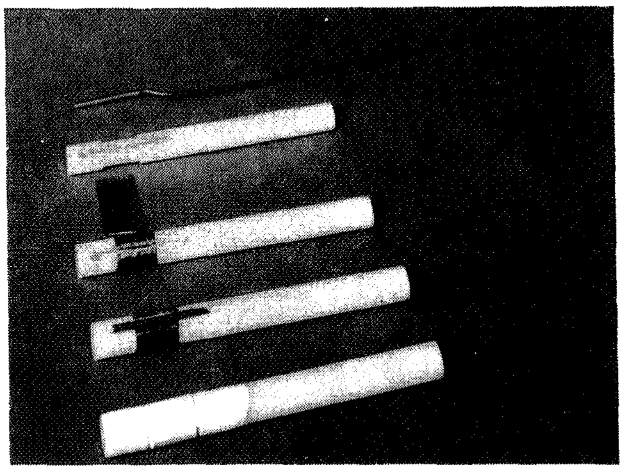
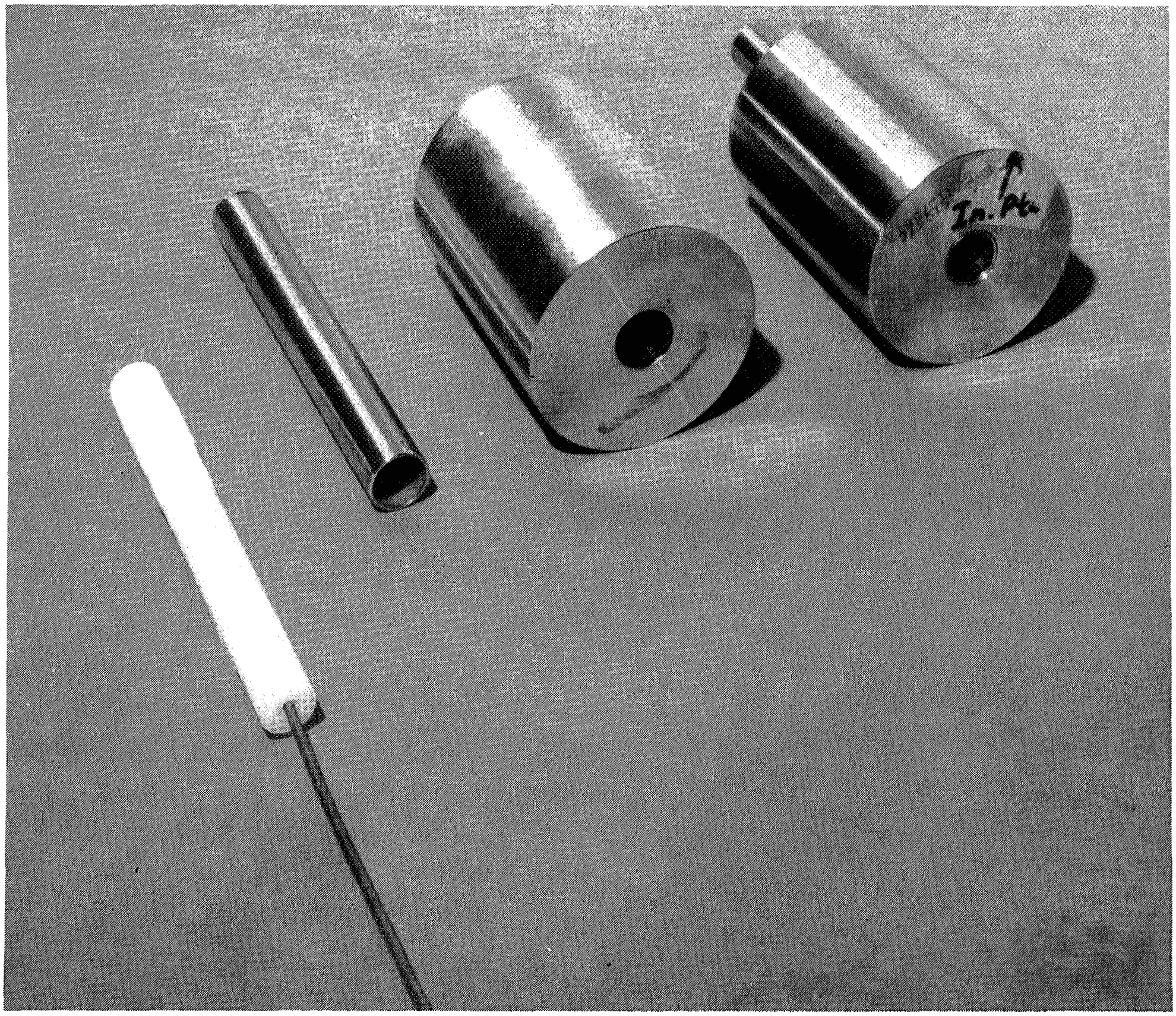


CROSS SECTION OF EXPLOSIVE WELDING INTERFACE WITHIN FITTINGS

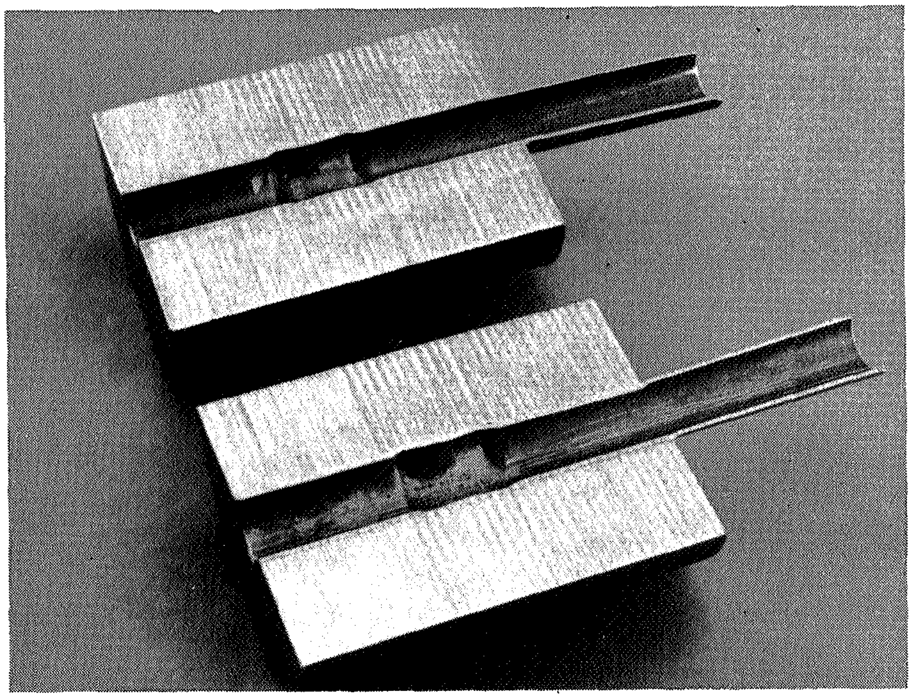
This photograph depicts the explosive materials and the explosive joining tool in various stages of assembly. The explosive joining principle is to insert the loaded tool inside the tube, and on initiation of the explosive, the tube is driven into the V notch in the fitting. The top object is the initiator, which consists of a 0.090-inch diameter, 0.005-inch wall, 1-inch long 304 stainless-steel tube containing a 0.40-inch length of packed RDX. Bonded into this tube is an 8 grains/foot RDX, lead sheathed mild detonating fuse (MDF). The white object is a nylon rod machined to accommodate the ribbon explosive and ultimately match the inside diameter of the tube to be joined. The 30 grains/foot ribbon explosive (third object) is wrapped around the tool (held in place with sticky-back tape) and trimmed to the dimensions of the initiator. The initiator is then inserted into an axial hole in the tool. This photograph shows a teflon tape overwrap to match the inside diameter of the tube to be joined. A different approach was more effective, using modeling clay around the explosive, fully contained by heat-shrinkable plastic tubing.



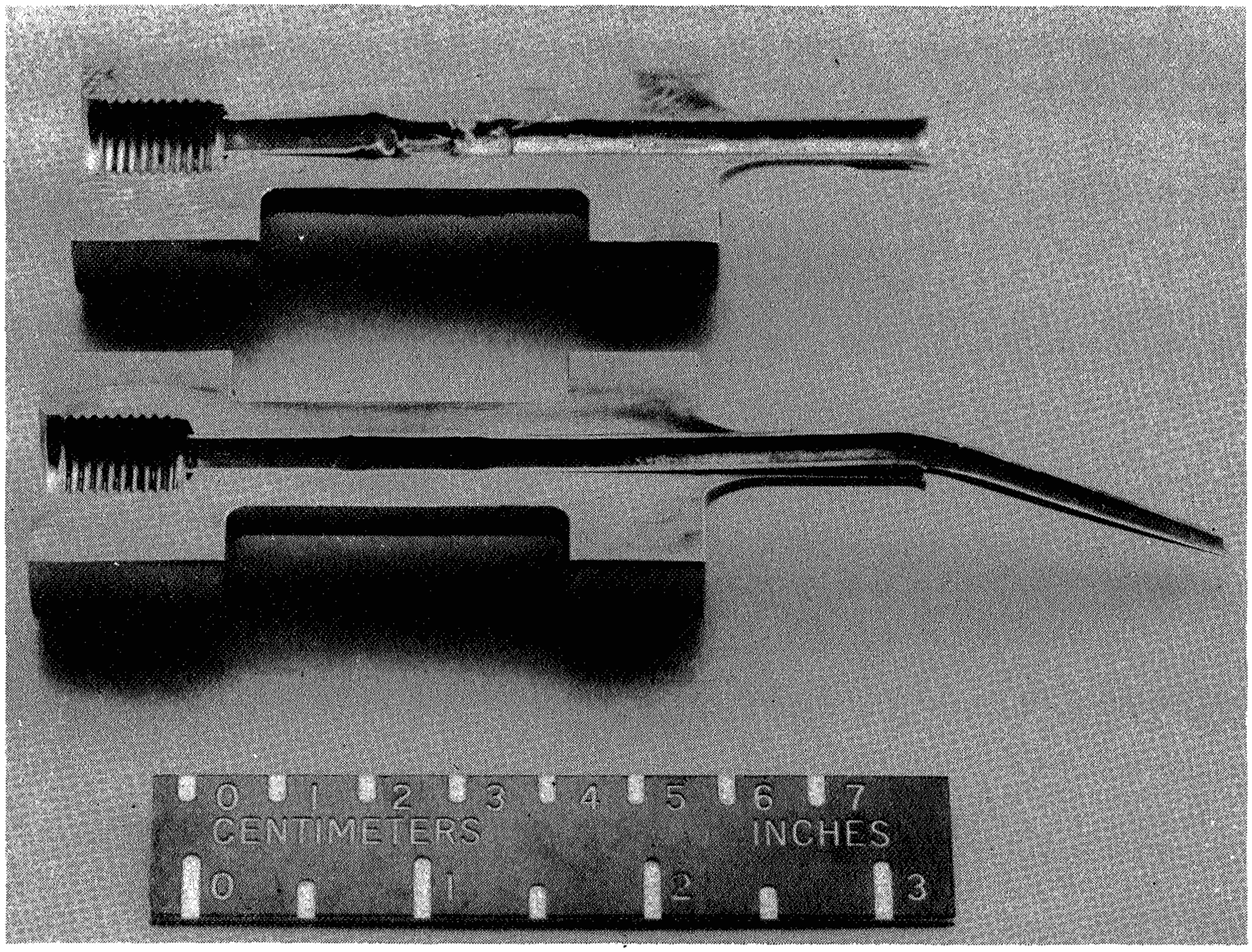
This photograph shows the loaded tool, a 0.5-inch tube and an experimental fitting in which has been machined the V notch. The fitting on the right contains an explosively joined tube.



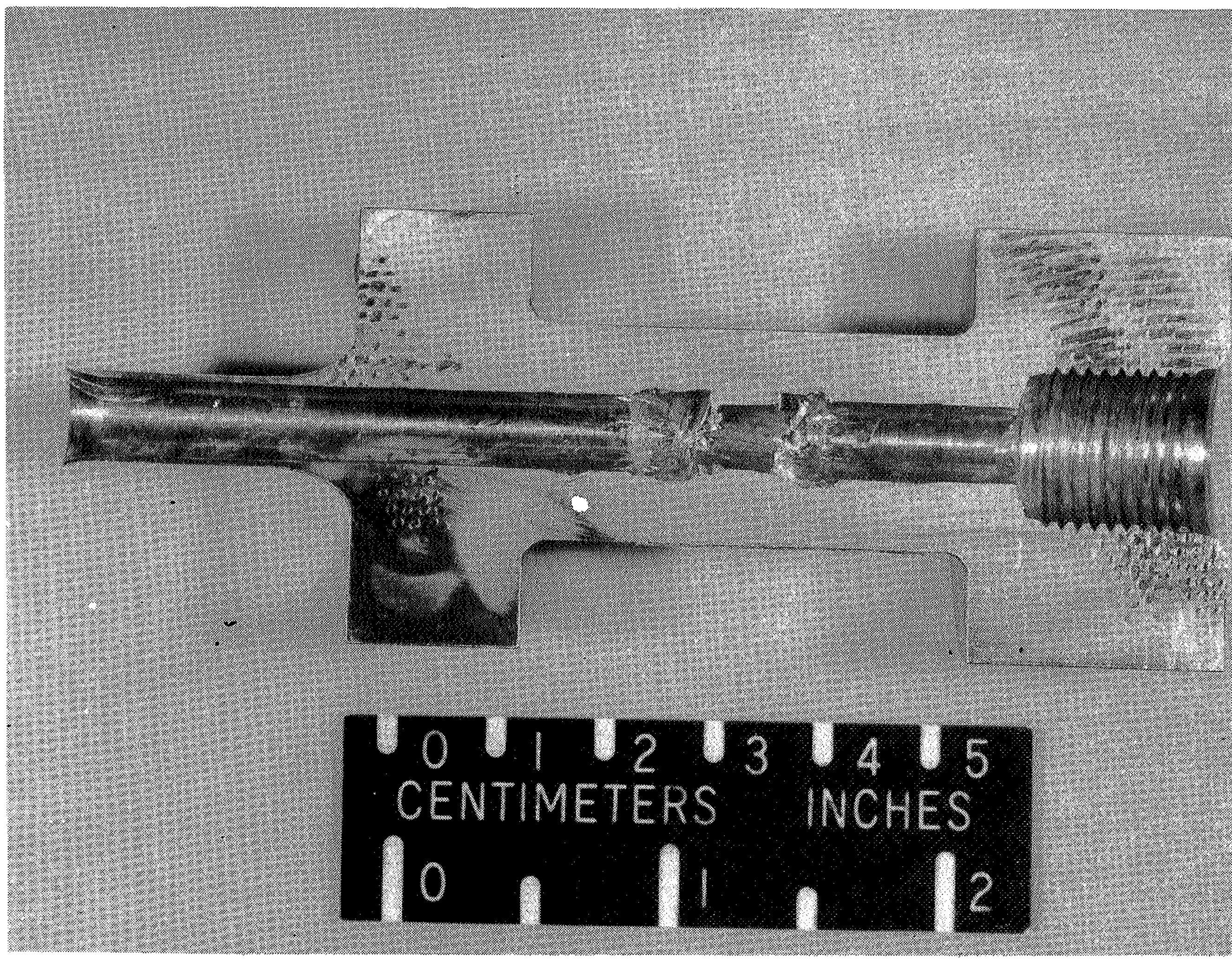
This photograph shows the fitting in the previous photograph, cross sectioned on its axis. The 0.5-inch tube was driven into the notch at the indented area. However, ultrasonic inspections and peel tests showed only partial bonds. Furthermore, lead from the ribbon explosive had been imbedded into the interior surface of the tube. The teflon tape had not exactly matched the tube's interior, leaving air gaps. Since the air is compressible, the explosively driven lead penetrated the teflon and impinged into the tube. The modeling clay with shrink tube described on the previous figure completely filled the internal volume, preventing lead transfer to the tube wall.



The 0.260 diameter, 0.026-inch wall fitting proved to be much more effective in terms of bond. A 15 grains/foot ribbon explosive was used in this test. The upper section was used for a peel test, shown in the next photograph.

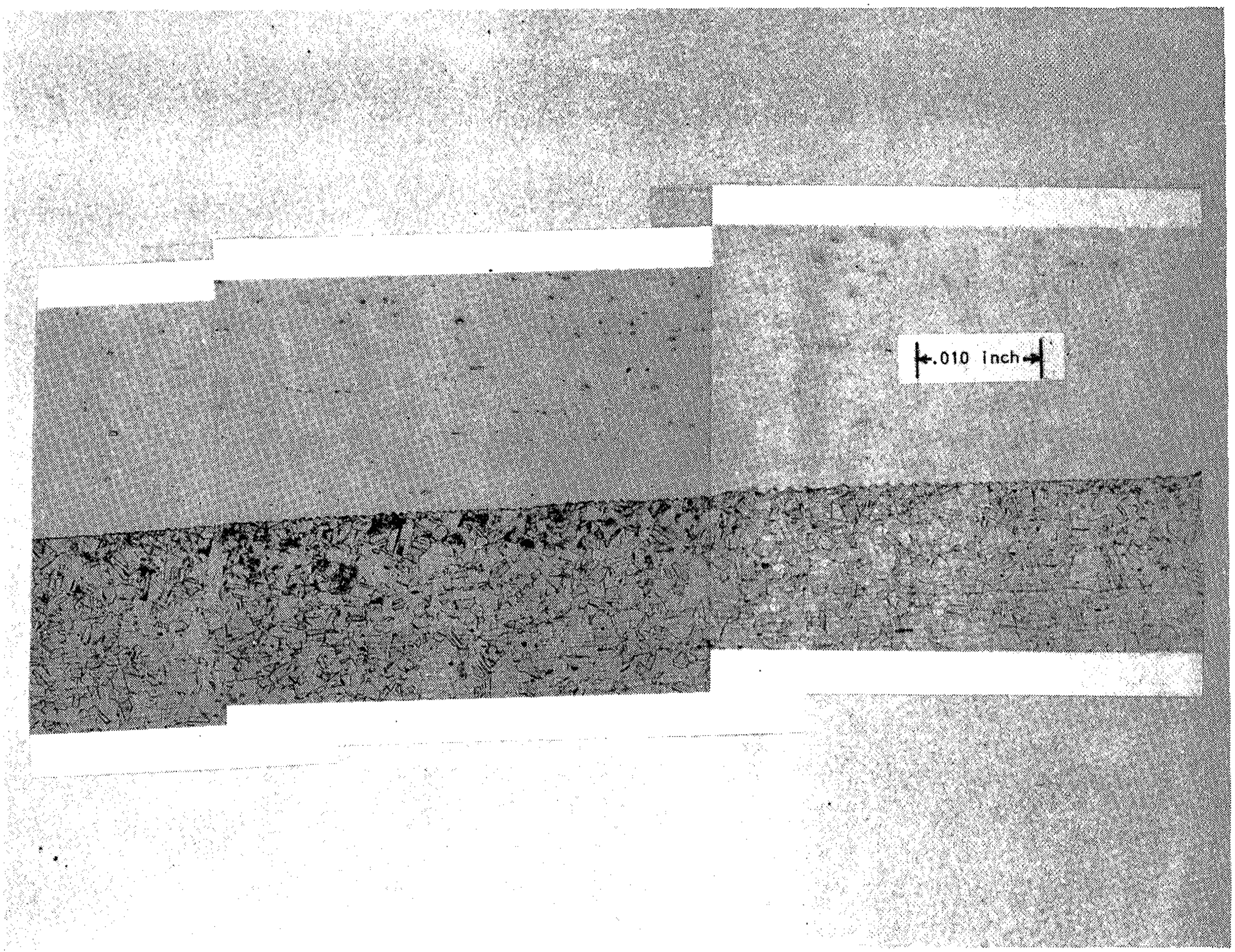


A cold chisel was driven into the bond interface as far as possible. In this case, approximately 0.25 inch of the tube length was bonded, nine times the 0.026-inch wall thickness. Only a bond length of 0.052 inch would fully support loads that would fail the tube.



This photograph shows a portion of the bond in the 0.260 diameter tube, which has the typical "wave" pattern of explosive joining. The largest "wave" pattern to the right has peak-to-peak dimensions of less than 0.001 inch.

To evaluate the effect of reduced explosive loads, a second test was conducted with a 10 grain/foot ribbon explosive. The bond length was reduced to approximately 0.150 inch.



The current results of the tube-to-fitting explosive joining evaluation are shown here.

1. The 316L is completely compatible with the three candidate refractory materials for explosive joining.
2. The 0.260 diameter tube has successfully met all joining requirements with excellent margins.
3. Planned are thermal shock tests in which the joints will be transferred from liquid nitrogen (-320°F) to a +400°F stabilized oven.
4. The 0.500-inch diameter tube is not bonded due to air entrapment in the V notch. The 30 grains/foot ribbon explosive's 0.510-inch width creates a pressure wave that forces the tube into the fitting wall and prevents the air in the V notch from escaping as the tube collapses into the notch. Narrower ribbon explosives have been attempted, but the more promising improvement would be to widen the notch and vent the air out of the fitting.
5. Helium leak checks are not a good indication of a good joint. Perfect seals were achieved without explosive bonding. The tube had only been swaged into the V notch.
6. Ultrasonic inspection utilizing pulses of sound, which reflect from opposite surfaces, provides an excellent evaluation method for explosive joining. An ultrasonic probe placed on the outside of the fitting provides a highly accurate measurement of the interior V-notch surface. Once "mapped," the process is repeated for the explosive joint. A bonded joint will appear as simply a greater thickness. Areas with no bond display a complex reflected signal from two surfaces instead of one.

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<u>CURRENT RESULTS</u>

- 316 L COMPATIBLE WITH ALL THREE FITTING MATERIALS
- THE .260 O.D. TUBE JOINT MET ALL TESTS TO DATE WITH EXCELLENT MARGINS
- NOT YET CONDUCTED THERMAL SHOCK TESTS
- THE .500 O.D. TUBE JOINT NOT BONDING
    - AIR ENTRAPMENT DURING JOINING OPERATION
    - USE NARROWER RIBBON EXPLOSIVE OR WIDER NOTCH
- HELIUM LEAK CHECKS NOT INDICATION OF GOOD JOINT; EXPLOSIVE SWAGE PRODUCED ABSOLUTE SEAL
- ULTRASONIC INSPECTION IS EXCELLENT
    - EXTERNAL TO FITTING APPROACH
    - MAP INTERNAL SURFACE OF FITTING
    - COMPARE MAP WITH PROFILE OBTAINED WITH TUBE INSTALLED

The current conclusions are:

1. The Langley explosive joining process is indeed viable for this tube-to-fitting application.
2. No incompatibility of materials has been detected.
3. Ultrasonic inspection provides the best evaluation of the joint and will provide the needed confidence of the joint in the final application.
4. The 0.500-inch diameter tube has not yet been adequately joined. Success is anticipated with a wider V-notch that allows the trapped air to vent during explosive joining.
5. Thermal shock testing (-320 to +400°F) will be conducted. Past experience with explosively bonded joints in steel has indicated no problems.

SHUTTLE ENGINE TUBE-TO-FITTING EXPLOSIVE JOINING

CURRENT CONCLUSIONS

- LaRC EXPLOSIVE JOINING IS VIABLE FOR THIS APPLICATION
- NO INCOMPATABILITY OF MATERIALS HAS BEEN DETECTED
- ULTRASONIC INSPECTION IS THE BEST NON-DESTRUCTIVE TESTING
- THE .500 DIA JOINT EXPERIENCES INTERFACE PROBLEMS
- THERMAL TESTING HAS YET TO BE ACCOMPLISHED