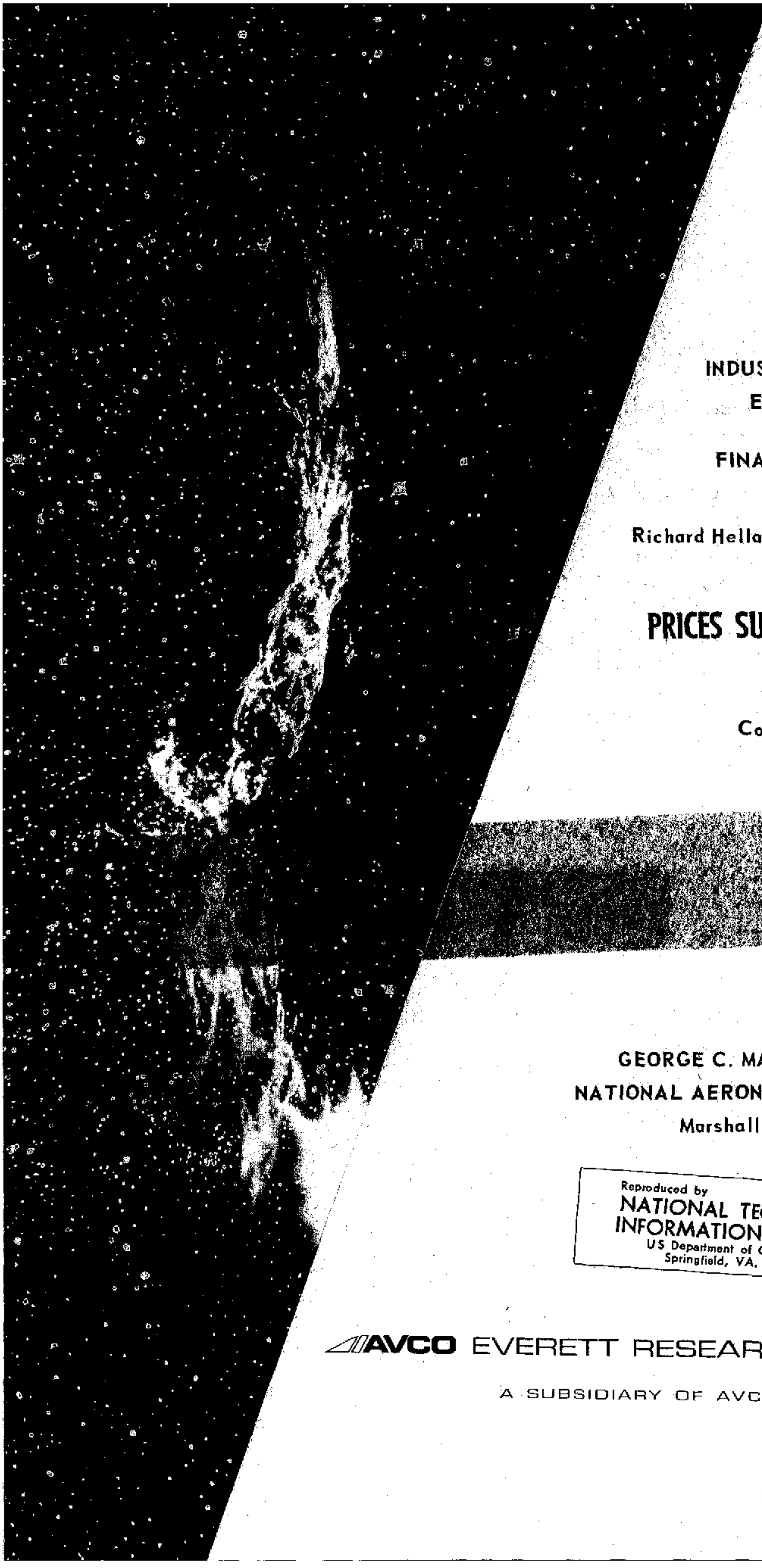

INDUSTRIAL LASER WELDING EVALUATION STUDY

FINAL TECHNICAL REPORT

Richard Hella, Edward Locke and Stanley Ream

PRICES SUBJECT TO CHANGE

Contract No. NAS8-28610
November 1974

prepared for

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Marshall Space Flight Center, Alabama

AVCO EVERETT RESEARCH LABORATORY, INC.

A SUBSIDIARY OF AVCO CORPORATION

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by

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* Formerly with AERL, Inc., currently with Locke Technology, Inc., Wakefield, Mass.

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I. INTRODUCTION

The advent of very high power laser welding systems has resulted in a potential increase in manufacturing capability within the aerospace industry. Through the use of these large lasers, the superior welding properties presently achievable with electron beam welding can hopefully be achieved with a laser beam, but without the attendant vacuum requirements necessary for the vacuum electron beam welding, or the cumbersome pumping head required with the out-of-vacuum electron beam equipment.

The objective of this program has been to evaluate high power laser welding for fabricating space vehicle boosters. This evaluation was made for 1/4" and 1/2" aluminum (2219) and 1/4" and 1/2" D6AC steel. The Avco HPL* 10 kW industrial laser was used to perform the evaluation. The objective has been achieved through the completion of the following technical tasks:

- Task I Parameter study to optimize welding and material parameters.
- Task II Preparation of welded panels for MSFC evaluation.
- Task III Demonstration of the repeatability of laser welding equipment.

In addition, the design concept for a laser welding system capable of welding large space vehicle boosters has been developed.

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II. SUMMARY

The optimization study involved the generation of approximately 150 welds. Early in the program the decision was made to make butt welds, rather than bead on plate (BOP) welds because of the possible influence of the material edge condition (oxide, fitup, etc.) on the weld quality.

It was determined that good quality welds could be achieved in both the 1/4" and 1/2" D6AC, but a limited amount of preheat was required (450°F - 600°F). If no preheat was used, the welds usually cracked within several minutes of being made.

The 1/4" 2219 aluminum was successfully welded only after a considerable effort was made to develop a water-cooled shielding hood. The hood finally used was an outgrowth of a noncooled hood designed and built at MSFC.[1] While full penetration of 1/2" 2219 aluminum was easily achieved using this hood, excessive and erratic dropthrough prevented the generation of good welds. By milling the material down to 7/16" and increasing the welding speed, acceptable top and underbead geometrics were produced. However, these welds showed excessive porosity. The pores were about 1/16" dia. and occurred at a rate of about 20/in. and were located near the weld root. A further reduction in thickness to 3/8" reduced the porosity to a rate of about 5 - 10/in. Attempts to reduce porosity further by variations in speed, power, gas shielding, or edge preparation, were to no avail.

(1) R. Poorman, NSFC, COR-EH-42

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III. DESCRIPTION OF EQUIPMENT

The description of the Avco HPL 10 kW laser used for this program is given in Appendix I. In this section, a more detailed description of tooling and gas shielding is given.

A. WELDING WORK STATION

A closeup photograph of the welding work station is shown in Fig. 1. The collimated laser beam is focused by an F/7 telescope to an approximately 0.030" dia. spot positioned at the joint of the pieces to be welded. As an aid to aligning the laser beam to the joint, the red beam from a He/Ne laser is folded into the optical system and is coaxial with the high power laser beam. The workpiece is held in place by a fixture mounted to the motorized milling machine base. The light duty welding fixture shown in Fig. 1, which was adequate for the 6" welds of Task I, was too flimsy for the 18" welds in the 1/2" steel required for Task II. A more rugged fixture, shown in Fig. 2, was built for this purpose. This fixture provided underbeat shielding in a 1/2" x 1/4" grove milled into the 2" thick baseplate, and located directly under the weld point. The plates to be welded were held in position by a number of 1" thick by 1-1/2" wide fingers.

B. GAS SHIELDING

Gases for both top and underbead shielding are controlled and metered from a gas manifold located just outside the work station. For a limited series of tests on 3/8" aluminum, a separate helium bottle, regulator and flow meter were hard piped directly to the shielding hood to minimize the possibility of impurities (especially water) being introduced into the shielding gas.

For all of the D6AC steel welds, the hood shown in Fig. 3 was used. This hood contains both a forward facing gas jet (used to prevent ionization of the laser generated metal vapor) and a trailing shield (to prevent oxidation of the weld molten metal). Experience has proven that a helium gas jet, combined with an argon-rich trailing shield gas, produces smooth, porosity-free welds in most steels. However, when used with aluminum, this hood usually produces a rough top head, and a porous weld.

The key to successful aluminum welds was the use of a hood designed and built by the MSFC technical monitor.[1] This hood provided a chimney for the laser beam to pass through the hood body, and enter the workpiece. Shielding gas is supplied both in front of, and behind the interaction point by way of a fine mesh diffuser.

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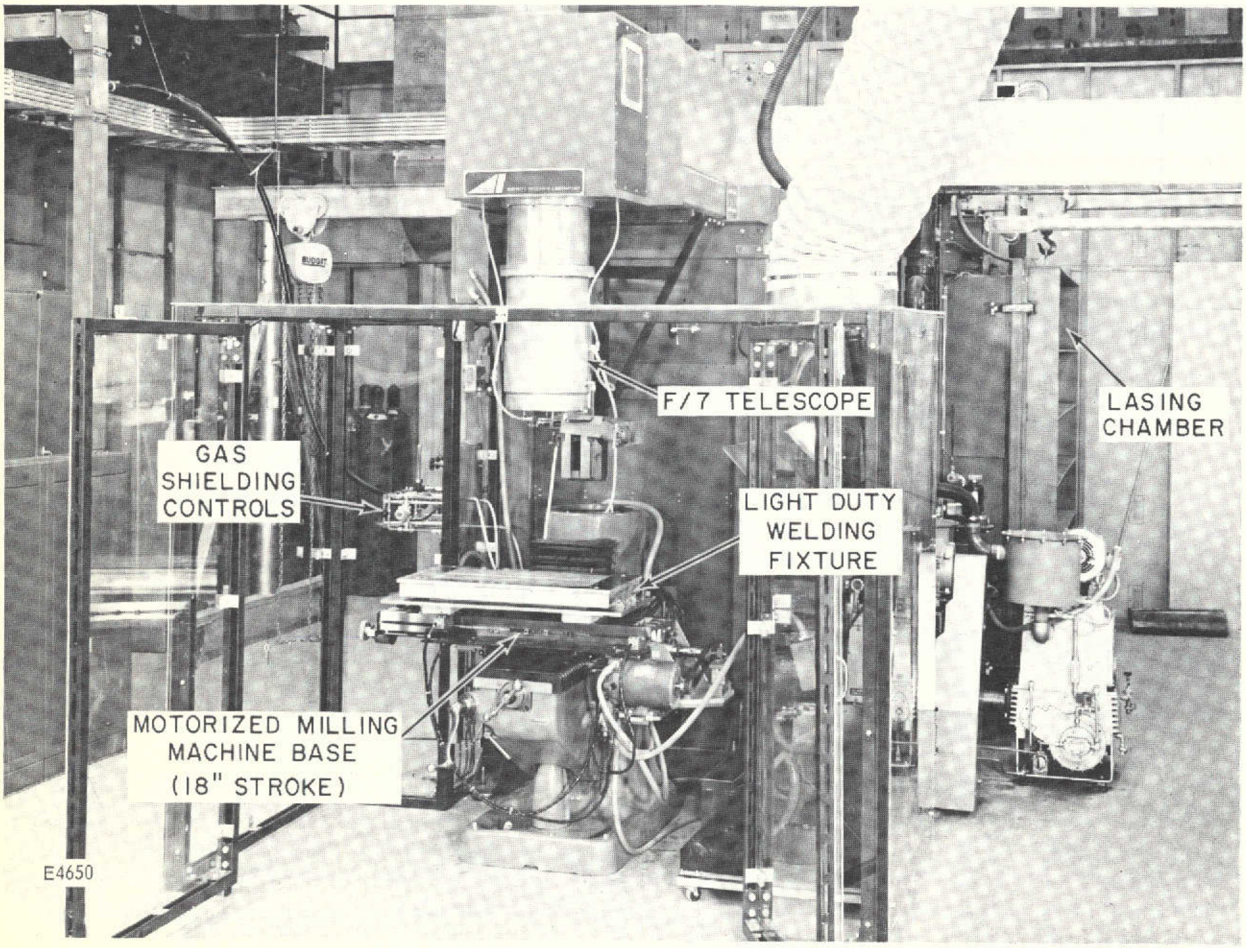


Fig. 1 Photograph of Welding Workstation of the Avco HPL Laser System Used for this Program

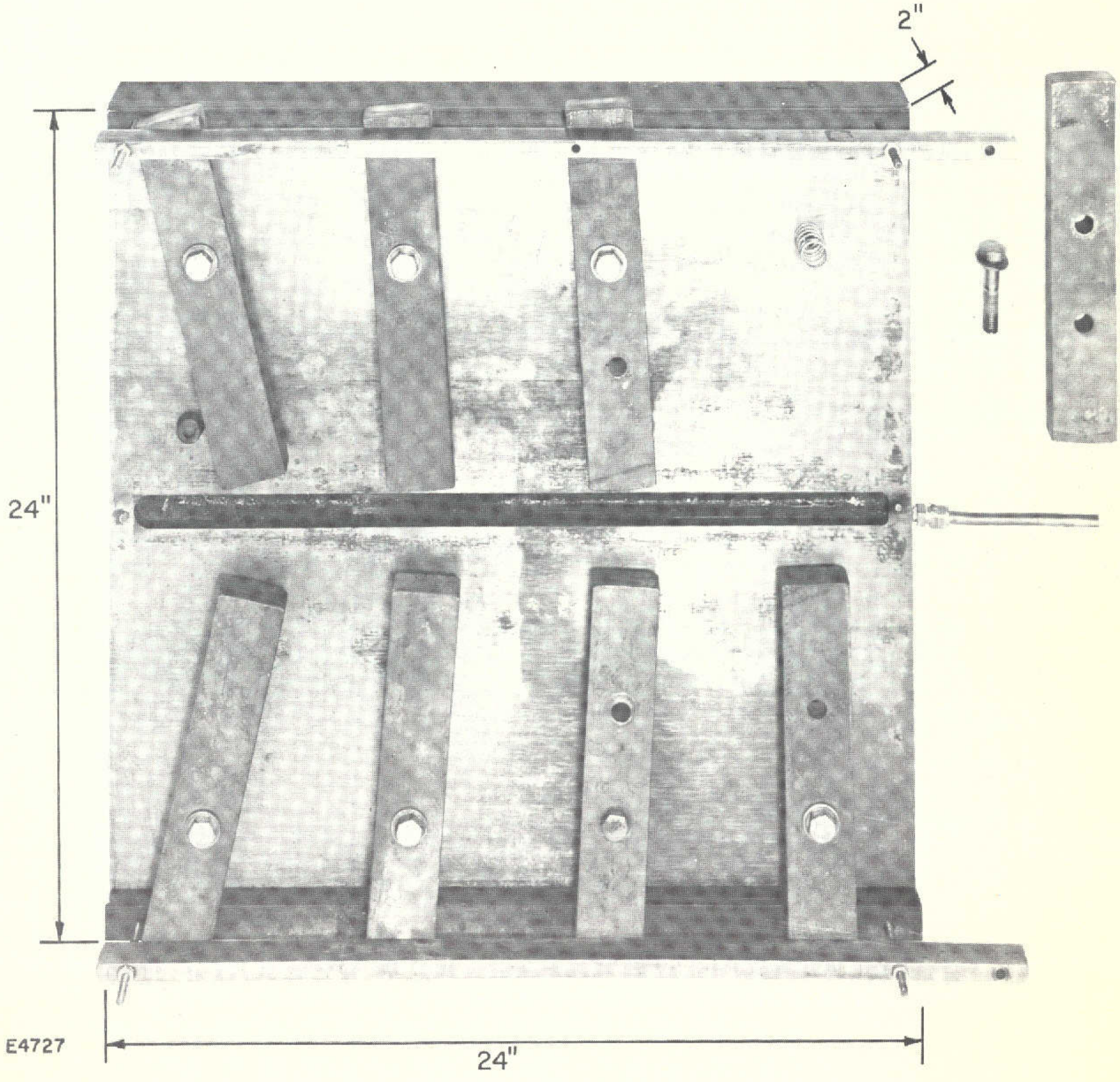


Fig. 2 Photograph of Heavy Duty Welding Fixture Used to Secure 24" Panels for Laser Welding

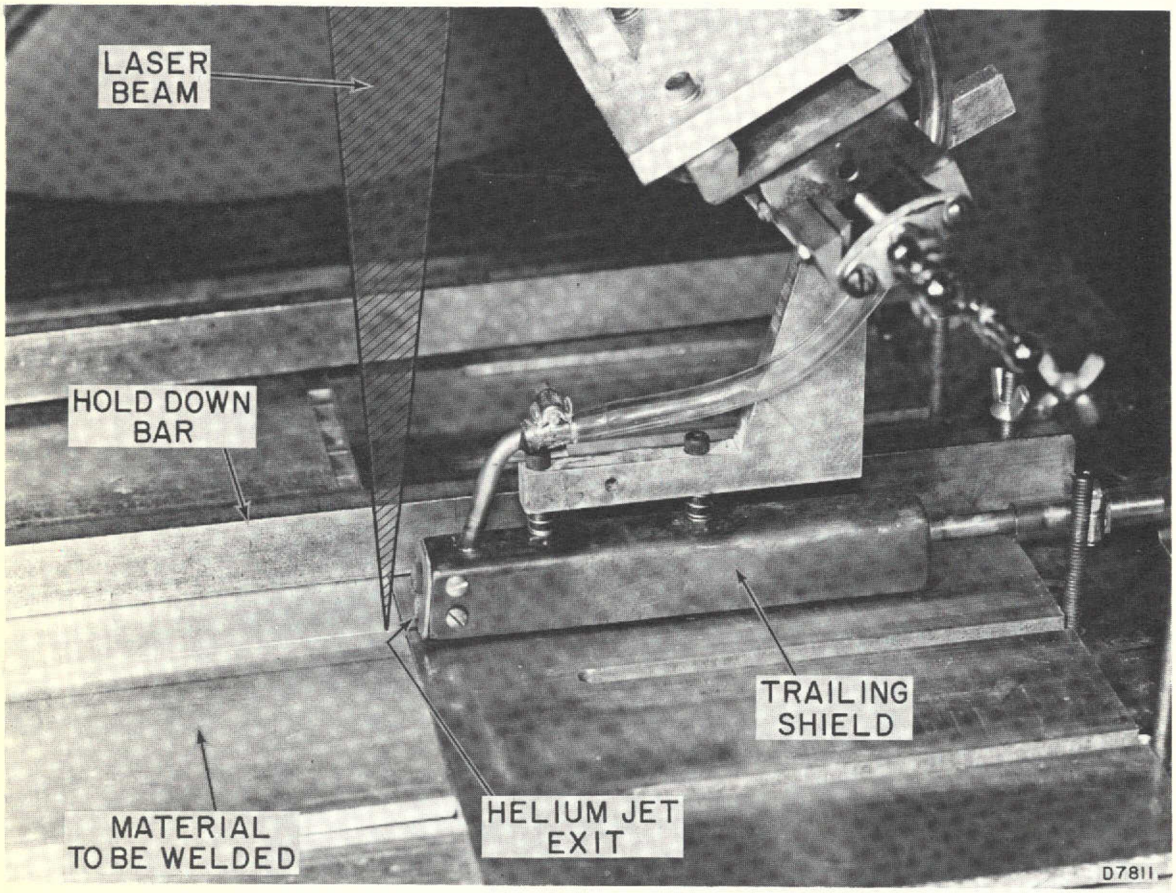


Fig. 3 Hood 6-A Used for Welding Both 1/4" and 1/2" D6AC

The design characteristics of this hood, and its evolution throughout this program are shown in Fig. 4. The hood as originally supplied by MSFC, and referred to as the NASA-1 hood, used a pressed stainless steel mesh as the diffuser, both along the bottom, and around the chimney. The first welds made in the 1/4" aluminum with this hood were very promising, but the steel mesh at the bottom of the chimney burned out after several welds (welds 285-287, Table I). A second, identical hood (NASA 2) suffered the same fate after one run (No. 293). This steel mesh was then replaced with a 1/16" thick porous bronze plate, epoxied in place, and the hood thus modified was designated NASA M1. The initial welds made with this hood were not good because of epoxy outgasing. After outgasing treatment, however, a limited weld study involving different mixtures of helium and argon was made.

Due to the continued uncertainty of epoxy contamination, a second porous bronze plate was prepared, and soft soldered in place. At the same time, a 3/8" copper tubing chimney was installed in place of the pressed steel wool chimney. With this modification, NASA M2, the first really excellent 1/4" aluminum weld was made, and delivered to MSFC for their evaluation (weld 310).

After several welds, the soft solder began to diffuse into the porous bronze, thereby filling the pores and ruining the hood. Therefore, an attempt to silver solder the porous bronze was made. Also, a 3/8" copper tubing chimney without any sidewall holes was installed. This hood (NASA M3) lasted somewhat longer, but the porous bronze and the chimney base began to melt after a number of runs.

To add to the durability of the chimney, a more massive, heavier walled chimney was used. This modification, called the NASA M4, and shown schematically in Fig. 4, still did not prevent burnout of the bronze diffuser in the region surrounding the chimney. A photograph of a typical burned out diffuser is shown in Fig. 5(a).

The next modification involved three changes: (1) Make a heavier walled body with a machined seat for mounting the diffuser; (2) use a water-coded chimney with a broad base in good thermal contact with the diffuser; (3) use a copper diffuser made out of 1/32" thick copper sheet with 0.025" dia. holes spaced every 0.060" apart. This hood, designated NASCO, is shown schematically in Fig. 4, and a photograph is shown in Fig. 5(b). No further problems were encountered with this hood.

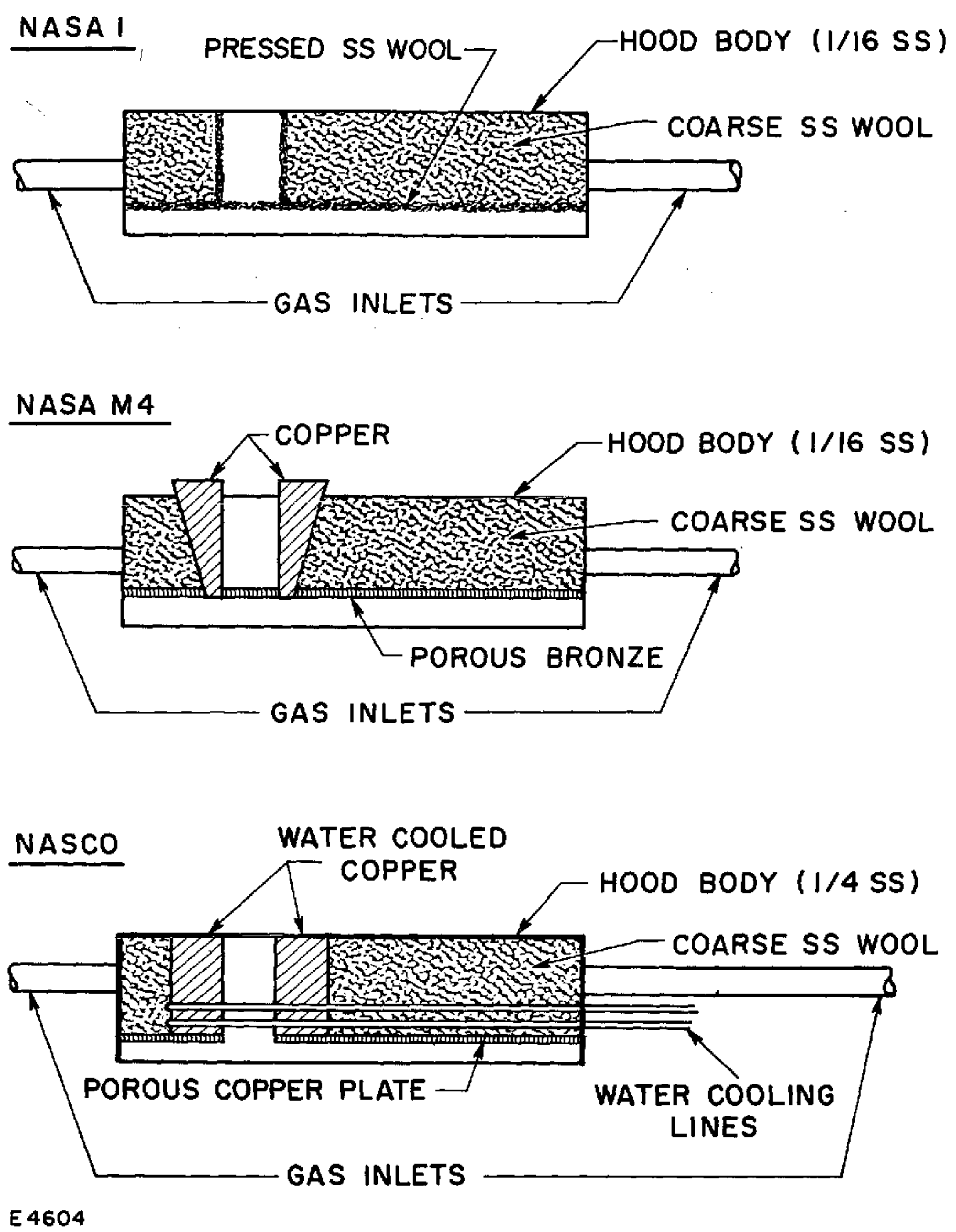


Fig. 4 Evaluation of NASA Type Hood to Achieve Reliable, Durable Performance

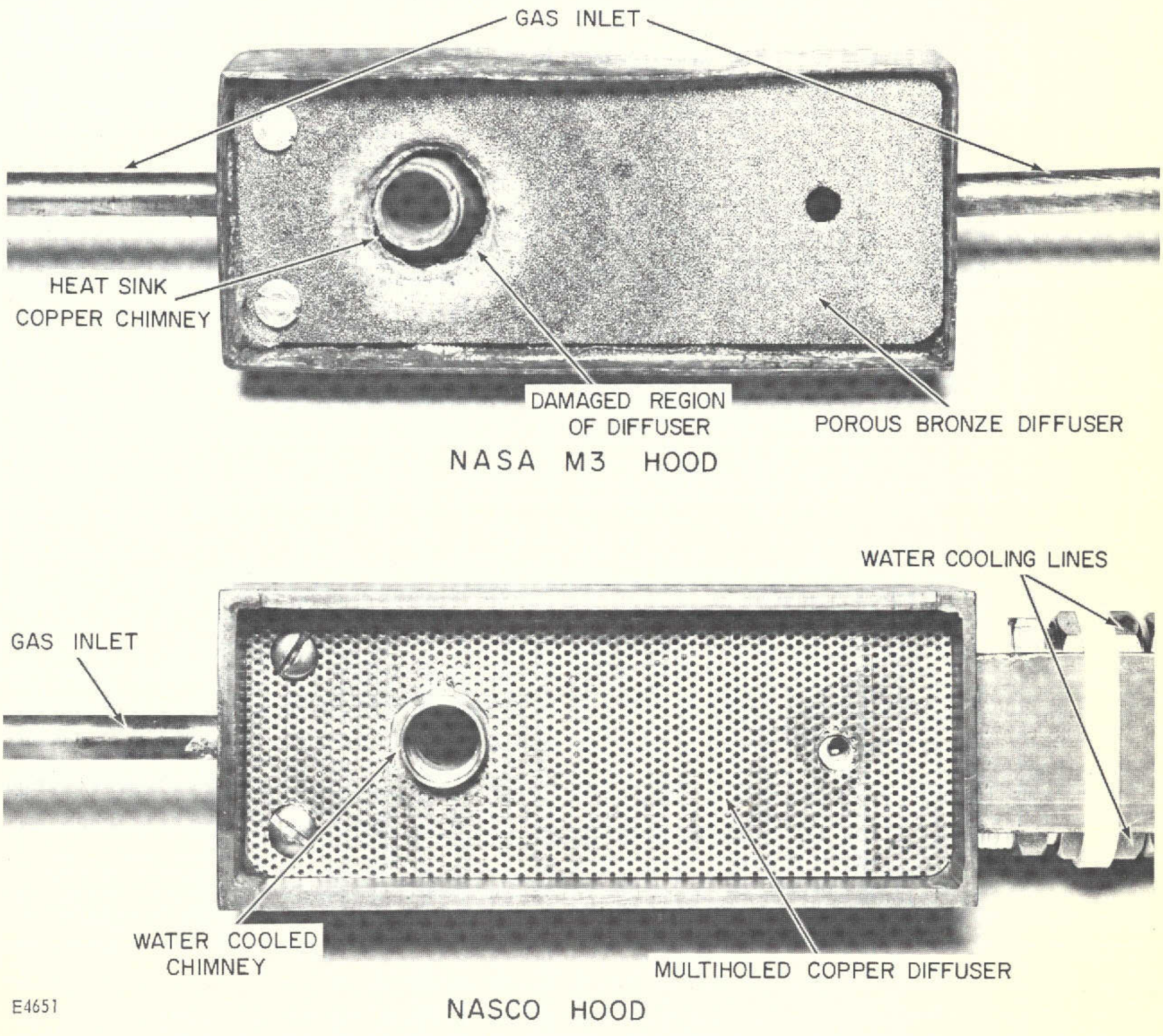


Fig. 5 A) Bottom View of NASA M3 Hood Showing Damaged Diffuser Plate
B) Bottom View of NASCO Hood, Which was not Damaged

IV. WELDING PROCEDURE

For all welds, the sequence of events was as follows: (1) install proper shielding hood; (2) adjust shielding gas composition and flow rates; (3) dial feed rate and laser power into control console; (4) prepare edges of material; (5) load material into welding fixture and align joint with coaxial visible laser beam; (6) actuate "automatic operation" button on control console, which starts shielding gas flow for 5 seconds, then starts table which actuates limit switches to start and stop laser, then maintains shielding gas flow for another five seconds after the weld is completed.

If a preheat treatment was to be used, the procedure would be modified accordingly. The preheating was accomplished in a small oven and plate temperature just prior to welding was measured using a Temple stick. For runs involving post-heating, the welded panel was immediately removed from the welding fixture and placed in the oven adjusted to the appropriate temperature.

After the welded panel was removed from the welding fixture, and cooled sufficiently to handle (either by water quench or air cooling) a visual examination of the weld was made. If the visual appearance was good, a determination of the porosity level was made. In the case of aluminum, this was done by breaking the plates along the weld and examining the fused metal. For the D6AC steel, X-rays of selected pieces were made.

Based on the results of the visual inspection and porosity assessment, the welding procedure was modified to improve the quality. The welding procedure modification was based more on intuition and experience than on a formal parametric test series involving a matrix of variables.

V. EXPERIMENTAL RESULTS FROM PARAMETER STUDY (TASK I)

In this section, an overview of the parameter study performed to optimize welding parameters is presented. Table I contains summary conditions and results for the welds made for this study.

A. ALUMINUM, 1/4 INCH

A large portion of the effort required to optimize welding of 1/4" aluminum was devoted to the development of a proper hood, as described in Section III. In addition to this effort, investigation of the following parameters were made: telescope-to-work distance, feed rate, and shielding gas delivery, composition and flow rate. Most of these welds were done at a laser power of 15 kW, although it was felt instructive to make some welds at power from 13 to 16 kW.

1. Telescope-to-Work Distance

Shown in Fig. 6 is the variation of penetration (shown as the percentage of full penetration) with telescope-to-work distance. For this series (welds 312, 319, 320, and 321) the NASA M3 hood was used with 40 CFH helium and 10 CFH argon shielding gas. The power was 16 kW and the feed rate was 175 IPM. Maximum penetration occurred at a workpiece distance of 28-1/16" from the telescope. Other than a few exceptions (to broaden the beam, for example), this workpiece distance was maintained for all welds through 948. Between this weld and the next series for this program, starting with 1569, the telescope was readjusted and a slightly different distance was used for these later runs. The determination of the new optimum workpiece distance is discussed in Section V-C, p. 23.

2. Feed Rate

At a power level of approximately 15 kW, and a work distance of 28-1/16", welds were made at feed rates varying from 130 IPM to 200 IPM. While the gas shielding parameters were not maintained exactly the same for this series, (mostly because of the hood modifications) the general result indicated that good penetration was achieved at speeds of approximately 160 - 175 IPM.

In addition to the "NASA" type gas shielding hoods, three other types were used. An off-axis gas nozzle successfully used with low carbon steel was tried because of its simplicity in construction and use. While it gave respectable values of penetration, it produced an upper bead that was much too rough to be acceptable. The second type of gas hood, designated hood 6-A and discussed earlier, also produced unacceptably rough welds. While acceptable bead appearance and penetration was obtained using a side

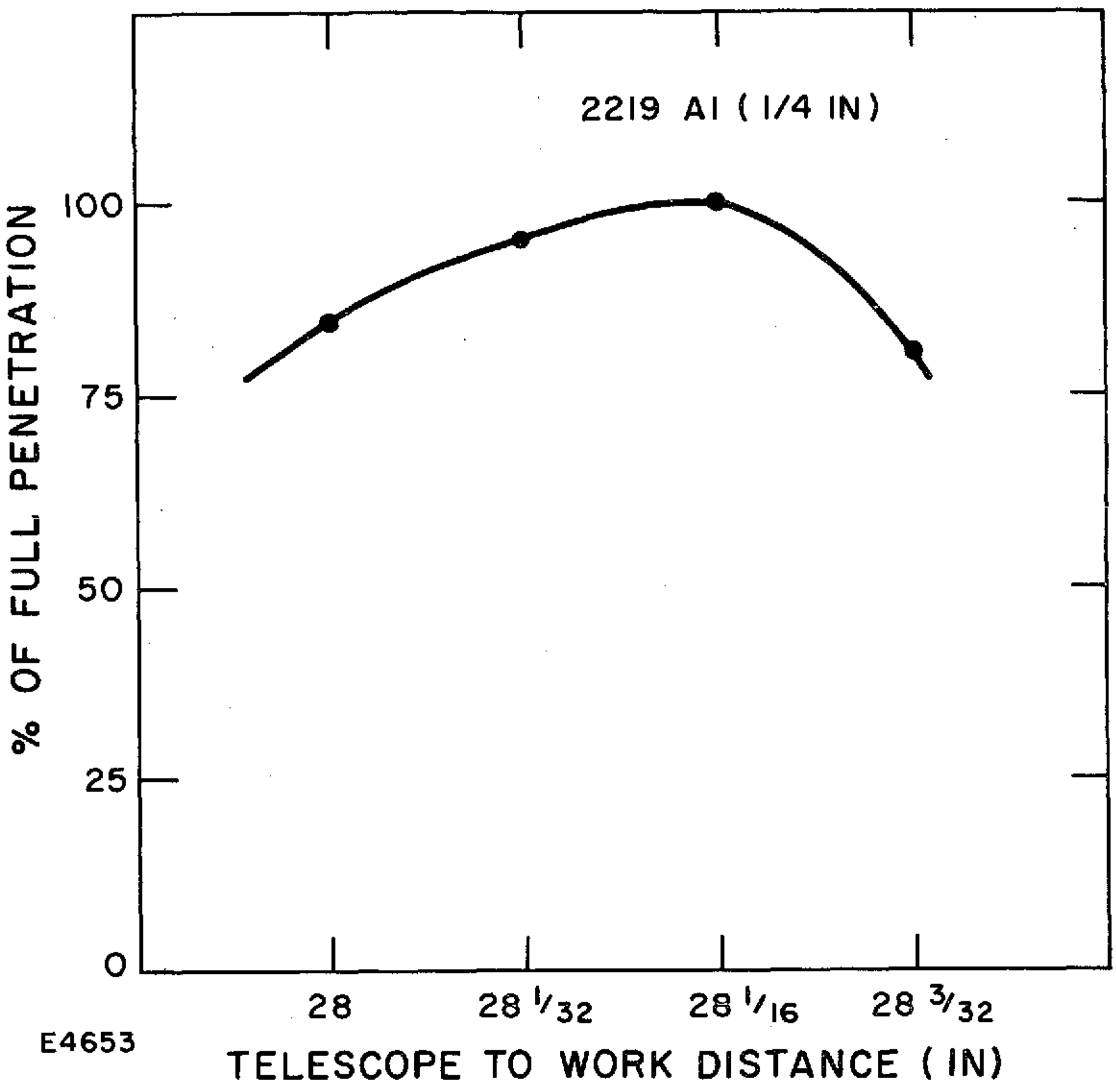


Fig. 6 Variation of Penetration with Telescope to Work Distance for 1/4" Aluminum

TABLE I

SUMMARY CONDITIONS AND RESULTS FOR TASK I WELDS

Run No.	Mat'l	P	S	F	Hood	Shielding Gas: Upper	Shielding Gas: Lower	Edge Prep	Results
278	1/4 Al	14.5	130	28 1/16	off axis	50 He, 15 Ar	4 He, 6 Ar	Scrape	EP; RTB
279		14	130						EP; RTB
280			200	28					LOP (90%)
281		15							IP
282								Kellers etch & scrape	IP, joint opened up
283		16				50 CO_2			Large plasma ball, little pen.
284A						30 CO_2			" " " " "
284B						20 CO_2			" " " " "
285		15			NASA 1	40 He, 10 Ar			LOP (80%), STB
286			175					Scrape	LOP (95%), STB
287									LOP (95%), STB, hood damaged
288				27 15/16	6A	Jet: 40 He, 28 Ar Trailer: 25 Ar			LOP (75%), RTB
289A				28 1/16					Little penetration
289B						Jet: 50 He, 5 Ar Trailer: 25 Ar			IP, RTB
290						Jet: 50 He Trailer: 25 Ar			IP, RTB
291					NASA MI	50 He, 5 Ar	6 Ar		GP first 4", then LOP hood damaged
292									GP, hood damaged
293					NASA 2		10 He		LOP (80%), hood burned out
294					NASA MI				IP, STB
295								0.004" shims in joint	GP, STB
296				28			25 He		LOP (75%), STB
297			160						LOP (90%), STB
298								Kellers etch & scrape	IP, STB
299			175			55 He		Scrape	IP, hood hung up on weld
300						75 He	15 He		IP, hood hung up on weld
303				28 1/16		40 He, 30 Ar	6 He	Scrape & tack	IP, STB

P = Power (kW)
S = Welding Speed (IPM)
F = Telescope to Work Distance (in.)

EP Excessive Penetration
GP Good Penetration
IP Intermittent Penetration
LOP Lack of Penetration
POR Porosity
STB Smooth Top Bead
RTB Rough Top Bead

TABLE I (Cont.)

SUMMARY CONDITIONS AND RESULTS FOR TASK I WELDS

Run No.	Mat'l	P	S	F	Hood	Shielding Gas: Upper	Shielding Gas: Lower	Edge Prep	Results
304	1/4" Al	15	175	28 1/16	Side manifold	200 He	6 Ar	Scrape & tack	IP, STB
305									IP, STB
306		14							Broke tack weld
307								Scrape & stronger tack	IP, STB
308		16			NASA M2	40 He, 10 Ar			GP, STB
309									GP, STB solder in hood diffusing
310*						50 He, 10 Ar			GP, narrower top bead, hood hot
311						3.5 Ar			GP, narrower top bead, damaged hood
312				28	NASA M3	40 He, 10 Ar			LOP (85%), STB
319				28 1/32					LOP (95%), STB
320				28 3/32					LOP (80%), STB
321				28 1/16					GP, STB
322			140	28 1/16					EP, STB
323		13							IP, STB, damaged porous bronze
324						60 He, 14 Ar			EP, blow holes in weld
325						35 He, 8 Ar			Improper joint alignment
326									Melted chimney in hood
327					NASA M4				Melted chimney in hood more
329	1/4" Stal	15	120		6A	Jet: 50 CO_2 Trailer: 60 CO_2		Acetone cleaned & tack	Large plasma, little penetration
330						Jet: 30 CO_2 Trailer: 60 CO_2			Large plasma, little penetration
331						Jet: 50 He Trailer: 60 CO_2			LOP, STB
332A			100					BOP	LOP, STB
332B		16							IP, STB
333A								Acetone cleaned & tack	LOP, evidence of cracking
333B		17							LOP, evidence of cracking
333C							10 He		LOP, evidence of cracking

*Shipped to MSFC.

P = Power (kW)
S = Welding Speed (IPM)
F = Telescope to Work Distance (in.)

EP	Excessive Penetration
GP	Good Penetration
IP	Intermittent Penetration
LOP	Lack of Penetration
POR	Porosity
STB	Smooth Top Bead
RTB	Rough Top Bead

TABLE I (Cont.)

SUMMARY CONDITIONS AND RESULTS FOR TASK I WELDS

Run No	Mat'l	P	S	F	Hood	Shielding Gas Upper	Shielding Gas Lower	Edge Prep	Results
334A	1/4" steel	10	60	28-1/16	6A	Jet:50 He Trailer:50 CO_2	10 He	acetone cleaned & tack	IP, cracking
334B			52						GP, cracking
334C			44						GP, no cracking
335A		17	80			Jet:50 He Trailer:50 Ar			GP, cracking
335B		13	60					(poor fit up)	GP, RTB, undercut
335C									GP, GTB, no cracking
336			70						GP, GTB, no cracking
337		16	150					900°F preheat	LOP
338			120						IP
339			100						GP, but light
340		18							GP
344*			90			Jet:75 He Trailer:50 CO_2		550°F preheat	400°F, 20 min post heat, GP
761A	1/2" steel	14.5	37				10 Ar	tack and 700°F preheat	GP, beam misaligned to point
761B									GP, beam misaligned to point
761C								tack	GP, cracking
762								BOP	LOP
763A								tack & 350°F preheat(1)	GP, TB (piece was in oven 24 hrs)
763B*								tack & 350°F preheat(1)	GP, STB, sent out for X-ray
763C						Jet:80 He Trailer:50 He		tack & 450°F preheat(1)	GP, STB
763D			40					tack & 600°F preheat(1)	GP, STB
771	1/4" Al	15	175		NASCO	40 He, 10 Ar	6 Ar	BOP	Large plasma ball, little pen
772								scrape and tack	GP, STB
773A	1/2" Al		85					scrape and tack	LOP(.370") POR at bottom

*Shipped to MSFC.

P = Power (kW)
S = Welding Speed (IPM)
F = Telescope to work distance (in.)

EP Excessive Penetration
GP Good Penetration
IP Intermittent Penetration
LOP Lack of Penetration
POR Porosity
STB Smooth Top Bead
RTB Rough Top Bead

TABLE I (Cont.)

SUMMARY CONDITIONS AND RESULTS FOR TASK I WELDS

Run No	Mat'l	P	S	F	Hood	Shielding Gas Upper	Shielding Gas Lower	Edge Prep	Results
773B	1/2" Al	15	60	28-1/16	NASCO	40 He, 10 Ar	6 Ar	scrape and tack	LOP (.37" - .44") POR at bottom
773C			50						LOP (.37 start, full end)
773D								"rough" flycut	LOP (.37" - .44") very POR
773E								.015 "V" gap	LOP (.37" - .44") very POR
774								.040 "V" gap	.44 to EP, drop through
776A					6A	Jet:40 He, 10 Ar Trailer:25 Ar		.015 "V" gap	IP, drop through, RTB
776B			85			Jet: 60 He Trailer:15 Ar			IP, RTB, hood very hot
776C						Jet:75 He Trailer:15 Ar			LOP (.45) RTB
776D						Jet:50 He Trailer:15 Ar			LOP, RTB
776E						Jet:100 He Trailer:15 Ar			LOP, RTB, less plasma
776F						Jet:75 He Trailer:15 Ar		(run in reverse direction)	smoother bead, LOP(7/16") POR
781A						Jet:80 He Trailer:15 Ar		Butt, 12° lagging angle	LOP (3/8) RTB
781B			60			O		Butt, 12° lagging angle	large plasma, LOP (0.2")
781C						Jet:60 He Trailer:15 Ar		Butt, 12° lagging angle	LOP (.45") RTB
781D								Butt, 12° lagging angle and Kellers etch	LOP (.45") RTB
781E								Butt, 12° lagging angle and nut scraped	LOP (.45") RTB
781F			55					Butt, 12° lagging angle and nut scraped	LOP (.45") RTB
894A		17	60		NASCO	60 He	6 He	scrape and tack	LOP (.4") STB, POR
894B			50					scrape and tack	LOP (.45") STB, POR
895A			45						IP, but drop through at full pen
895B			50			100 He			LOP (.45) STB

P = Power (kW)
S = Welding Speed (IPM)
F = Telescope to work distance (in.)

EP Excessive Penetration
GP Good Penetration
IP Intermittant Penetration
LOP Lack of Penetration
POR Porosity
STB Smooth Top Bead
RTB Rough Top Bead

TABLE I (Cont.)

SUMMARY CONDITIONS AND RESULTS FOR TASK I WELDS

Run No.	Mat'l	P	S	F	Hood	Shielding Gas Upper	Shielding Gas Lower	Edge Prep	Results
896A	1/2 "Al	19	50	28 1/16	NASCO	60 He	6 He	Scrape & Tack	LOP (3/8")
897		17				150 He			IP
898A						200 He			IP,
899				28					GP first half, LOP rest
902				27 31/32					LOP (3/8)
903				28		250 He			LOP (7/16) first half, drop through rest
904				27 7/8		150 He, 44 Ar			LOP (3/8 - 7/16) STB
905A									LOP (3/8 - 7/16) STB
905B				27 15/16					LOP (7/16) STB
906				28					LOP (7/16) STB
909								Sand blasted & tack	LOP (7/16) STB
911								Kellers etch & tack	LOP (7/16) RTB
912		40						scrape & tack	LOP (7/16) RTB
939	7/16 "Al	18	50						GP, STB, POR
940			60			0	0		big plasma ball, LOP
941						150 He	44 Ar		GP, STB, POR
942									LOP, STB, POR
943									GP, STB, POR
948									LOP, STB, POR
1569A	3/8 Al	15	80	28 3/16[1]					EP, POR (4/in, 1/16 " dia)
1569B			90					Alcanox wash	IP, POR (20/in)
1569C		12	60						GP, POR (10/in)
1574A		13							EP, POR, bad undercut
1574B[2]		12.4							EP, POR (4/in)

(1) F/7 telescope re-mounted, resulting in change of work distance for max penetration from 28 1/16" to 28 3/16".

(2) Cleaned entire underbead shielding.

P = power (kW)
S = welding speed (IPM)
F = telescope to work distance (in.)

LOP Lack or Penetration
POR Porosity
EP Excessive Penetration
GP Good Penetration
IP Intermittant Penetration

POR porosity
STB smooth top bead
RTB rough top bead

TABLE I (Cont.)

SUMMARY CONDITIONS AND RESULTS FOR TASK I WELDS

Run No.	Mat'l	P	S	F	Hood	Shielding Gas Upper	Shielding Gas Lower	Edge Prep	Results
1583A	1/4 Al	15	165	28 3/16	NASCO	50 He, 12 Ar	10 He	Scrape & Tack	GP, no POR, STB
1583B		14							LOP near middle, no POR, STB
1583C		16							EP, undercut, no POR
1583D	3/8 Al	15	80						GP, STB, POR (12/in, 1/16" dia)
1592B		13						BOP 300°F preheat	IP, STB, POR (15/in, 1/16" dia)
1592D								BOP 400°F preheat	GP, STB, POR (11/in, 1/16"dia)
1592E		15						Butt, scrape & tack	GP, STB, POR (11/in, 1/16"dia)
1598A	1/2 steel		35	28 1/16	6 A	Jet 80 He Trailer 25 Ar		BOP	0.441
1598B				28 1/8					0.468
1598C				28 3/16					0.470
1598D				28 1/4					0.465
1598E				28 5/16					0.459
1600A-1			34	28 7/32				Butt, tack	GP, crack after 3 hrs
1600A-2			30						GP, crack after 3 hrs
1600B-1			37						GP
1600B-2			40						LOP
1600C	(24")		39					500°F preheat & tack	IP
1601A			35					450°F preheat & tack	EP
1601B			37					400°F preheat & tack	IP
1613C			35				6 He	450°F preheat & tack	EP, undercut
1613D			37						misaligned: missed joint
1613E						Jet 80 He Trailer 50 Ar			GP

P = power (kW)
S = welding speed (IPM)
F = telescope to work distance (in.)

EP excessive penetration
GP good penetration
IP intermittant penetration
LOP lack of penetration
POR porosity
STB smooth top bead
RTB rough top bead

delivery gas shield (welds 304 - 307), this approach was not pursued because of the difficulty and impracticality of this type of shielding.

3. Shielding Gas Composition

Combinations of helium, argon and carbon dioxide were tried in several hoods. As observed from welds 283, 284A and 284B, CO_2 delivered from the off-axis nozzle always produced a strong plasma interaction with the aluminum, and minimal penetration resulted. Excessive argon also produced the same result. For example, in welds 288 and 289A, 28 CFH argon was mixed with 40 CFH helium for use in the jet of hood 6A. The result was very little penetration and significant plasma formation. Using the NASA type hoods, care was taken to avoid too much argon because the result was bound to be excessive plasma formation, which, with this hood, was guaranteed to cause severe diffuser damage.

With regard to underbead shielding, previous experience indicated that moderate amounts of helium or argon were adequate.

4. Shielding Gas Flow Rate

Having limited hood configurations to the NASA type, and gas compositions to mixtures of helium and argon, several flow rates and mixture ratios were tried (welds 308 - 311, 323 - 326). Too much argon would cause ionization, and too little would not counteract the natural buoyancy of the light helium, resulting in air contamination. The best values were 50 CFH helium and 12 CFH argon.

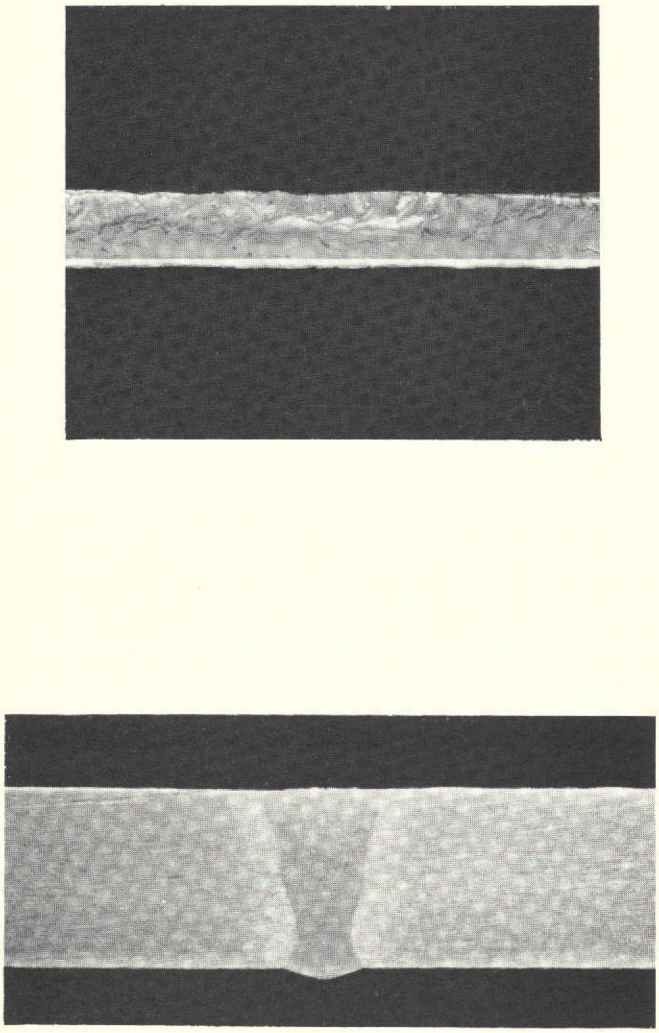
5. Miscellaneous

In addition to the above parametric tests, a weld was made with a 0.004" gap between plates (weld 295). A slightly greater level of penetration was achieved, but otherwise there was no difference in bead appearance. Also in an attempt to improve absorptivity, Kellers' etch was applied to the faces of the plates in welds 282 and 298. No significant effect was observed.

6. Results

Based on the foregoing studies, the following conditions were tentatively chosen as optimum for welding the 1/4" 2219 aluminum at a laser power of 16 kW: Feed: 175 IPM; Work Distance: 28-1/16"; Hood: NASA Type; Upperbead shielding: 50 CFH helium, 10 CFH argon; Underbead shielding: 6 CFH argon or 10 CFH helium. Weld No. 310 was made at these values. However, the conditions were slightly modified later in the program (runs 1583A, B and C) after the NASCO hood was operational. The power was reduced to 15 kW and the feed reduced to 165 IPM. Also the work distance was changed to 28-3/16" to compensate for the telescope readjustment.

1/4" Al 2219



E4720

Fig. 7 Cross-Sectional View and Face View of Broken Weld in 1/4" 2219 Aluminum Welded at 165 IPM

One-half of weld No. 310 was selected for X-ray and tensile testing and the other half was sent to MSFC for their evaluation. In both cases the results were the same: water clear X-rays and yield strengths of approximately 44 ksi. Compared to a T6 base metal strength of 63 ksi, this corresponds to approximately 70% joint efficiency. At a speed of 175 IPM and a laser power of 15 kW (which, because of losses in the beam manipulator, and some surface reflection, results in approximately 10 kW into the aluminum), this corresponds to an energy input of approximately 2.45 kJ/in.

A photograph of an etched cross section and a face view of a broken weld is shown in Fig. 7. No porosity is apparent.

B. STEEL, D6AC, 1/4 INCH

Based on previous experience with other types of steel, the only shielding hood to be used was the 6-A hood. Also, the telescope-to-work distance was maintained at the 28-1/16" value established for the aluminum. The main parameters investigated were preheat, feed rate, power, shielding gas composition and flow rate.

1. Preheat, Power and Feed Rate

Plotted in Fig. 8 is the feed rate vs laser power for penetration of the 1/4" D6AC steel under both no preheat and 900°F preheat conditions (welds 334B - 340). Cracking of the welds developed within minutes at both high and low powers on some welds (334B, 335A) but not on others (334C, 335C, 336). However, no cracking was observed with either 900°F or 550°F preheat. All future welds in this material were performed with at least 400°F preheat and no further cracking problem occurred.

2. Shielding Gas Composition and Flow Rate

Several welds were made using CO_2 as the jet gas for hood 6-A. The motivation was the lower cost of CO_2 compared to helium. However, in both cases (329, 330), very low penetration and a large visible plasma formation resulted. All other welds were therefore made with a helium jet at 50 - 75 CFH.

Both argon and CO_2 appeared to work equally well as a shielding gas in the trailer shield of hood 6-A, and were used interchangeably at flow rates of 50 - 60 CFH.

3. Results

At a laser power level of 18 kW, a feed rate of 90 IPM and a preheat of 550°F, X-ray clear welds were made in the 1/4" D6AC steel using hood 6-A with a 75 CFH helium jet, 50 CFH CO_2 trailer gas shielding and 10 CFH argon underbead shielding. Run No. 344, made at these conditions, was normalized at 1600°F and tempered at 750°F for 30 min. and air cooled. Half of this weld was sent to MSFC for their evaluation and the other half

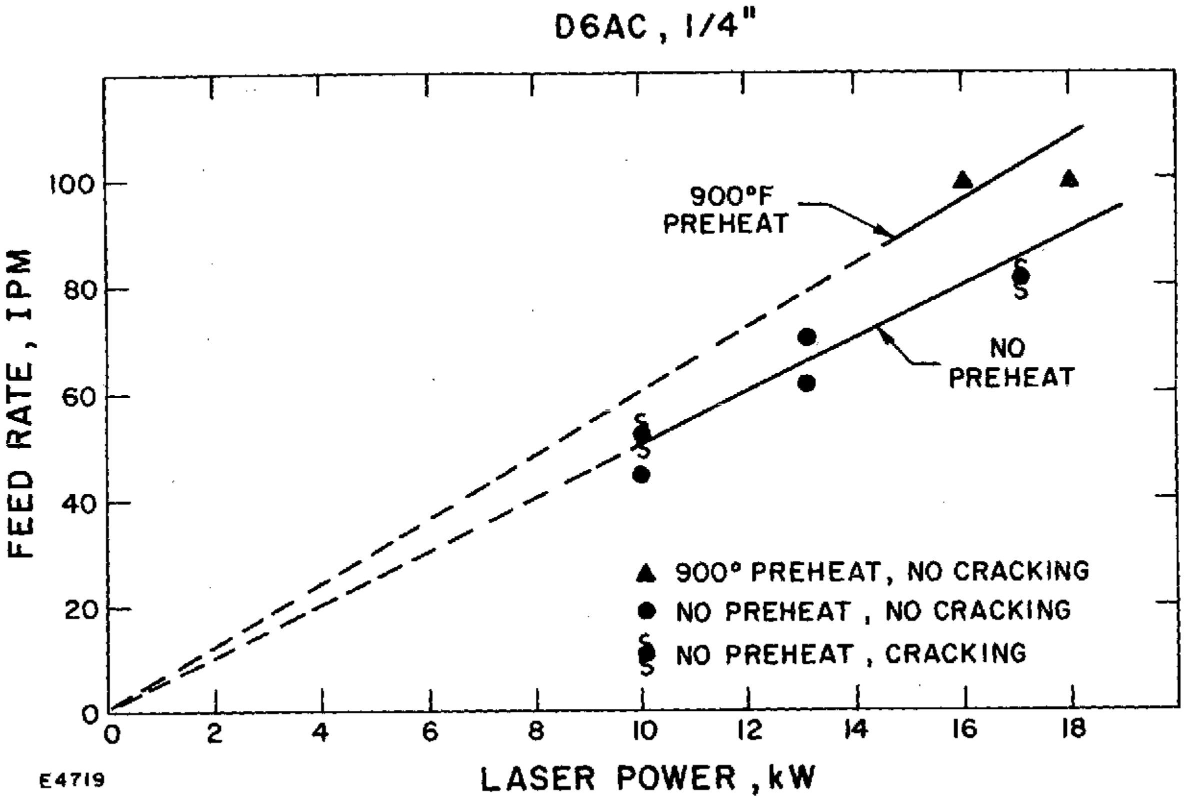


Fig. 8 Variation of Full Penetration Feed Rate with Laser Power in 1/4" D6AC Steel with no Preheat and 900°F Preheat

tensile tested at Sciaby. In both cases, failure of the tensile specimen occurred well outside the weld and heat affected zone.

Figure 9 shows an etched cross section of weld No. 344 and a face view of an unpreheated weld that cracked. In neither case is there any indication of porosity, except in the partial penetration regions near the beginning of the weld.

C. STEEL, 1/2 INCH D6AC

Based on the cracking experience with the 1/4" D6AC steel, only one attempt to weld in an unpreheated condition was made in the initial optimization study of this material. This weld, No. 761C, cracked shortly after being welded. A face photo of it is shown in Fig. 10. From this photo it is seen that the full penetration region appears to be free of any porosity. However, during the first half inch, in which the penetration increased from zero to the full half inch, porosity is observed near the weld root.

Preheat values of 350°F, 450°F and 600°F were used. Except for one weld (763A, which was kept in the air-filled oven at 350°F overnight, resulting in a significant oxide buildup and poor top bead appearance), all values of preheat yielded good welds, with acceptable bead geometrics. The laser power for these welds (763B, C and D) was 14.5 kW, at a feed rate of 37 IPM to 40 IPM. Hood 6-A, with a helium jet of 80 CFH, and a trailer helium shielding gas at 50 CFH, was used. A 6 CFH argon underbead gas was used. The telescope-to-workpiece distance was maintained at the 28-1/16" value determined from the 1/4" welds. A water clear X-ray of weld 763B was made, and the weld itself was sent to MSFC for their evaluation. A cross section of weld 763D is shown in Fig. 10.

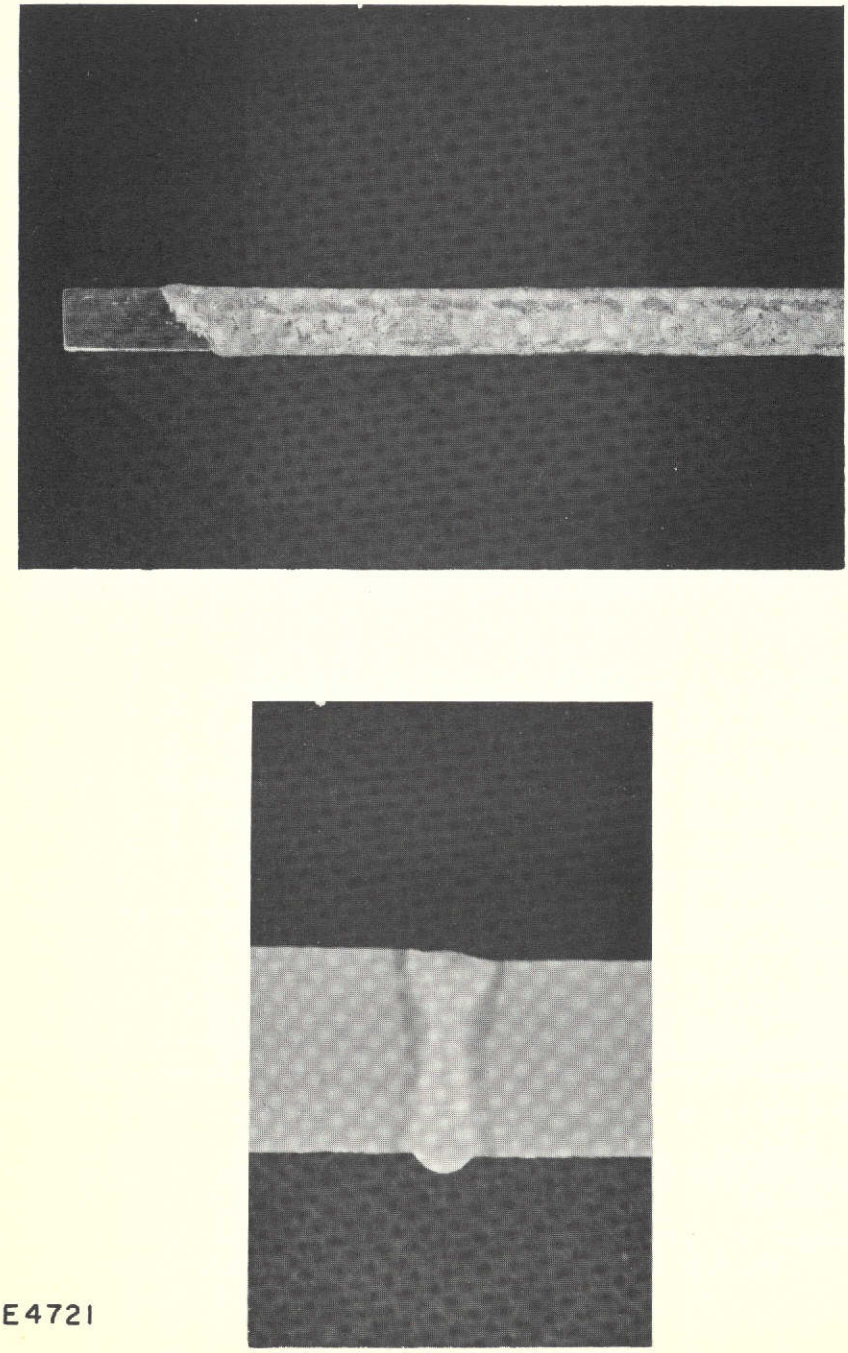
A second optimization series was run on this material just prior to welding the 24" panels for Task II. This series was run after the telescope was readjusted. To check the optimum telescope-to-workpiece distance, a BOP series was performed at work distances varying from 28-1/16" to 28-5/16" (welds 1598A - 1598E). The result, plotted in Fig. 11, shows a relatively constant penetration at work distances from 28-1/8" to 28-5/16".

Several additional attempts to obtain good welds without preheat were made at a power of 15 kW and speeds of 30, 34 and 37 IPM. Two out of these three welds cracked within several hours of being welded. This result reinforced the conclusion of the earlier study that preheat is needed to weld this material reliably. Several additional welds were then made using a preheat of 450°F and gas shielding similar to that used for the first series. In general, the earlier results were duplicated.

D. ALUMINUM, 1/2 INCH 2219

The optimization study for this material involved the following parameters: power, work distance, joint design and impingement angle. Within each of these studies, variations in feed rate and shielding gas flow rate

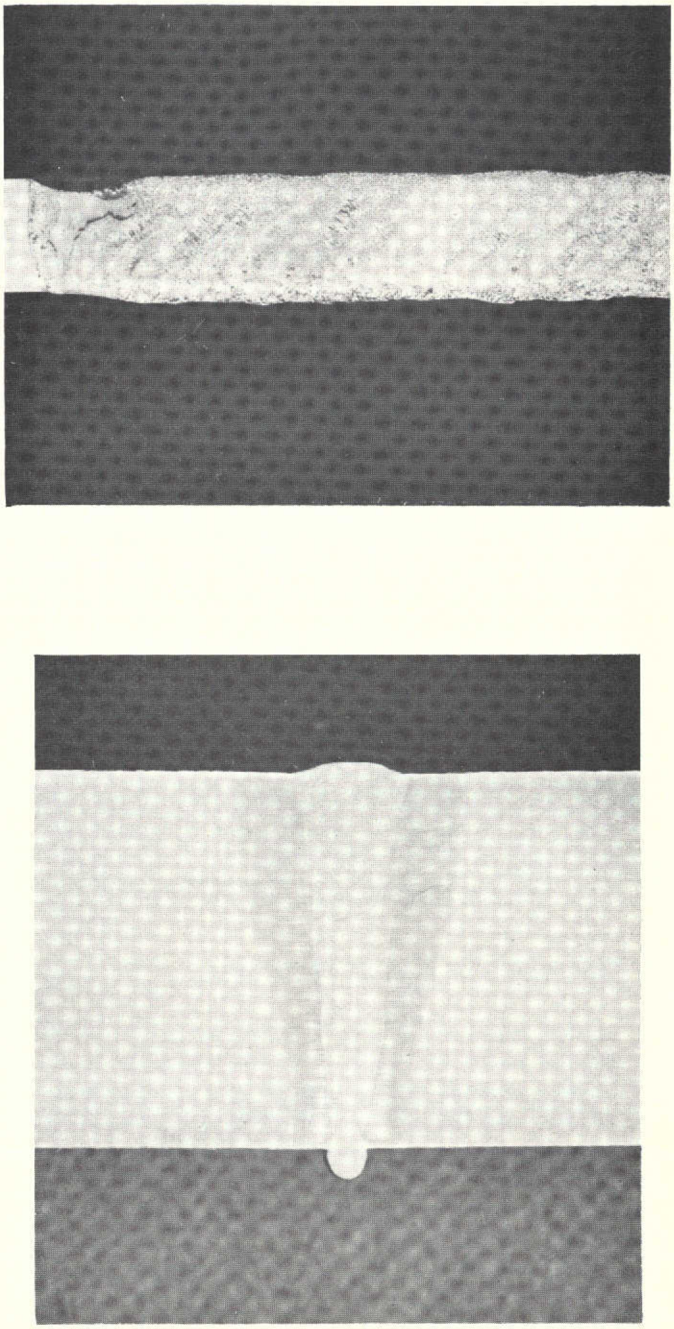
1/4" D6AC STEEL



E4721

Fig. 9   Cross-Section View and Face View of Cracked Weld in 1/4" D6AC Steel Welded at 100 IPM

1/2" D6AC STEEL



E4722

Fig. 10 Cross-Sectional View and Face View of Cracked Weld in 1/2" D6AC Steel Welded at 40 IPM

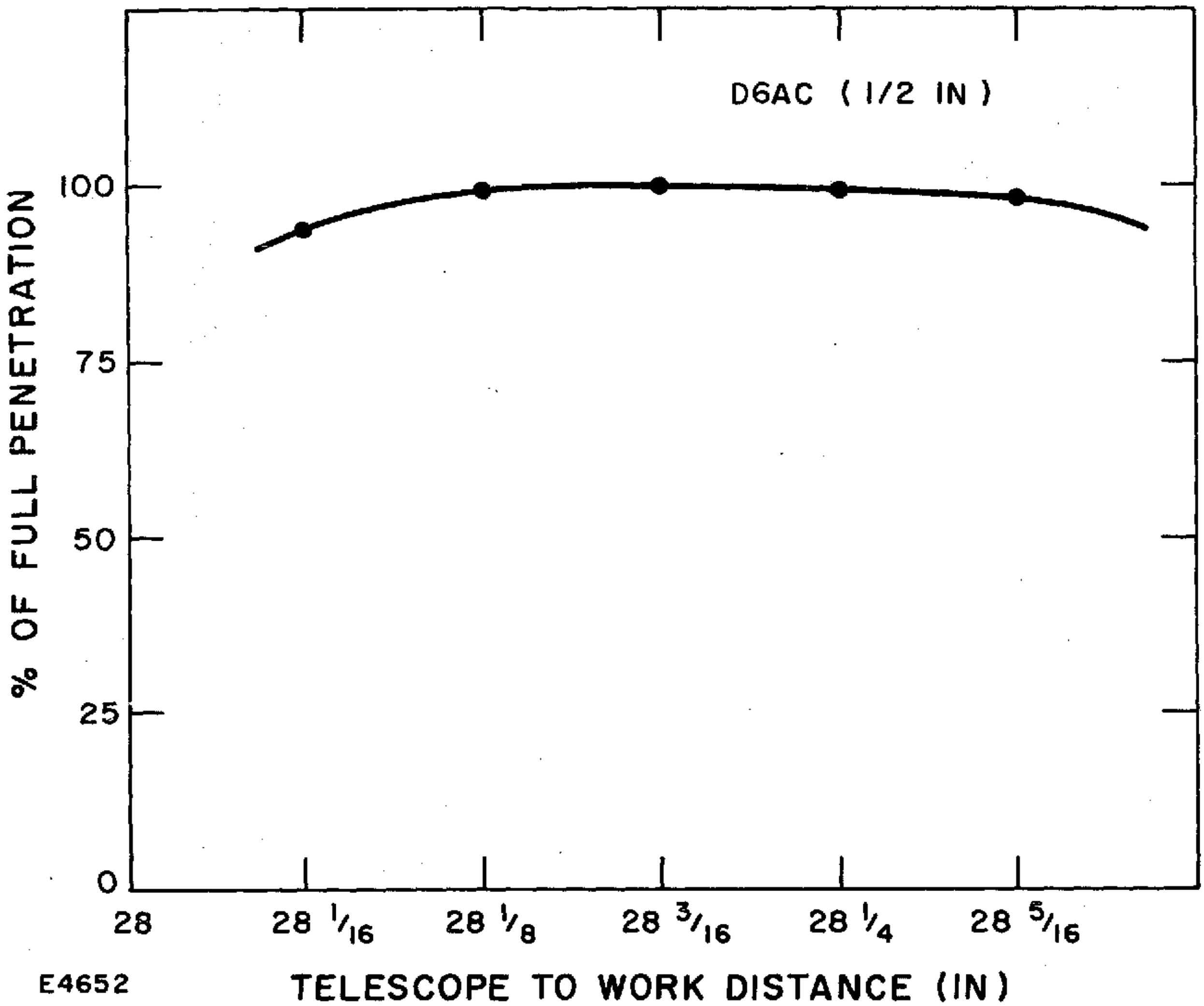


Fig. 11 Variation of Penetration with Telescope to Work Distance for 1/2" D6AC Steel

were made when indicated to improve the weld quality. In addition, the edges of the 1/2" material were milled down to 7/16", then to 3/8" to observe the influence of material thickness on weld quality. For the 3/8" thickness, the aluminum was preheated to decrease solidification rates. Both the NASA type hood and hood 6-A were used.

1. Joint Design

Since one of the most easily identified problems with 1/2" aluminum was to fully penetrate at speeds high enough to prevent excessive dropthrough, an attempt to augment penetration at higher feed rates was made by using a "V" shaped joint, with 0.015" opening at the top. Intermittent penetration could be achieved at 85 IPM, compared to 50 IPM with a tight butt joint. These welds (773E through 776F) were made at a laser power of 15 kW with hood 6-A. In general, this hood allowed deeper penetrations than the NASCO hood, which appeared to limit penetration to 3/8" for a tight butt joint at 50 IPM. However, with a jet flow rate sufficiently high to minimize the plasma formation (75 - 100 CFH helium) the disturbance of the upper bead was excessive. A slightly better, but still unacceptable bead geometry resulted from reversing the welding direction (weld 776F) thereby directing the helium jet along the already welded metal.

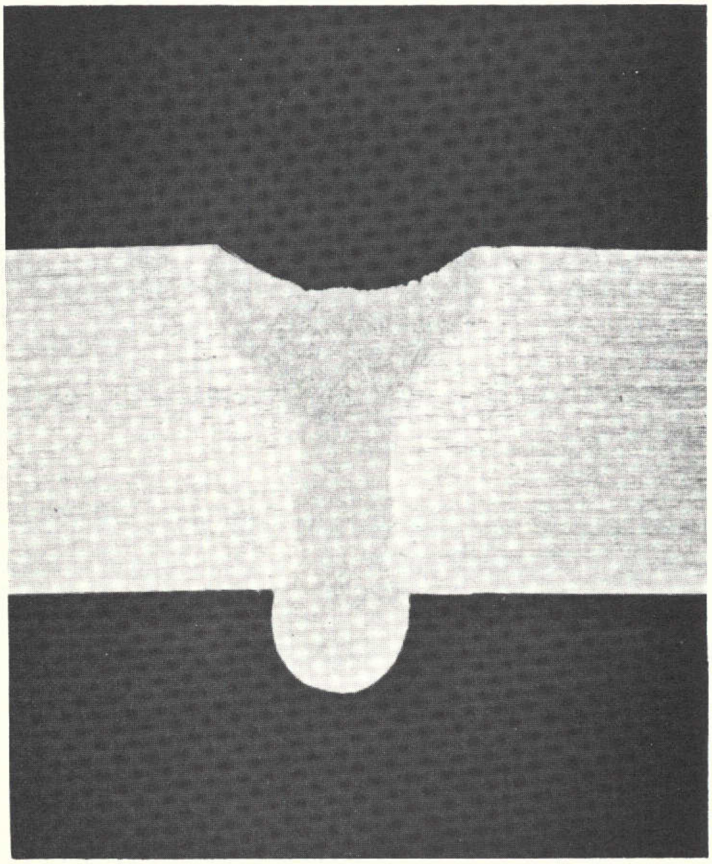
2. Impingement Angle

Before returning to the NASCO hood, it was decided to investigate the effect of changing the beam angle of incidence. To accomplish this, a small traversing table was mounted on the milling machine base, but tipped 12° from the horizontal. The plates to be welded were mounted on this table and moved in the downhill direction for welding, thereby employing a lagging beam impingement angle. Six welds were made with this setup (welds 781A - 781F). For one weld (781B) the gas shielding was accidently not turned on, and the resulting plasma and negligible penetration underlined the necessity of maintaining a gas flow across the weld point. Two welds, 781E and F, were made without scraping the surface of the aluminum. Another (781D) was made with Kellers' etch applied to the plate edges. None of these measures made any significant difference in the penetration, top bead smoothness, or the porosity. In all cases the penetration was limited to 0.4 - 0.45 inch, the upper bead was unacceptably rough and there was an excessive amount of porosity, especially near the weld root.

3. Power and Focus Work Distance

In a second attempt to weld fast enough to prevent excessive dropthrough, the laser power was increased up to 19 kW. Also, the work distance was decreased from 28-1/16" to 27-15/16". The NASCO hood was used for this series (894A - 912) because of the resulting smooth upper bead. The results, however, were the same; intermittent penetration, excessive dropthrough at full penetration and porosity. A typical cross section showing moderate, but still unacceptable dropthrough is shown in Fig. 12. This cross section was made at a position in the weld just after full penetration was achieved, but before the dropthrough became excessive.

1/2" Al 2219



E4723

Fig. 12 Cross Section of 1/2" 2219 Aluminum Welded at 50 IPM

4. Decrease in Thickness to 7/16 Inch

A series of 6 welds (939 - 948) was made in aluminum for which the edges to be welded were milled to a thickness of 7/16". These welds were made with the NASCO hood at 18 kW and, with one exception, at 60 IPM. In general, the 1/16" decrease in thickness was sufficient to prevent the excessive dropthrough experienced with the full 1/2" material. Thus, nice looking, consistent, smooth top and underbeads were achieved. However, the welds when broken open had an excessive level of porosity. Both of these characteristics can be seen in Fig. 13 which shows a cross section and a face view of a broken weld. A porosity level of about 15 - 30 pores per inch, each about 1/16" in diameter, can be seen.

5. Decrease in Thickness to 3/8 Inch

Since the 1/4" welds were free of porosity and the 7/16" welds had excessive porosity, it was decided to reduce the thickness of the half-inch plates to 3/8". The first series of five welds (1569A - 1574B) was made at a power of 12 to 15 kW with the NASCO hood at feed rates of 60 to 90 IPM. The bead geometry and consistency were good, but when broken open, substantial porosity (4 - 15 pores per inch) was evident. At this point it was decided to weld again the 1/4" aluminum to be sure the resulting welds were porosity free, as they had been in the earlier series. Thus welds 1583A - 1583C were made in the 1/4" plate at powers of 14, 15 and 16 kW and a feed rate of 165 IPM. As before, welds with a good bead geometry, with no apparent porosity, were obtained.

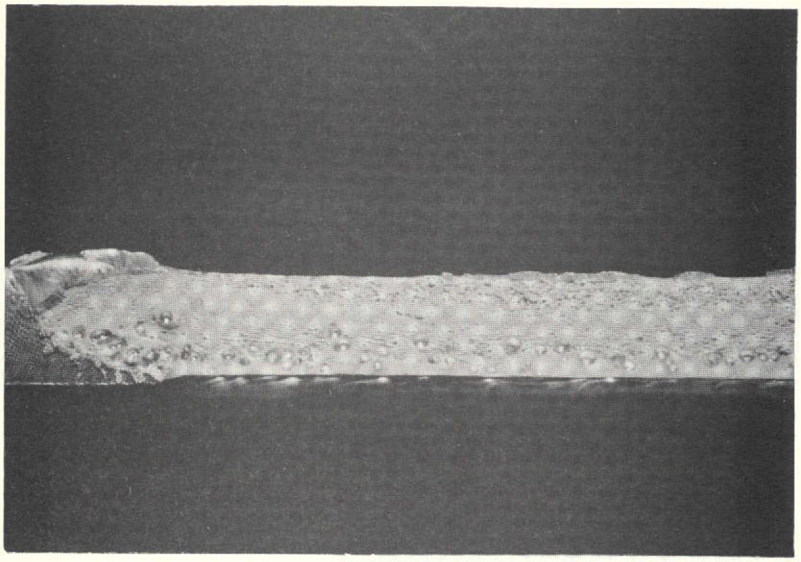
A final welding series (1592B - 1592D) on the 3/8" aluminum plate was made using plates preheated to temperatures up to 400°F. It was reasoned that if the porosity was due to an entrainment of shielding gas, using preheated plates would decrease the solidification rate and allow the gas to escape from the molten metal. However, the resulting BOP welds showed the same porosity characteristics as the nonpreheated welds.

Figure 14 shows a typical cross section and face view of the 3/8" welds.

6. Results

The general results for the heavy aluminum welds are: the NASCO hood provides a smooth bead geometry; intermittent penetration with excessive dropthrough in the full penetration region occurs in the 1/2" thickness; a good, consistent bead geometry can be achieved with both the 7/16" and the 3/8" thicknesses, but these welds exhibit excessive porosity near the weld root.

7/16" Al 2219



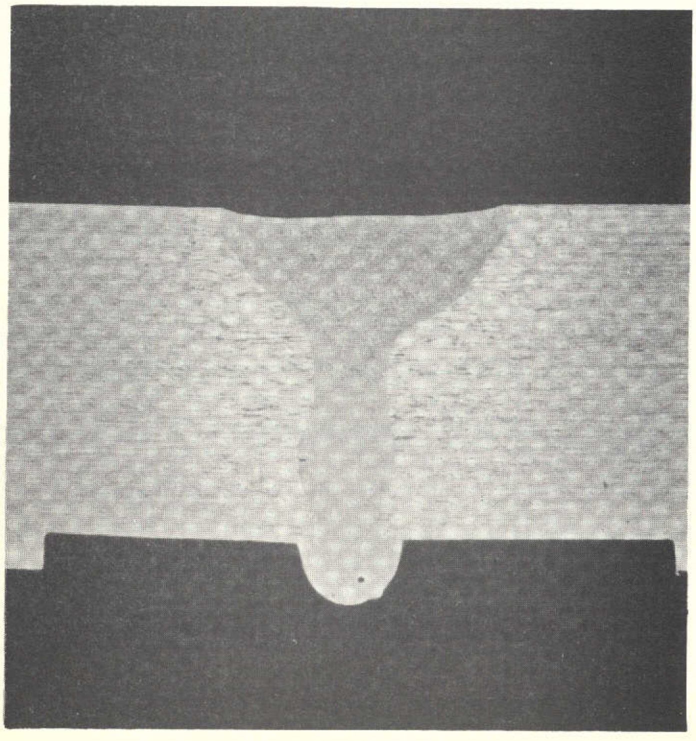


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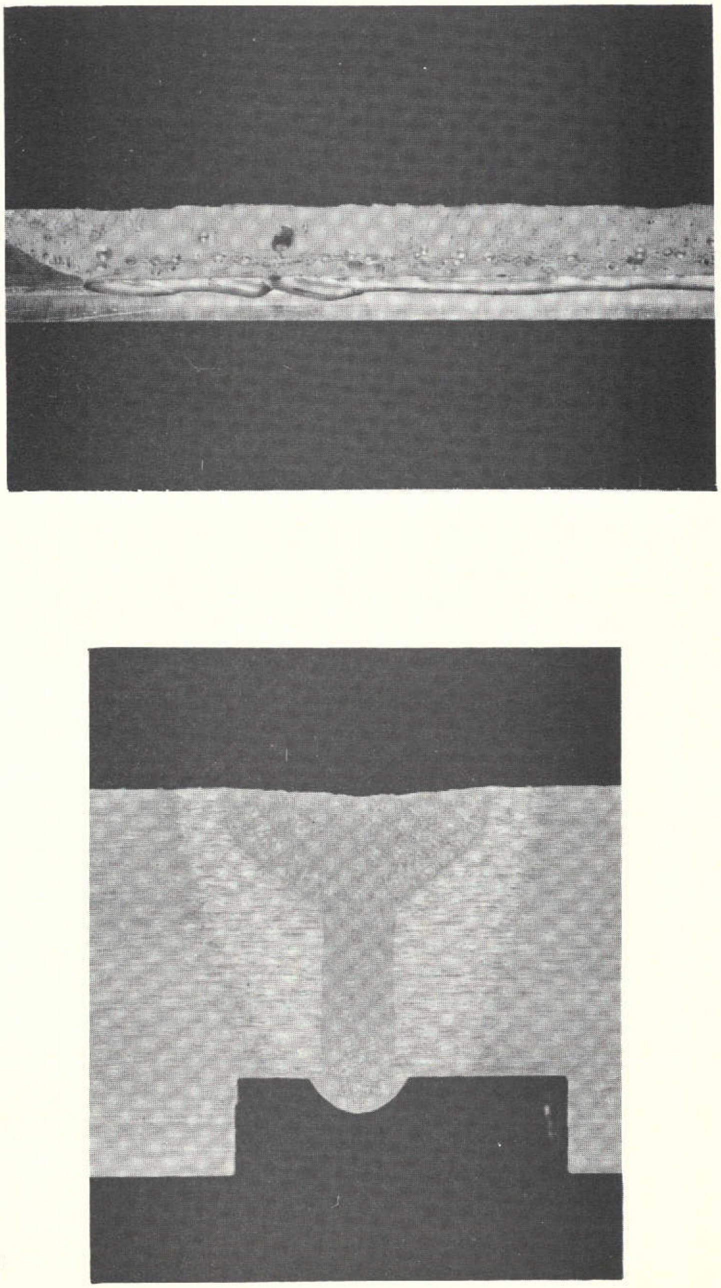
Fig. 13 Cross Section and Face View of Broken Weld in 7/16" 2219 Aluminum Welded at 60 IPM

3/8" Al 2219



E4725

Fig. 14 Cross Section and Face View of Broken Weld in 3/8" 2219 Aluminum Welded at 80 IPM

VI. PLATE WELDING (TASK II)

Based on the parameter study of Task I, optimum conditions were chosen for producing 16" long welds in the 24" panels supplied by MSFC. Such welds were made in both the 1/4" and 1/2" D6AC, and in the 1/4" 2219 aluminum. Because of the lack of success in achieving porous-free welds in the heavier aluminum, no long welds were made in that material.

The welds were made using the previously described heavy duty welding fixture, shown in Fig. 2. All welds were tacked before welding.

A. STEEL, 1/2 INCH D6AC

The conditions chosen for this material were: power - 15 kW, feed - 36 IPM, work distance - 28-7/32", hood - 6A with 70 CFH helium jet and 50 CFH argon trailer gas, and 6 CFH helium for underbead shielding, and a preheating to 450°F before welding.

A total of 9 panels were welded, and six are being returned to MSFC. These panels are: 1614A, 1614B, 1615A, 1615B, 1616A, and 1616B. In all but one of these panels, the uniform bead geometry obtained during Task I in the 6" welds was not duplicated over the entire 16 inches of welding. In general, the beginning 6 to 10 inches were uniform, then the underbeads began to display a periodic drop through, resulting in underbead "drops" hanging about 0.2" to 0.3" below the plate, and occurring every inch or so. In panel 1615A, this phenomenon starts right at the beginning of the weld, and persisted throughout the entire length. On the other hand, weld 1616B exhibited a uniform underbead for the entire weld length. In one of the panels (1615B) the tack broke, causing excessive undercutting.

In two of the remaining panels, 1600C and 1619A, the excessive feed rate of 39 IPM caused intermittent penetration. The final panel, 1616C, exhibited severe drop through and undercutting.

B. STEEL, 1/4 INCH D6AC

The conditions selected for this material were: power - 15 kW, feed - 100 IPM, work distance - 28-7/32", hood: 6A with 100 CFH helium jet, 50 CFH argon trailer gas, and 10 CFH helium underbead shielding. These plates were preheated to 450°F.

A total of nine plates were welded under these conditions, and all but one are being sent to MSFC. These panels are: 1619B, 1620A, 1623A, 1623B, 1623C, 1624A, 1624B and 1624C. The remaining panel, 1620B, was rejected because a tack broke during welding. The bead geometry for all of these welds was very consistent.

C. ALUMINUM, 1/4 INCH 2219

The conditions selected for the 1/4" aluminum welds were: power - 15 kW, feed - 165 IPM, work distance - 28-3/16", hood - NASCO with 50 CFH helium and 12 CFH argon, and 10 CFH helium underbead shielding.

A total of 17 panels were welded. Since only 12 pairs of plates were available, a number of welds were cut out, and the plates re-welded. The reason so many panels were welded was the difficulty of obtaining a consistent bead geometry throughout the 16" welds. Occasional eruptions of the molten metal occurred during welding, resulting in holes in the weld, followed by short (1/8") areas of incomplete penetration. A number of procedure variations were tried, including edge scraping with a scraper instead of a file, the use of a shallow running tack instead of a series of point tacks, and a notch cut in the joint to prevent under-bead shielding gas from producing a positive pressure on the molten underbead. None of these measures was successful in eliminating the occasional holes in the weld, but the notching of the joints seemed to yield the best results. Consequently, the last nine welds were made under these conditions, and all are being returned to MSFC for their evaluation. They are: 1630D, 1630G, 1631A, 1631B, 1631C, 1631D, 1631E, 1631F and 1631G.

VII. WELD REPEATABILITY (TASK III)

As described in Section IV on Welding Procedure, the laser power and feed rate values are dialed into the control console before each weld is made. Because of the closed loop power control system on this laser (see Appendix I), the output power is stable and repeatable on a day-to-day basis within an accuracy of better than 2%. As a check on this repeatability, three cross sections were cut, one from each of three individual welds in 1/4" aluminum made at the same dial settings, but spaced over a period of approximately 75 hours. The three sections, from panels 1625A (a 6" setup panel), 1630D, and 1631G, are shown in Fig. 15. The reproducibility, as judged by the cross sections, appears quite good.

1/4" Al 2219

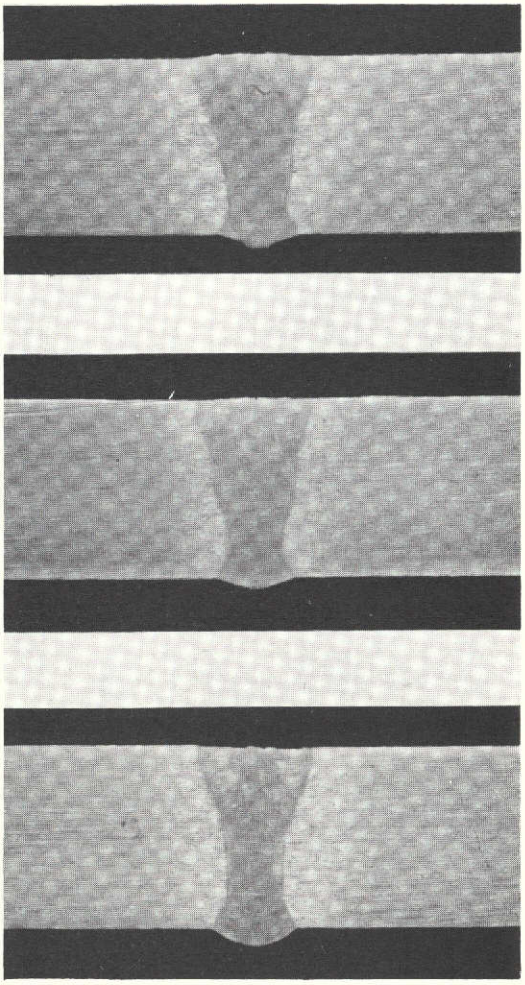


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Fig. 15 Three Cross Sections of Three Panels of 1/4" 2219 Aluminum Welded with Identical Dial Settings over a 72 Hour Period

VIII. CONCLUSIONS

Based on the results of this program, it can be tentatively* concluded that laser welding of D6AC steel in thicknesses up to 1/2" and 2219 aluminum up to 1/4" can be successfully accomplished with the Avco HPL industrial laser at a power of 15 kW.

For the D6AC steel, a limited amount of preheating ($450^{o}F$) is needed to prevent cracking. The resultant welds appear to be free of porosity. In the 16" welds of 1/2" material, however, "dropping" of the underbead occurred, usually part way through the weld. This is thought to be due to a slight degree of heat buildup ahead of the weld due to forward conduction from the previously welded metal. This being the case, a slight reduction in laser power after the weld is started might bring the problem under control. The 1/4" panels were extremely consistent and reproducible over the entire length. Preliminary tensile tests in both 1/4" and 1/2" samples resulted in fracture within the base metal, indicating a high quality weld.

The laser welds of short lengths (5") of 1/4" 2219 aluminum produced a consistent weld bead geometry, and yielded porous free welds which achieved a strength of approximately 70% of the base metal. When making the longer 16" welds, however, an occasional "blow holes" would occur, followed by a short region of lack of penetration. The cause of these faults are not known.

Heavier sections of aluminum, up to 1/2", could easily and regularly be penetrated. However, when 1/2" plate was fully penetrated, excessive drop through of the molten metal was observed. When section thickness was reduced to 7/16", a stable bead geometry was produced, but excessive porosity was observed near the weld root. Slightly less, but still excessive porosity was observed in 3/8" full penetration welds. The cause of this is not definitively known, but is probably due to the shape and dynamics of the keyhole, which cause molten aluminum to entrain and trap small amounts of shielding gas. Since the freezing rates are very rapid, the entrained gas is unable to escape from the molten metal.

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*Firm conclusions on weld quality must await the physical property tests which will be performed by MSFC on the welded panels delivered to them as part of this program. The tentative conclusions are based on visual weld appearance, very limited radiographic tests, and preliminary tensile tests performed on the short welds of Task I.

IX. RECOMMENDATIONS

Detailed recommendations must await the results of the MSFC physical property tests. However, several recommendations can be made on the basis of results reported herein.

A. STEEL, D6AC

Additional long panels of 1/2" material should be welded with a programmed decrease in power after achievement of full penetration to reduce underbead "drop" formations. This could probably be accomplished with slight modifications to the existing control circuits of the HPL industrial laser.

B. ALUMINUM, 2219

Additional long panels of 1/4" material should be welded with a fast time response recording power meter to establish any possible correlation between weld intermittency and blow holes, and short term power variations. The fast detector used on the closed loop power control could be used for this purpose.

For the heavier aluminum, the wider, but more straight sided focused laser beam achieved with a newly assembled F/21 focusing telescope should be tried. Preliminary welding tests in steel with this telescope have produced welds with narrower beads in the thicker sections (1/2" - 5/8"). Also, thick sections can be welded at a higher feed rate. Both of these effects should help achieve a more stable bead geometry in the 1/2" aluminum, and might reduce the porosity level.

APPENDIX I

AVCO HPL* 10 kW LASER SYSTEM

This laser is the highest power industrial system currently available. To date, three such systems have been built, and a fourth is under construction.

The HPL laser processing system consists of a main lasing chamber, power supplies, controls and beam manipulator. These units are interconnected by piping and electrical cables to form a complete functioning system.

A. LASING CHAMBER

Within the chamber (Fig. 16) is the closed-cycle wind tunnel (including blowers and heat exchangers needed to remove excess heat from the lasing cavity), and the 2 mirror optical cavity in which the lasing action takes place. At the very high power level of this system, there are no reliable window materials to allow transmission of the laser beam through the chamber wall. To circumvent this problem, the laser beam is brought to a focus at the chamber wall by a third mirror, and is then transmitted through a set of small holes in the wall. This "aerodynamic window" is designed to balance the pressure differential between the low-pressure lasing chamber and the outside atmosphere, and prevent any air from entering the cavity. Consequently, with this design, there is no need for a material window.

Because of the particular type of optical cavity used in the laser, referred to as an unstable oscillator, the beam is hollow at all locations other than the focal point, where it has a Gaussian distribution.

B. POWER SUPPLIES AND CONTROLS

The power supplies are housed in separate containers and connected to the laser through insulated and shielded cables. Each power supply is completely regulated by closed loop controls so as to maintain the selected voltage. A closed loop control system samples the laser output power and automatically adjusts that power to equal the value set by the operator. Upslope and downslope controls provide zero to full power adjustments from 0.2 to 10 sec. The stability and reproducibility achieved with this closed loop system is better than 2%. Evidence of this can be seen in Fig. 17 which shows the output power history of seven individual runs, all recorded on the same chart. The power levels for all runs was the same - 15 kW, but the upslopes and downslopes were varied from 0.25 sec to 3 sec.

*Trademark of the Avco Everett Research Laboratory, Inc.

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AVCO HPL-10 LASER

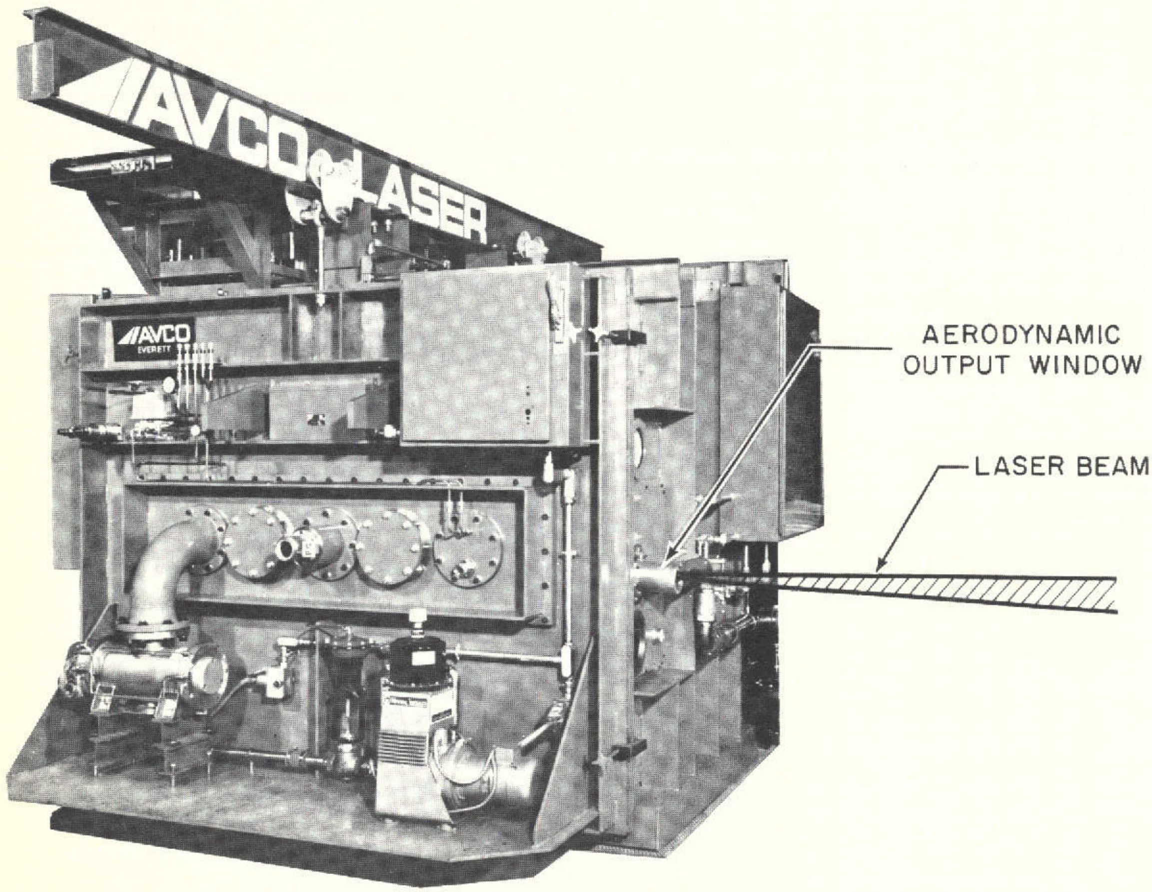

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Fig. 16 Photograph of Main Lasing Chamber of Avco HPL Industrial Laser used for this Program

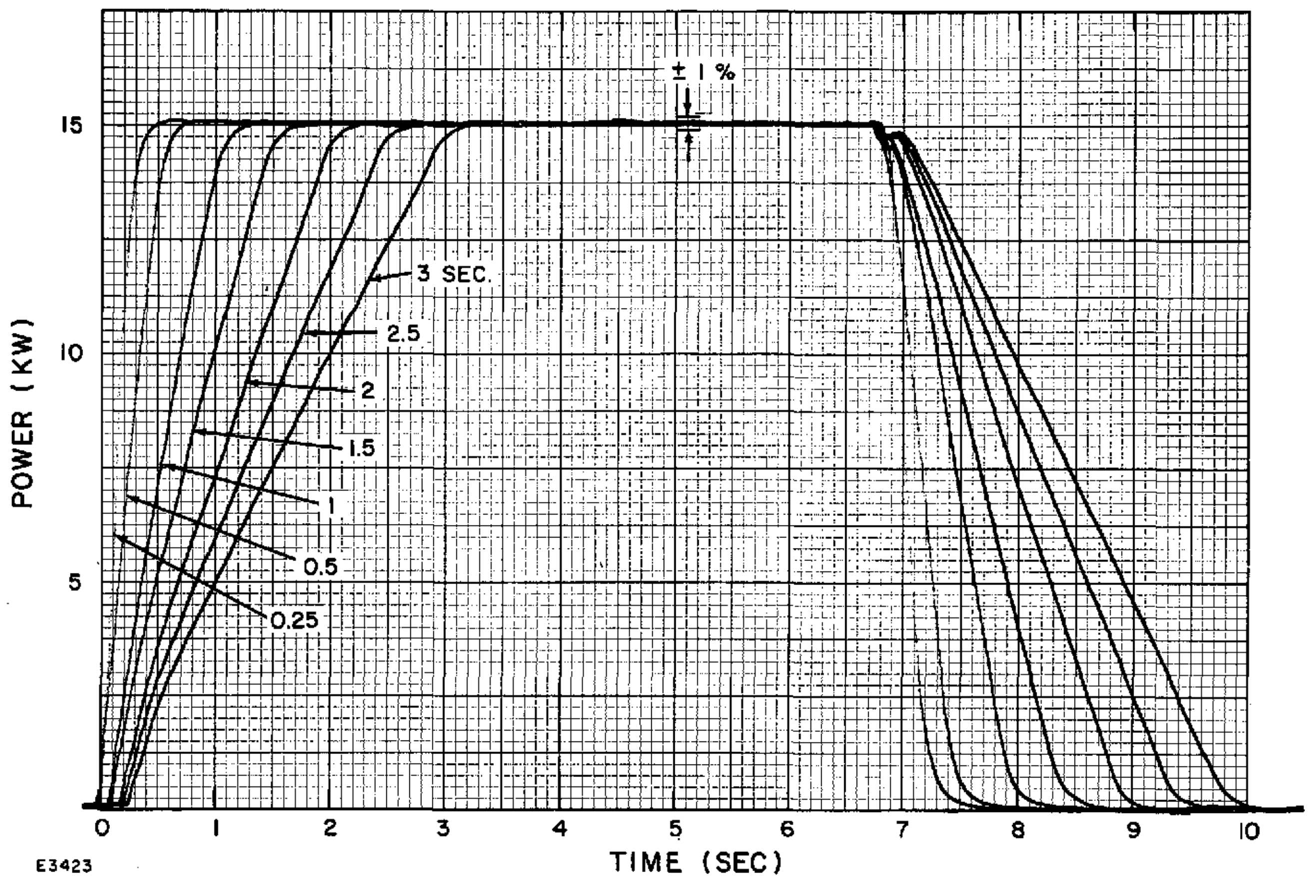


Fig. 17 Chart Recording of Repeated Beam Power Level Measurements at Various Upslope and Downslope Dial Settings

The operating console contains all necessary functions for operating, monitoring, and controlling the system. The laser power and workstation controls are manually or semi-automatically controlled by an operator. For a production application, the entire system can be controlled via numerical or computer control.

C. BEAM MANIPULATOR

The beam manipulator for the system currently in operation at the Avco Everett Research Laboratory is shown schematically in Fig. 18. This system focuses the output beam from the lasing chamber either onto a workpiece located at workstation one or workstation two. The workpiece is then transversed through the laser beam to accomplish the desired process.

The first mirror in the beam manipulator collimates the diverging beam which emerges from the aerodynamic window. A flat mirror then deflects the beam in an upward direction to the rotating mirror which directs this parallel, 3-inch diameter beam to either workstation one or two. Very accurate microswitches are actuated at the travel limit of mirror rotation to ensure proper optical alignment before the appropriate control console is activated. Once this interlock is engaged, the first workstation control is inoperative. When the laser power cycle has been completed, the beam can be used for either station, on a first-come, first-served basis.

The distance between workstations can be as great as several hundred yards. The beam, as it spans this distance, is contained in a simple sheet metal enclosure for safety reasons. More than two workstations can be used, if deemed necessary by the particular application. Such time sharing techniques can greatly increase the utilization of the laser system by allowing several time-synchronized production lines to use the same laser source. For example, while a particular assembly is being set up for processing at one station, a similar, already set up part can be processed at another station. Also, if a single part requires two different processes, such as welding and heat treating, one workstation could be set up for welding, the other for heat treating.

A sheet steel cabinet, with large hinged doors, encloses the beam manipulator. This enclosure isolates the high power laser beam from the working area, and allows a filtered blower system to generate a slight positive pressure inside the beam manipulator to prevent dust from collecting on the optical elements. Large clear plastic doors which do not transmit any of the infrared laser beam enclose the immediate work area. These doors, which must be closed before the system will operate, prevent the operator from being exposed to any laser radiation. A photo of the system is shown in Fig. 19.

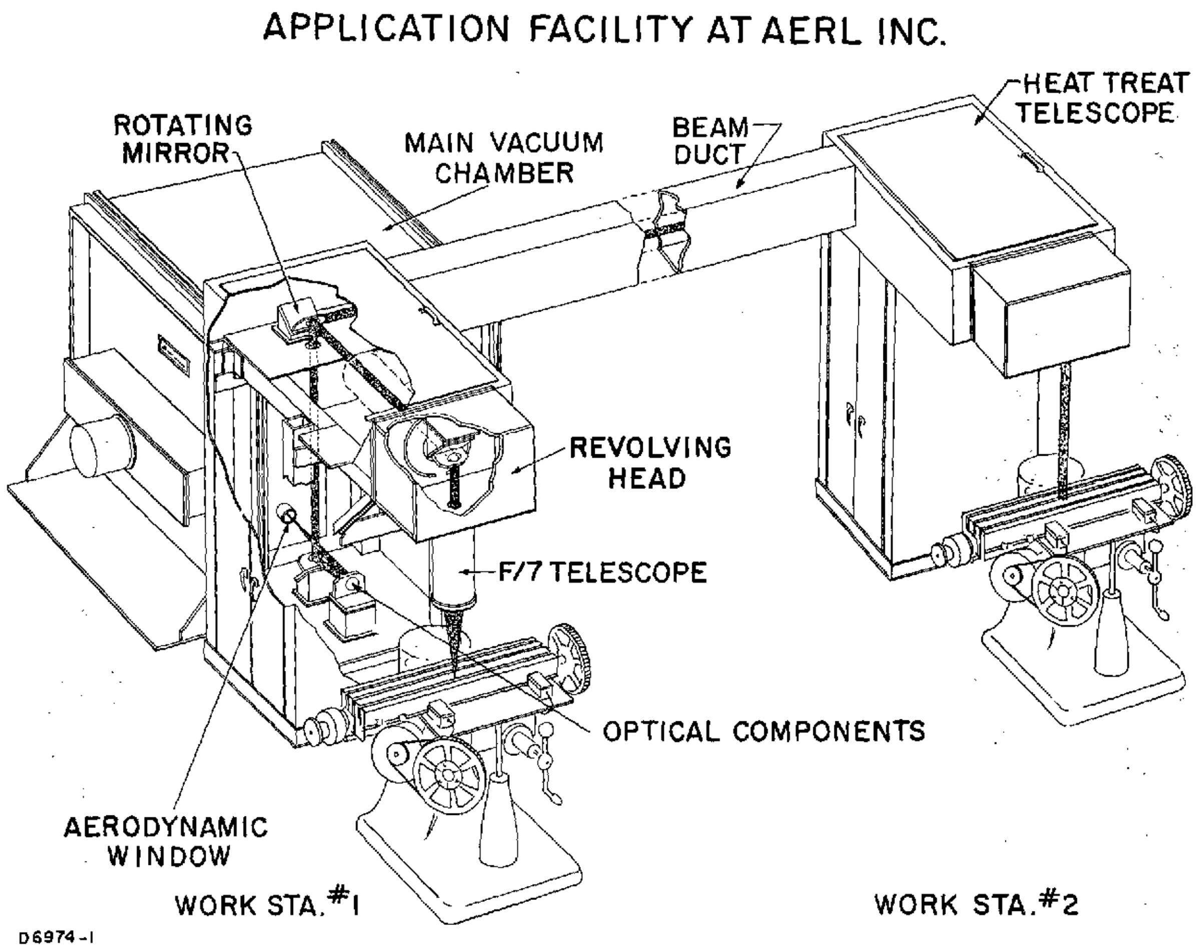
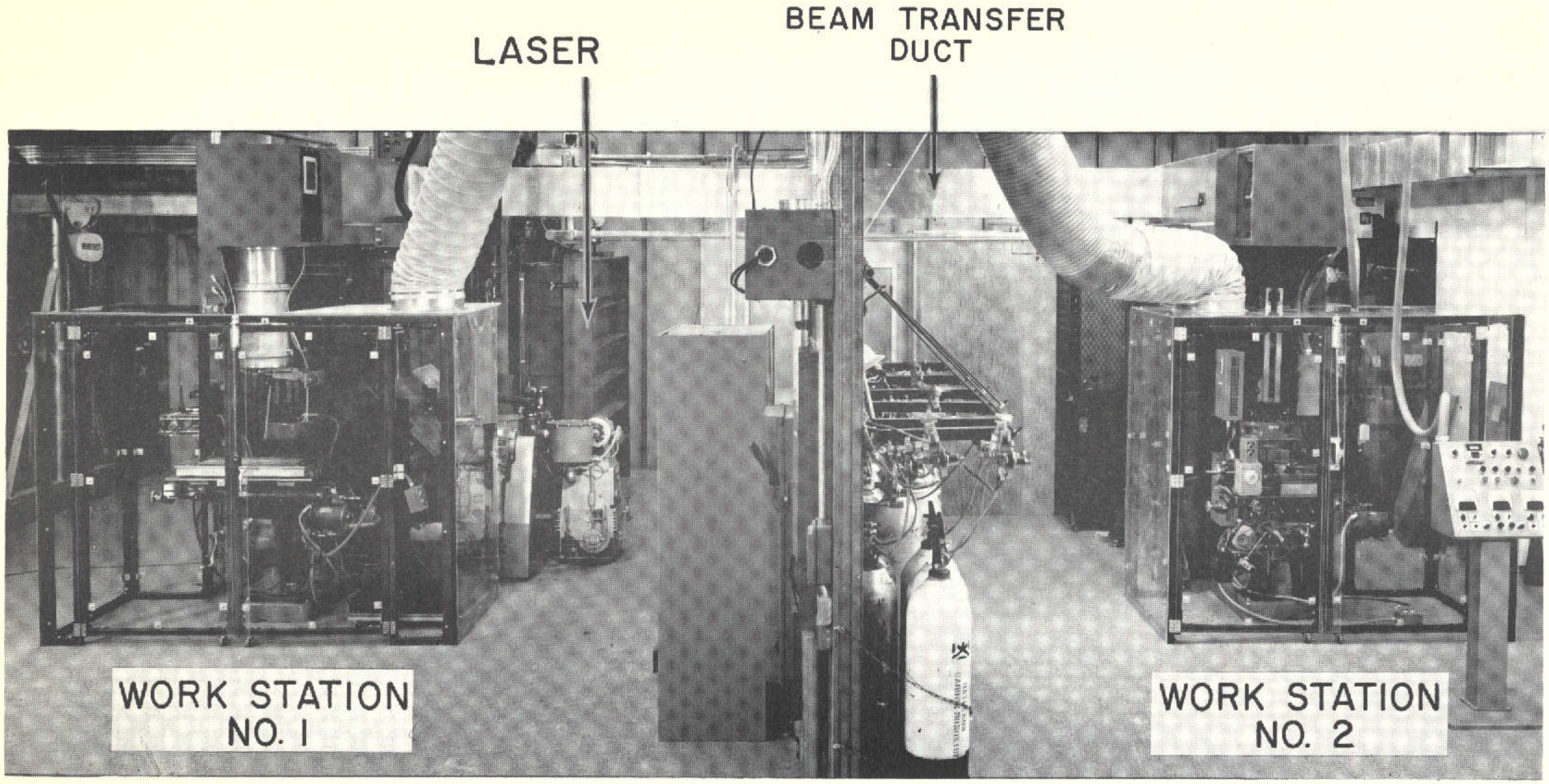


Fig. 18 Schematic of Two Station Avco HPL Industrial Laser Metal Processing System Located at Avco Everett Research Laboratory, Inc.

TIME SHARED LASER SYSTEM WITH TWO WORK STATIONS



D7588

Fig. 19 Photograph of Two Station Avco HPL Industrial Laser Metal Processing System Located at Avco Everett Research Laboratory, Inc.

APPENDIX II

LARGE STRUCTURE LASER WELDER

Shown in drawing DS2397 is a layout for a laser system to weld large structures such as space vehicle boosters. The system consists of a large three-axis positioner which locates the welding head in close proximity to the section to be welded. The welding head itself is capable of an additional 4 axes of motion, two positional and two angular. A seam tracker located within this welding head would guide the entire system along the joint to be welded. Such a system, complete with laser, beam manipulator and controls, would probably cost in the neighborhood of $750, 000 to $1, 000, 000.

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